Combat Aircraft Scenario Tradeoff Models for Conceptual Design Evaluation

by

Antonio Trani Cabrera

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APPROVED:

D.R. Drew

A.G. Hobeika

S. Ardekani

B.S. Blanchard

J.G. Casali

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Antonio Trani Cabrera

Donald R. Drew

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(Abstract)

The purpose of this research is to apply engineering-based knowledge to the field of combat aircraft survivability, and to create scenario-specific models in order to estimate the tradeoff between aircraft survivability and lethality metrics at the encounter and sortie levels. The development of scenario-specific models serves to identify and quantify technological changes that have leverage on the overall performance of the aircraft from a survivability point of view. Also, the models focus on the fighter aircraft susceptibility assessment and are capable of incorporating outputs from offline studies as inputs, such as in the area of *vulnerability* assessment where extensive data bases are available.

The mission scenario models are microscopic in nature and relate important conceptual aircraft design parameters such as thrust-to-mass ratio, wing loading, empty mass, maneuverability, etc. and operational parameters (e.g., weapon payload, range, loiter time, flight profiles, etc.) to the aircraft sortie survivability and lethality under various threat scenarios.

This research proposes a methodology to estimate survivability and lethality aircraft performance at the sortie level where aircraft parameters can be implemented into scenario specific models to assess their impact upon survivability-related metrics. While the project was conceived with naval aircraft in mind, the methodology, to the extent possible, is not to be aircraft-specific and thus could be applied to any particular design at the conceptual stage.

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Dedication

I would like to dedicate this dissertation to all the members of my immediate and extended families for their continuous encouragement and support through my years of college life. To my beloved wife, , this dissertation is a tribute to her love, patience, and understanding for all the times we did not share together through the research.

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1.0 Introduction

1.1 Background of the Problem

The design, procurement, and logistic support of any complex system requires a clear appreciation of many technical and non-technical disciplines needed to convert a well identified *need* into a useful and cost-effective system. As the level of technological sophistication brought to a particular system increases, there seems to be a corresponding difficulty in assesing tradeoffs between the operational, design, and cost characteristics associated with the system. This difficulty arises mainly due to the uncertainty in estimating the "value" of state-of-the-art technology in terms of system effectiveness. The problem then is defining how much technology should it be incorporated into a new or modified system in order to to boost its performance to a level that is appealing to the customer, but at the same time acceptable in economic terms.

The design process of military aircraft represents a particular field where decisions are generally based upon tradeoff studies derived from thousands of detailed analyses at various levels and between several disciplines in order to determine levels of acceptable performance in a tightly constrained economic environment. Recent trends in modern combat aircraft

development seem to suggest that future projects will in fact be "shared" ventures between several partner companies or even countries in order to absorb the exorbitant economic resources involved in a single design project. This particular phenomenon is currently spreading not only through European nations with the development of the European Fighter Aircraft (EFA) by four nations and the French Rafale D, but also within United States with the teamwork efforts among the seven largest aircraft manufacturers (i.e. McDonnell Douglas, Lockheed, General Dynamics, Boeing, Northrop, Rockwell, and Grumman) in order to secure contracts with the armed forces in the development and testing of the Advanced Tactical Aircraft (ATA) for the Department of the Navy and the Advanced Tactical Fighter (ATF) for the Air Force.

Gansler [1987] suggests that the acquisition cost of fighter and attack aircraft has skyrocketed at an average rate of seven percent annually in the past thirty years. In some cases the cost of procuring equivalent-role aircraft has risen more than ten times such as in the case of air superiority fighters from the fifties and seventies. In 1951, a Rockwell International F-100 "super-sabre" fighter was procured at about 2.5 million dollars (FY-81) while in 1971 a McDonnell Douglas F-15 was valued at 26.0 million dollars (FY-81) according to Gansler [1987]. Obviously one can perceive the potential procurement price escalation for aircraft to enter service in the middle 1990's if the trend were to continue. The same trend, when applied to the number of military aircraft procured each year, yields surprising results for the last three decades. In the fifties, procurements of 3000 aircraft per year were affordable; in the eighties, just over 300 are acceptable [North, 1986]. Thus, every year the armed forces are confronted with smaller fleets of hopefully more capable aircraft to confront an ever growing number of threats. The point to be made from this discussion is that system effectiveness and costs are the major driving constraints in the design and full scale development of a military aircraft. Unfortunately, there is no easy way to reconcile these two attributes, and aircraft designers are faced with the ever more difficult task to develop versatile aircraft that not only should perform well under various scenarios but that are also reliable and maintainable, thus keeping life-cycle cost at an affordable level. In order to

establish a framework from where to judge concepts, the designer has to clearly understand the aircraft system operational requirements provided by the customer and establish adequate measures of merit (MOM) to objectively compare designs.

Aircraft design is indeed an iterative process in which many compromises need to be made in order to arrive at an acceptable solution. Aircraft operational requirements are often in conflict and optimization techniques and sensitivity studies are generally needed to arrive at a "best" alternative. Table 1.1 lists some of the aircraft characteristics that typically would be considered in the conceptual design of an advanced fighter aircraft [Nicolai, 1975]. Although these aircraft attributes have been listed as separate groups it is important to understand that many of them are intimately related. For example, in a typical ground attack mission scenario, one can consider as a valid metric of system effectiveness the number of targets destroyed per aircraft attrited. In order to achieve high values of this metric the aircraft not only should possess reasonably high values of sortie survivability, but also, high weapons lethality and subsystems reliability in order to minimize the number of sorties (i.e., thuis reducing the susceptibility of aircraft to ground fire) and time required to accomplish the mission goal. Another example of the highly coupled nature of these design parameters can be deduced from several studies by Herbst [1983], Parker [1986], Callahan [1986], McAtee [1987], and Skow et al [1986] which point out the importance of *instantaneous* aircraft performance in order to survive a modern air-to-air engagement with all-aspect weapon capability. Hence, aircraft survivability is dependent upon aircraft performance. The question arises as how important this causal link really is. In other words, the quantification of these relationships must be made in a realistic combat scenario if more *survivable* systems are to be procured. The issue of survivability and how it relates to aircraft design is only part of the type of analysis that one has to consider when procuring an expensive and complex system such as a combat aircraft.

Nevertheless, its role is so important that it is the prime motivation behind this research. Survivability, as a design discipline, has always been considered as an integral part of the aircraft design and development process. Unfortunately, many past ventures it have either

Table 1.1 Aircraft Attributes Addressed in Conceptual Design (adapted from Nicolai)

	Attribute	Example
1	Size and Mass	Gross Mass, Wingspan, Length, Aspect Ratio
2	Performance	Dash Speed, Payload, Range, Maneuverability Metrics, Combat Ceiling, Takeoff and Landing Field Requirements
3	Cost	Life Cycle, Acquisition, Maintenance, Logistic Support
4	Environment	Carrier Suitability, All-weather Strike Capability
5	Survivability and Lethality	Probability of Sortie Survival, Single Shot Kill Probability, Probability of Aircraft Hit.
6	Safety	Spin Departure Resistance, Engine-out Condition, Crew Escape System, Stall Buffet Boundaries
7	Handling Qualities	Static Margin, Direction Stability, Pitch Stability, Roll Damping, High Angle of Attack Controllability
8	Comfort	Ride Qualities, Cabin Noise, Vibration Levels
9	Logistic Factors	Maintainability, Supportability, Subsystem Reliability

been relegated to a secondary role or neglected at early stages of the design process where its impact on the final product could have been most valuable. In the Viet Nam conflict for example, the United States lost over 2500 fixed wing aircraft [North, 1985], most of them due to small-caliber ground fire. It became evident at the time that aircraft survivability was not properly addressed in some of the aircraft involved in the conflict and "quick" fixtures had to be used in order to reduce the aircraft *susceptibility*, the probability of the aircraft being hit, and to also reduce the aircraft *vulnerability*, the probability of being killed given a hit. The end result of this costly lesson is the fact that survivability should be viewed from a systems engineering point of view, and should be incorporated at the early stages in the design and development process in order to procure more survivable aircraft at minimum life-cycle cost.

1.2 Future Navy Based Advanced Tactical Aircraft

Currently, in the development stage the Advanced Tactical Aircraft (ATA) and the Advanced Fighter Aircraft (ATF) will represent a new generation of fighter aircraft to be introduced into service with a "design-to-cost" philosophy in mind in order to avoid the potential escalation of prices beyond the desired thirty five million dollar acquisition unit price. This target acquisition cost seems difficult to achieve for the level of technology needed to counter future threats well into the twenty-first century but the services are confident it can be met. The two designs will share common technology since obviously this will tend to lower the development cost. However, their design characteristics will be unique since each aircraft will be optimized for different roles. The naval role adds several tight constraints to a design due to the stringent approach and landing requirements which necessitate an oversized landing gear and good low speed handling qualities. At the same time, aircraft size is limited to suit existing carrier facilities such as elevators, hangars, catapult launchers, and arresting systems. For example, for two modern aircraft such as the McDonnell Douglas F-15A and the

F/A-18 the landing masses differ by about 20 percent in favor of the land-based F-15A. However, due to the high sink speed requirements for naval operations (e.g. more than double the maximum design sink speed), the F/A-18 requires a landing gear 250 kg. heavier than its land-based counterpart [McDonnell Douglas, 1985]. From this point on, the focus of interest of this research will concentrate in naval aircraft operations, since it is in this combat arena where multirole capability takes particular importance due to the inherent air carrier space limitations. The aircraft carrier takes the "airfield" to the battle and, thus, needs to be properly equipped for almost any contingency.

Carrier operations span a multitude of missions which need to be conducted by a relatively small number of aircraft. Antisubmarine warfare (ASW), search and rescue (SAR), early warning and strike control (AWACS), electronic countermeasures support (ESM), and the transport of personnel and equipment are some of the aircraft operations delegated to very specialized aircraft other than high performance fighters. Fighter aircraft on board the carrier perform close air support missions (CAS), target interdiction (TI), combat air patrol (CAP), fighter escort (FE), reconnaissance (RECCE), and surface attack or defense suppression (SA). A brief description of these roles and required aircraft characteristics is given below.

1.2.1 Close Air Support (CAS)

Close air support missions are performed against targets that are in the proximity of friendly forces [Ball, 1985]. The idea is to destroy threats that represent a difficult target for ground forces. Necessary aircraft attributes are good payload capability, good low level handling qualities, high maneuverability, all-weather capability, high sortie rate capability, low vulnerability, high subsystems reliability etc. Current naval aircraft devoted to this role are the LTV A-7 "Corsair", the Grumman A-6 "Intruder", the McDonnell Douglas F/A-18 "Hornet", and the McDonnell Douglas AV-8B.

1.2.2 Interdiction (I)

This type of mission is usually carried towards threats located at great distances from the friendly forces. Its purpose is to target military installations that could potentially become a threat to friendly forces. Good aircraft characteristics are high payload-range capability, high maneuverability, good low level handling qualities, all-weather capability, low pilot workload, low vulnerability, high subsystem reliability etc. Naval aircraft fulfilling this role are the Grumman A-6, and the F/A-18 although the latter one is very limited in range-weapons capability.

1.2.3 Combat Air Patrol (CAP)

This mission is devoted to intercept and destroy enemy aircraft that pose a threat to the aircraft carrier battle group (CBG). The aircraft fulfilling this mission should have an extremely good loiter capability, good radar detection and tracking capability, long range stand-off weapons, and high dash speed capability. This mission, when integrated with the antisubmarine warfare (ASW) and early warning (AWACS) missions, is known as fleet air defense. The only current naval aircraft capable of fulfilling this role is the Grumman F-14 "Tomcat".

1.2.4 Fighter Escort (FE)

The purpose of this type of mission is to provide coverage to companion attacking aircraft (e.g. bombers) against potential enemy aircraft, thus denying air superiority from the enemy. Shaw [1986] identifies several variants of fighter escort missions: 1) reception escort, 2)

detached escort, 3) close escort, and 4) remote escort. This classification is based upon the location of the escorting fleet with respect to the main attacking force. The fourth variation is is sometimes considered an entirely "independent" mission and, as such, is termed "fighter sweep"; however, it is generaly followed by an attack. Fighter sweep and remote escort are used interchangeably through this research because of the apparent subjectivity involved in differentiating between them. Ideal characteristics for aircraft performing this mission are high dash speed, high maneuverability, good air-to-air weapons, look-down shoot-down and all-weather capabilities. Current aircraft in the Navy inventory performing this mission are the McDonnell F/A-18 and the Grumman F-14.

1.2.5 Reconnaissance (RECCE)

As it name implies, this mission assesses the location, movement, or status of threat elements before or after a strike [Ball, 1985]. Aircraft attributes required are high dash speed, good maneuverability, long range, good subsystem reliability, and an array of data collecting sensors. Aircraft devoted to this role are the McDonnell Douglas RF-4 and specially equipped Grumman F-14.

1.2.6 Surface Attack (SA)

Surface attack, ground attack, and defense suppression describe the mission that attempts to destroy or jam enemy air defense systems involving electromagnetic sensors [Ball, 1985]. This mission involves medium to long distance flights in order to reach the target area. Desirable aircraft characteristics are similar to those of the target interdiction mission with heavier electronic countermeasures equipment. Currently, the Grumman A-6 and McDonnell Douglas F/A-18 perform this role.

1.3 Objective of the Research

The purpose of this research is to apply engineering-based knowledge to the field of combat aircraft survivability, and to create scenario-specific models in order to estimate the tradeoff between aircraft survivability and lethality metrics at the sortie level. These models will be structured in order to identify technological changes that have leverage on the overall performance of the aircraft from a survivability point of view. Also, they will be able to incorporate outputs from offline studies as inputs, such as in the area of *vulnerability* assessment where extensive data bases are available throughout the Survivability/Lethality Information Analysis Center (SURVIAC) [Vice, 1986].

The complete scope of this research should be viewed in the context of developing an aircraft survivability and lethality tradeoffs methodology that will be a decision making tool for those individuals involved in the design, procurement, and support of new or modified military aircraft. It is felt that existing aircraft survivability methodologies have not addressed properly the intrinsic interactions between aircraft survivability, combat effectiveness, and attrition [Drew et al, 1986]. Most of the models in use today are short sighted by considering only the effectiveness of the force in question, while completely neglecting the interactions that take place between combatants. The creation of mission tradeoff and scenario-specific models that account for the characteristics of the threat as well, as those of the forces of interest seems to fulfill the necessity of a more generalized and realistic approach to estimate aircraft survivability.

Table 1.2 depicts the model organization to envisioned for the complete aircraft survivability and lethality tradeoffs methodology. The left hand side represents mission scenario models to be developed in this research while the right hand side represent the respective mission tradeoff models associated with the former ones. Also, shown is a multimission scenario and a multimission tradeoff model used to evaluate aircraft survivability performance of proposed multimission aircraft.

The mission scenario models are microscopic in nature and relate important conceptual aircraft design parameters (e.g., penetration speed, signatures, weight, maneuverability, etc.), and the operational parameters (e.g., weapon payload, range, loiter time, flight profiles, etc.) to the aircraft sortie survivability, given a particular threat scenario as depicted in Table 1.3. The outputs of these models are then used in the tradeoff models to assess mission survivability (levels 4 and 5 in Table 1.3) and further extended to level 6 by means of even more macroscopic models already developed such as SURMAN [Drew and Tran, 1984].

1.4 Relation of This Research with Companion Models

A research project has been under way at Virginia Tech to develop a methodology for conceptual design evaluation by determining the effect of aircraft performance parameters and survivability enhancement features on combat survivability and effectiveness. Previous work has been performed in the development of a resource allocation tradeoff model (level 6 on Table 1.3) such as SURMAN [Drew and Tran, 1984] where cost and procurement of fighter aircraft were considered to assess the best aircraft allocation policies at the national level. Also, Levels 5 and 4 have in Table 1.3 have been addressed by Malakhoff [1988] where a tradeoff methodology was developed to evaluate aircraft system survivability efectiveness at the mission level. It should be recalled that by a mission it is meant that aircraft from a given fleet perform several sorties in order to achieve a goal (e.g., to launch a predetermined number of weapons). This research proposes a methodology to estimate survivability and lethality aircraft performance at the sortie level (Level 3 of Table 1.3) where aircraft parameters can be implemented into scenario specific models to assess their impact upon survivability-related metrics. While the project was conceived with naval aircraft in mind, the methodology, to the extent possible, is not to be aircraft-specific and thus could be applied to any particular design.

Table 1.2 Research Model Organization		
Scenario Model	Tradeoff Model	Aircraft Type
Surface Attack Mission Scenario	Surface Attack Mission Tradeoff	Attack/Close Air Support
Air Superiority Mission Scenario	Air Superiority Mission Tradeoff	Air Superiority Tactical Aircraft
Multimission Mission Scenario	Multimission Mission Tradeoff	Multimission Aircraft

This dissertation represents the work accomplished in the development of computer simulation models to be used (1) to microscopically evaluate different survivability-related performance concepts such as susceptibility, vulnerability, lethality and inventory in a total weapon system environment for a new or modified combat aircraft, and (2) to perform trade-off analysis between the aircraft's design/operational features and its mission requirements. This work is an application and extension of research performed under the long-term cooperative effort between the Joint Technical Coordinating Group for Aircraft Survivability (JTCG/AS) and Virginia Polytechnic Institute and State University (VPI&SU) in the area of survivability management (SURMAN).

A basic tenet of the survivability discipline is that survivability considerations must be incorporated at the earliest time in the development cycle of the aircraft in order to optimize costs/benefits. This is also true for other considerations such as mission effectiveness, force effectiveness, and affordability. Thus, in order to achieve a complete and sound development plan for future aircraft, these considerations must be studied and evaluated throughout their development cycle, from concept formulation to design and implementation.

There are five major areas of emphasis to be covered in a complete survivability study: susceptibility, vulnerability, lethality, inventory, and systems evaluation. Susceptibility focuses

on those mechanisms that lead to the detection of the aircraft and avoidance of its being hit. Vulnerability addresses the ability of the aircraft to withstand different levels of damage [MIL-336-1, 1982]. Lethality addresses the effectiveness of the aircraft as a defensive and offensive weapon system. Inventory concerns such issues as procurement and affordability, because one of the objectives of the project is to provide a mechanism for performing tradeoff analyses among the overall force effectiveness. Finally, the system's evaluation part of the model synthesizes the results of all the essential elements of consideration to provide a means for evaluating the effectiveness of the aircraft at the tactical level as well as at the force-on-force level. The first three areas mentioned above are engineering oriented. Their purpose is to synthesize the engineering knowledge for making management decisions. Thus, the models will be structured in order to identify technological changes that have leverage on the overall performance of the aircraft. Additionally, they will be able to receive outputs of offline studies as inputs [Drew et al, 1987].

Survivability-related modeling can be thought of as spanning several levels as shown in Table 1.3 In this context, the engineering analysis of survivability represents a bottom-up approach starting at the lowest level, Level 1, where the end-game interactions between the damage mechanisms of the threat and the target are assessed to define the so-called single shot kill probabilities. Survivability management, on the other hand, represents top-down approach having its roots in the resource allocation level (Level 6). Levels 2, 3, and 4 provide the mechanism relating the engineering/design parameters (e.g., speed, signatures, weight, excess energy, etc.), and the operational parameters (e.g., payload, range, flight profile, etc.) to the aircraft survivability. In Levels 5 and 6, the thrust area is in relating the aircraft survivability to the parameters that describe the overall force effectiveness so that the changes in technology, operations and/or management policies can be evaluated. This dissertation deals with engineering *survivability* issues corresponding to Levels 2 and 3 where encounter and sortie survivability measures are derived from detailed mission scenario models. The ultimate goal is to quantify the effects of design decision variables that impact the survivability of the aircraft under various scenario conditions.

Table 1.3 Survivability Analysis Hierarchy

Level	Description	Key Parameters
1	Vulnerability Assessment Munitions Effectiveness Assessment	Aircraft Single Shot Prob. of Kill, Pssk(A/C) Threat Single Shot Prob. of Kill, Pssk(Threat)
2	Encounter Survivability Assessment Encounter Lethality Assessment	Aircraft Survivability/Encounter, Ps/e Aircraft Lethality/Encounter, Ps/e
3	Sortie Survivability Assessment Sortie Lethality Assessment	Aircraft Survivability/Sortie, Ps/s Aircraft Lethality/Sortie, Pk/s
4	Mission Attainment Survivability/Effectiveness Determination	Campaign Survivability, Ps/c Mission Attainment Measure, MAM Measure of Mission Success, MOMS
5	Survivability Cost-Effectiveness Tradeoffs	Relative Exchange Ratio, RER Aircraft Replacement Cost, RC Possible Crew Loss, PCL
6	Resource Allocation Tradeoffs	Budget to R&D, O&M, and Procurement

1.5 Survivability in the Systems Engineering Process

The implementation of survivability elements into a complex system, such as a modern combat aircraft, can be better understood in the context of the systems engineering process. This process allows designers and decision makers to adopt a rational approach to transform an operational need into the development of an efficient product for consumer use [Blanchard and Fabrycky, 1981]. When applied to the fighter aircraft survivability discipline, the system engineering process encompasses a wide range of activities spanning from the identification of the mission threat and the aircraft survivability operational needs, depicted in Block 1 in Fig. 1.1, all the way to the phase-out of the survivability equipment and its associated logistic resources (Block 9). Figure 1.1 illustrates the typical survivability life-cycle and its intimate association with the systems life-cycle. Activities on the right hand side are meant to illustrate typical steps followed in the planning, design, and development of the survivability subsystem of an advanced fighter aircraft. The main concern throughout the entire cycle is to develop a well balanced survivability subsystem that will enhance the aircraft capability to successfully complete its mission within prescribed performance and cost considerations.

An important point to be made here is the fact that activities shown as part of the survivability cycle are actually executed within the context of the entire aircraft systems engineering process, since a close integration between many design disciplines is necessary to ultimately achieve an efficient product. For example, the extensive use of metal matrix composite materials in the new generation fighter aircraft could have significant advantages other than sizable mass reductions. From the *vulnerability* point of view, certain composite materials (e.g., reinforced carbon and aromatic polyamide fibers) have tensile strength and hardness properties superior to those of aluminum, making them less prone to threat damage [Horne, 1986]. Furthermore, these new materials have the potential of reducing the *susceptibility* of the aircraft due to radar signature reduction. The reduction of these two survivability-related variables can have a strong influence in the aircraft material selection

even at the conceptual design stage. Hence, it is important that early configuration decisions be made considering survivability related constraints as part of systems analysis process (Block 2). Following the order of the survivability life-cycle, it is seen in Block 3 that once aircraft alternatives are identified, these should be tested in survivability models ranging from mission scenario and effectiveness to end-game survivability models to determine aircraft performance under a variety of scenarios. This research concentrates in the scenario modeling arena to provide aircraft designers and decision makers with a quick method to assess aircraft survivability at the sortie level.

During the complete aircraft systems evaluation, survivability results from this block should be weighted properly with hundreds of other parameters in order to establish a baseline configuration that will be the subject of more in-depth studies as shown in Block 4. At this stage, specific survivability design features are identified and synthesized with other aircraft disciplines (e.g., powerplant, aerodynamics, structures, etc.) to establish the aircraft system definition (Block 5) and submit the survivability program plan for customer for approval [Ball 1985]. The next step is to begin construction of pre-production elements and subsystems to validate their performance though a generally rigorous and lengthy test and validation phase. Constant reviews of the survivability program should be made at this stage in order to insure proper adherence to the program plan. In Block 7, the integration of the production survivability elements and subsystems takes place while, in Block 8, a continuous reassessment of the threat and survivability operational requirements is made to anticipate engineering changes necessary to maintain a desired level of performance operationally. It should be realized that Block 8 could be very dynamic and, thus, require large amounts of human and hardware resources (and many operational improvements) in order to counter new emerging threats. Current trends in the military aircraft operational environment suggest that useful life expectancies ranging from, 15 to 25 years, are typical for fighter-type aircraft. This relatively long service life, when coupled with disproportionate growth in several fields of aviation technology (e.g. aviation electronics), could bring a system obsolete in a very short time.

This last issue is especially true for *susceptibility* reduction mechanisms such as jammers, expendables, and guided threat suppression weapons which could be potentially nullified through the use of counter-countermeasures. While emphasis has been placed on survivability-related features to highlight their relevance in the overall systems engineering process, there are other equally important areas that are are addressed through the process and which could be largely affected by the aircraft survivability. Among them is the number of logistic support resources throughout the entire life-cycle. Some of the most relevant aspects of logistic support are also shown as part of the systems engineering cycle. Depending upon the actual hardware, the effects of a *good* survivability design could have a large effect upon the logistic support required. The rationale behind this argument can, in part, be attributed to the fact that a more survivable aircraft force requires less units in order to accomplish the same tactical goal than a less survivable counterpart, thus reducing the number of logistic support elements, everything else being equal.

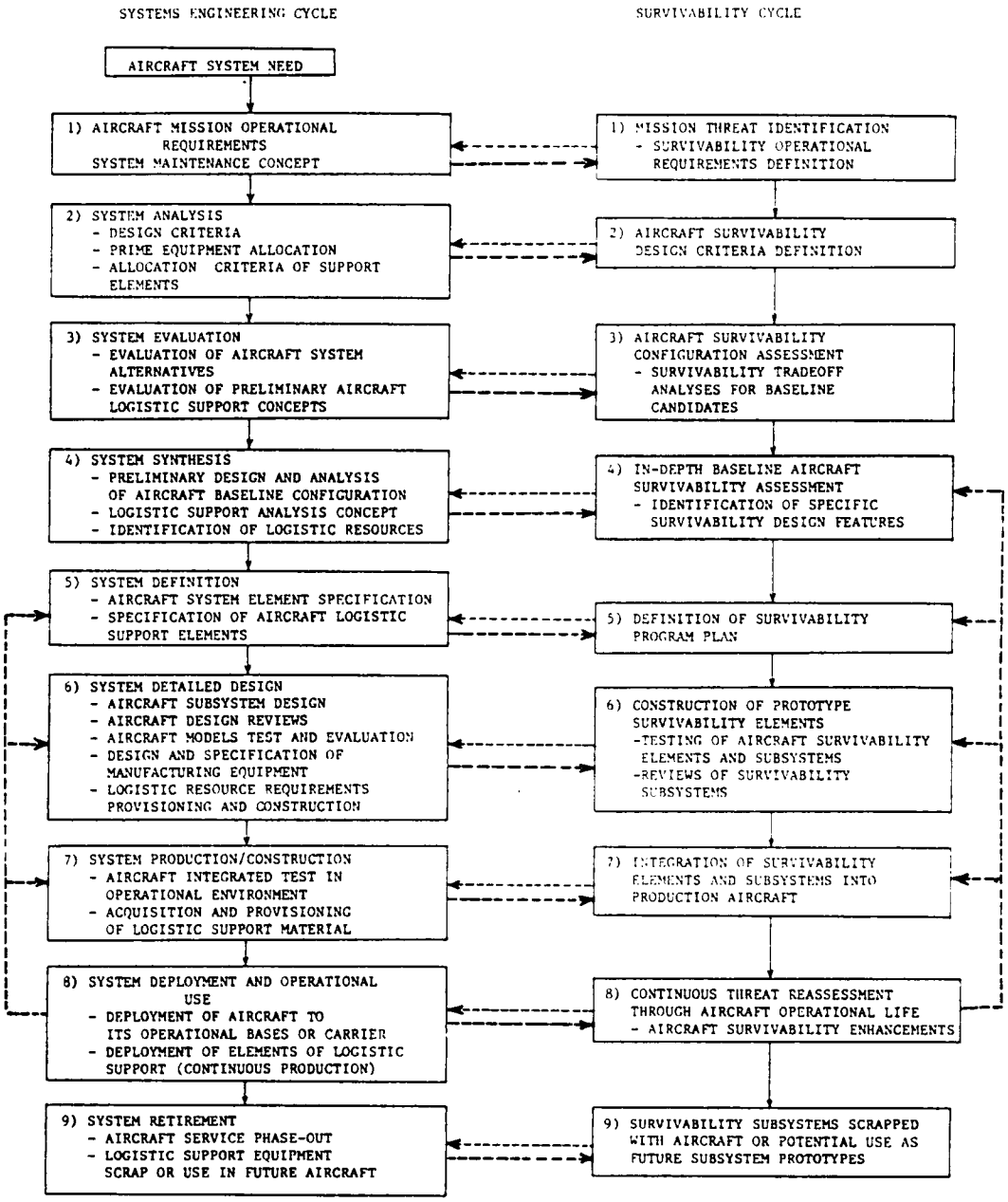


Figure 1.1 Survivability Discipline in the Systems Life Cycle.

2.0 Literature Review

Throughout history there have been manifestations of warfare activity among most human settlements. Although the motives of these unfortunate activities have in some cases not been clear, battles of diverse magnitude have been fought for religious, cultural, social, political, technological, and economic reasons. Man seems to have an inherent fascination for war that has led him to develop a multitude of strategies and weapons of all conceivable forms. One can imagine the first "strategists" relying upon common sense and *aposteriori* knowledge in order to develop simple tactical schemes and decide the outcome of simulated battles. Later, as battle elements increased in size and new weaponry was introduced into the engagements, the battles became more difficult to predict and man had to rely upon better means to analyze them. It seems that weapon technology developments have always been far ahead of any methodology to analyze the outcome of their employment. Well before the introduction of differential calculus by Liebnitz and Newton man had already fought battles of enormous moral and economic consequences and one cannot but wonder how strategists at the time planned for such events. During World War I, Frederick W. Lanchester, an english mathematician, was probably one of the first to characterize battles using differential equations [Springall, 1968]. Lanchester developed a general attrition model under the assumption that the attrition rates of two engaging forces would be some function of the force

sizes on each size and the attrition parameters (sometimes referred as attrition constants) associated with each force. In functional form Lanchester's equations can be written as follows:

$$\dot{X} = - F(\alpha,X,Y) \qquad \{2.1\}$$

and,

$$\dot{Y} = - G(\beta,X,Y) \qquad \{2.2\}$$

where, X and Y are the force sizes of the combatants, and α and β represent the attrition coefficients of each force. These coefficients represent the effectiveness of each force to destroy its opponent. Generally speaking α and β are functions of the number and accuracy of shots fired at the enemy. Lanchester developed two variations to this model: 1) the *linear* law and 2) the *square* models. The former one assumes that no concentration of fire is present (i.e. shots are fired indiscriminately at the enemy force without regard to the force state), while in the latter a concentration of fire is aimed at the surviving forces [Drew et al, 1986]. The linear model equations reduce to the following,

$$\dot{X} = - \alpha\ X\ Y \qquad \{2.3\}$$

and,

$$\dot{Y} = - \beta\ X\ Y \qquad \{2.4\}$$

while those of the square law model are,

$$\dot{X} = - \alpha\ Y \qquad \{2.5\}$$

and,

$$\dot{Y} = - \beta\ X \qquad \{2.6\}$$

Tactically speaking the linear law corresponds to a battle where no knowledge of the state of the opponent is available while the square law case arises when "perfect" information about the state of the aggressor is known throughout the engagement. These two extreme cases are justifiable in some specific cases. For example, a massive nuclear offense would invariably be closely related to the linear law model while an aerial engagement between several aircraft would probably be modeled using the square law . A further variation of these two cases would be to assume only perfect information for one of the sides. This approach adopted by Deitcham [1962] to model guerrilla warfare, is termed Lanchester's *mixed law*. Close form solutions for the deterministic and stochastic constant-coefficient Lanchester equations are available in the literature [Springall, 1968; Csaki, 1977; Santoso, 1984; Drew et al, 1986]. The difficulties start arising when time-varying effects are introduced in either the deterministic or stochastic models and in general numerical solutions are the best alternative [Springall, 1968]. Other researchers have introduced small variations to these models in order to account for heterogeneous forces [Weiss, 1959] and even replacement forces [Springall, 1968]. However, the solutions have been limited in scope to special cases. Santoso [1984] and Drew et al [1986] have used a more generalized attrition model which incorporates a linear combination of the linear law, square law, and two extra attrition factors for each of the combatants as shown in Eqs. 2.7 and 2.8. This model seems to be more realistic since the few correlations attempted to the Lanchester equations seem to lie somewhere between the linear and square law. This model has been solved analytically for four special cases and as in most Lanchester-type models can be implemented easily on a digital simulation.

$$\dot{X} = -\alpha Y - \gamma X - \nu X Y \qquad \{2.7\}$$

and,

$$\dot{Y} = -\beta X - \psi Y - \omega X Y \qquad \{2.8\}$$

where, X and Y are the force sizes of the combatants, and α and β represent the attrition effectiveness coefficients of each force or square law coefficients, γ and ψ are the added

attrition parameters, and ν and ω are interaction effectivess parameters or linear law coefficients [Drew et al]. Several efforts have been devoted to validate Lanchester-type models. Engel [1954] successfully validated a special deviation of the square law model with data from the battle of Iwo Jima fought during World War II. His model included a troop "replacement" term for the attacking force (i.e. american troops) to simulate the arrival of more troops at certain point in the battle. This model is shown in Eqs. 2.9 and 2.10.

$$\dot{X} = F(t) - \alpha Y \qquad \{2.9\}$$

and,

$$\dot{Y} = - \beta X \qquad \{2.10\}$$

where, X is the attacking force, Y the defending force, α and β are attrition effectiveness coefficients and $F(t)$ is the replenishment rate of attacking forces. In another effort Weiss [1966] applied a logarithmic term to the original Lanchester linear law to model selected battles in the U.S. Civil War with somewhat disappointing results at the beginning of the campaign. Peterson [1967] used the same modeling approach (Eqs. 2.11 and 2.12) in a one-on-one tank scenario.

$$\dot{X} = - \alpha X \ln(Y) \qquad \{2.11\}$$

and,

$$\dot{Y} = - \beta Y \ln(X) \qquad \{2.12\}$$

It is important to realize that although most of the deviations to the original Lanchester equations have been carried out for the deterministic time-invariant cases it is possible to augment the resolution and realism of a combat scenario by at least relaxing the time-invariant assumption.

Another approach to war modeling has been the use of game theory. This theory developed in the forties by Von Neumann and Morgenstern [Isaacs, 1965] was an attempt to predict economic behavior in competitive situations. However, as a mathematical approach that tried to establish best strategies between players in a competitive environment it immediately had repercussions in the field of military strategy. Berkowitzs and Dresher [1959] formulated a two-person multimove combat game in which the allocation of aircraft represented the moves of the game. They selected as *payoff* the distance advanced by ground forces as a function of the number of aircraft allocated to each strike. Although their model seemed to to yield good qualitative results for a campaign level it lacked specific considerations as far as the particular capabilities of the participants. In order to achieve better resolution of the actual interactions between players some researchers departed from the traditional matrix approach to game theory to initiate the field of differential games. Isaacs [1965] points out the fact that while a payoff matrix seems to be the right approach for simple two-player zero sum games the approach becomes less justifiable as the domain of the player's decisions increases (e.g. increases the size of the payoff matrix). Differential game theory then tries to analyze games among two or more players with classical tools such as differential equations. This approach although more promising in principle has been confined to relatively simple examples when applied to moving craft due to the large number of dimensions necessary to specify the state of the players. The basic principle of differential game theory is also finding the best strategy to optimize a given payoff (just as in traditional game theory). However, the set of control strategies available to each player are not necessarily bounded to a finite set but they could form part of a continuum (games of a degree). Hence, a differential game can be viewed as a *lengthy* traditional matrix game. Mathematically a differential game between two adversaries can be formulated as follows,

$$\dot{X}_i = F(X_1, X_2, \ldots, X_i, Y_1, Y_2, \ldots, Y_k, \gamma_1, \gamma_2, \ldots, \gamma_j) \qquad \{2.13\}$$

and,

$$\dot{Y}_k = F(Y_1, Y_2, \ldots, Y_k, X_1, X_2, \ldots, X_l, \psi_1, \psi_2, \ldots, \psi_l) \quad \{2.14\}$$

where, $\dot{X}_l$ and $\dot{Y}_k$ are the rate kinematic equations for each player, X_l and Y_k are the state variables, γ_l are the control or decision variables associate with player X, and ψ_l are the controls of Y. The purpose of the differential game is to find the values of γ_l and ψ_l that optimize the payoff for one of the players. Isaacs [1965] has formulated several interesting examples of differential game theory applied to vehicle pursuit problems as well as others dealing with simplified war scenarios. His formulation of the *homicidal chauffeur game* (a pursuit game between a car and a pedestrian) and the game of two cars for example, have both been used extensively with some mathematical embelishments through the years to solve a class of problems involving aerial pursuit in the horizontal plane [Peng and Vincent, 1975; Merz and Hague, 1977; Breakwell and Merz, 1977; Kelley and Lefton, 1977; Jarmark et al, 1981]. A generalization of all these models is the fact differential games are very sensitive to the basic assumptions made for the capture zones (i.e., regions where a player wins the game) of each player. Also, the analysis has been limited to terminal aircraft maneuvers and simplified vehicle kinematics. Another approach of similar scope to differential game theory is the formulation of end-game scenarios using optimal control theory. Several studies have focused in characterizing optimal control guidance laws to direct an aircraft or missile to an interception [Kelley and Lefton, 1977; Anderson, 1981; Ben-Asher, 1985]. Others have tried to establish optimal maneuvers to defeat an adversary [Kelley, 1973; Imado and Susumu, 1986]. These type of analyses are nevertheless important from our view point because they constitute sources of knowledge of end-game scenarios that naturally arise in aircraft survivability models. Falco and Carpenter [1981] point out that although some advances in the mathematical development of modern optimal control and differential game theories have been achieved in the past years there does not appear to be a systematic approach to even the simplest pursuit-evasion games. Their approach to estimate system combat effectiveness was based upon an stochastic learning computational method. This highly computational approach is based on the construction of a *decision table* containing probabilities of

successful evasion against a threat for various elementary vehicle maneuvers. An optimal strategy is derived from the table by choosing at each step in the simulation the maneuver with the largest probability of success (i.e., evasion). A reinforcement rule is used to update the decision table based upon previous results. Although the method seems to yield good results it is limited to end-game scenarios due to the large computational burden to achieve convergence in the results.

A third class of combat models to be surveyed here are those which we might call *mixed combat models* since they use an array of techniques and heuristics in order to estimate the outcome of the engagement. These models have also the characteristic to rely entirely upon digital computational schemes, most of them are classified or proprietary of the developing company (i.e., little information is known), and their main users are aircraft manufacturers and government agencies. Due to the specific nature of our research we will restrict this discussion to air-to-air and air-to-surface models since these two seem to cover most of the fighter aircraft missions of interest (see Section 1.5). In United States the Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS) is a tri-service organization devoted to coordinate research and development efforts within the aeronautical community to increase aircraft survivability. This organization maintains and distributes technical data bases and survivability related computer programs that are used by the survivability assessment community. According to the specific survivability discipline in which these programs are used it is possible to classify them in three groups [Ball, 1985]: 1) vulnerability-related, 2) susceptibility-related, and 3) system effectiveness-related. These three groups are summarized from in Tables 2.1 through 2.3 [MIL-336-1, 1982; Ball, 1985].

As can be seen from Tables 2.1 through 2.3 some of these models are highly specialized in nature. The majority of those in the vulnerability and survivability are in fact one-on-one end-game models that are difficult to generalize for a true M-on-N scenario (the only exception to this statement being PACAM V). On the other hand, the MTOM model is too broad and macroscopic to include explicitly aircraft design variables. Finally, TACOS II and EVADE are very specific and have long running times which make them cumbersome to use for

preliminary studies. These models provide powerful tools for specific problems but they seem to have problems of coherence between their outputs simply because they were developed at different times and for different needs. Hague [1981] developed a high resolution tactical combat model (MULTAC) in which aerial engagements of up to 20 aircraft can be simulated. The model offers a multitude of options for the engaging fleets and it makes use of either a cokill probability scheme or Monte Carlo simulation. The only criticism to be made about this model is the long duration of the simulation, taking in some instances several hours on a mainframe computer to complete a run [Hague, 1983].

In order to study systematically the interactions between aircraft survivability and the six levels presented in Table 1.3. Several researchers at Virginia Tech [Drew et al, 1986] have approached the issue of aircraft survivability using a top-down approach and a single methodology (i.e., Systems Dynamics) for all levels of analysis studied. Drew et al [1984] developed SURMAN, a computer model to manage aircraft survivability and technological substitution at the national security planning level (Level 6 in Table 1.3). This model was later complemented with more detailed applications of the systems dynamics methodology to Levels 5, 4, and 3 (Table 1.3) by Santoso [1984], Kadari [1985], Sathisan [1985], Trani [1986], and Malakhoff [1988].

Table 2.1 Summary of Vulnerability-Related Programs.	
Program	Description
FASTGEN	Models aircraft as a set of discrete flat triangular patches. Shotline generator used as input data to vulnerability programs.
COVART	Computes the vulnerable area of an entire aircraft based upon shotline generator data. Estimates repair times associated with the threat damage.
COMVAT	Quick vulnerability assessment program. Estimates aircraft vulnerable area based upon component average shielding.
POINTBURST	Computes aircraft vulnerability to internally detonating propagators.
ATTACK	One-on-one moedel to assess probability of kill of an aircraft by a missile. Incorporates several fuzing subroutines.
MECA	Estimates target vulnerability to externally detonating threats. Includes a large selection of targets and threat warheads Also includes various types of fuzing mechanisms
SHAZAM	Estimates air-to-air missile effectiveness. Compatible with shotline generator programs. Estimates the aircraft single shot kill probability.

Table 2.2 Summary of Susceptibility-Related Programs.	
Program	Description
BLUEMAX2	Generates an aircraft flight path by segment construction. Up to 30 segments can be introduced for the aircraft path description.
P001	One-on-one aircraft vs. ground-based gun simulation program. Advanced versions allow man-in-the-loop simulation.
SAMS	One-on-one surface-to-air missile generic simulation program. Models the end-game with missile guidance and navigation details. Fuzing and detonation are also modeled to estimate target kill probability.
PACAM V	Multiaircraft combat simulation model. Three-dimensional description of the aircraft. Incorporates air-to-surface missile capability.

Table 2.3 Summary of System Effectiveness Programs.	
Program	Description
TACOS II	Tactical Air-defense computer program. Simulates interactions between striking aircraft/missiles and ground air defense systems. Uses a Monte Carlo simulation scheme. Highly realistic taking several hours to run on an IBM 360 system.
EVADE	Evaluation of Air-Defense Effectiveness. Simulates air-to-surface engagements with an expected value scheme. Requires an extensive terrain data base (13 million individual patches). Environmental conditions can be also incorporated into the model.
MTOM	Mission Trade-Off Model. Estimates the impact of aircraft survivability enhancements on mission effectiveness and life cycle cost. Low resolution of the aircraft sortie parameters. Good accountability of costs allocation variables.

3.0 Methodology

3.1 Why Simulation?

Just as for any complex phenomena, the only practical means available to gain understanding of engagements between two opposing forces is through the development of, and experimentation with, a mathematical model that can be simulated [Drew et al, 1986]. There are many interpretations about the term simulation, however, for the purpose of this discussion it will be used in a broad sense to encompass not only the development of mathematical models but also in regard to their utilization context. There are several characteristics that make simulation uniquely suited to study complex battle models:

1) The models can be usually described mathematically in terms of differential or difference equations.

2) These models involve, in general, a multitude of *entities* possessing one or several *attributes* thus requiring a large number of *dimensions* to describe the state of the system.

3) The *activities* throughout the battle are highly dynamic and difficult to characterize in terms of constant coefficient differential/ difference equations.

4) Battles are adaptive in nature and thus difficult to be characterized with rigorous analytical tools. Hence, heuristics might play an important role in the model building process.

5) Battles are expensive and difficult to simulate even in combat drills thus making battle models almost impossible to verify.

Although this list cannot be considered exhaustive it highlights some of the difficulties associated with closed form analytical solutions to battle models. Obviously, many simplifying assumptions would have to made if one were to characterize a battle between two forces with many entities on each side using a manageable number of equations to be solved in close form. Examples of these simplifications are the models developed by Lanchester [Drew et al, 1986] to describe conventional warfare during World War I and more recently those of Diener [Csaki, 1977]. pertaining to nuclear warfare, among others. Nevertheless, these models have offered through the years the basic principles to develop more refined approaches to battle simulation and have won a niche among battle analysts.

As far as we are interested in exploring the outcome of engagements with multiple entities with different attributes on each side, the problem of dimensionality alone rules out any attempt to find a close form solution. It should be realized that the state description of an attacking aircraft in two dimensions implies at least the use of four nonlinear differential equations to describe the motion alone. If aircraft mass considerations play an important role in the outcome of the event simulated then a fifth equation is necessary. Now, assume that five of such aircraft perform a particular mission with different paths and thus different events and outcomes take place for each one such as being shot down or not. At this point one realizes that the system is now of twenty fifth order and that we have not even accounted for the potential equations associated with the threat on the ground or in the air. Obviously, simulation represents one good alternative to describe and analyze such a complex system.

Another strong argument that dictates the use of simulation in this research can be derived from the third point mentioned above concerning the potential time-variance of the coefficients associated with the differential equations describing the rates of the system. Consider for example the innocent looking attrition equations of an air engagement between two forces denoted by CBF and AGG, respectively. Assuming only threat suppression due to aimed fire [Drew et al, 1986] the equations reduce to the following,

$$\frac{dCBF(t)}{dt} = -AGG(t)_{se}\,AGG(t) \qquad \{3.1\}$$

$$\frac{dAGG(t)}{dt} = -CBF(t)_{se}\,CBF(t) \qquad \{3.2\}$$

where, CBF(t) and AGG(t) represent the number of friendly and aggressor aircraft at time t, CBF_{se} and AGG_{se} are aircraft system effectiveness parameters for friendly and aggressor forces, respectively. These systems effectiveness parameters are lumped terms that are functions of the lethality of the weapons used on each side and the state of the threat. At first glance it might seem an easy task to evaluate these two *effectiveness* coefficients. However due to the highly dynamic environment in which the engagement takes place there is no plausible close form of solution even for some of the most simplistic aircraft dynamics. Consider that both forces change their state at every point in the battle and thus the attrition effectiveness factors change accordingly depending upon hundredths of variables such as aircraft position, speed, heading, throttle setting, commanded load factor, etc. Clearly there is no mathematical approach that allows us to condense such a synergistic environment into two simple coefficients. This again rules out any attempt to solve this coupled second order system using standard Euler-type mathematical substitution techniques [Spiegel, 1982].

Lastly, the fact that some of the system rate variables are expressed in terms of nonlinear differential equations (e.g. aircraft equations of motion) pose yet another problem that can be resolved by standard linearization techniques such as small perturbations about a reference

point [Etkin, 1972]. These three arguments seem to justify the simulation approach used in this research.

Since most of the processes taking place in air combat and ground attack simulations are continuous in nature the categorization of our problem can be defined in the realm of continuous event simulation. This, of course, do not imply that discrete events such as the launch of a weapon cannot be modeled. On the contrary, as any "continuous simulation" becomes a "tightly packed" discrete event simulation when implemented in a digital computer. Several simulation languages have been developed specifically to cope with continuous event simulation, among them CSMP [IBM, 1986; Speckhart, 1976], ACSL [Mitchell, 1986; Trani, 1987], DYNAMO [Richarson, 1981; Pugh, 1983], SLAM [Pritsker, 1986], SIMNON [Astrom and Wittenmark, 1984], etc. However, any programming language can, in principle, be used to simulate most systems regardless to their complexity. At the same time various methodologies have been effectively used to analyze large scale systems involving variables from many different disciplines. Notable for their range of applications are Systems Dynamics developed in the sixties by Professor Jay Forrester [Forrester, 1961; Forrester, 1968; Forrester, 1969], and Loop Analysis and Time Averaging applied to complex models in the seventies by Richard Levins [Puccia and Levins, 1985]. An interesting commonality of these methodologies is the fact that both rely upon the notions of feedback and decision-making analysis. The former methodology was chosen for this research based on the author's familiarity with the subject and the more quantitative tools available.

3.2 *Systems Dynamics*

Systems Dynamics is based on the foundations of decision-making, feedback system structures, and simulation. Decision-making refers to the capability of the analyst to manipulate the systems control variables in order to obtain desired system states. Feedback

deals with the way information is to be used for decision-making and the way that actions affect developments that might influence future actions. Simulation permits decision makers and designers to view the implications of their choices over the future. Systems dynamics is used in the context of analyzing engagements between aircraft and a threat (e.g. other aircraft or designated ground defensive sites) in a highly dynamic environment. The end result is to allow the analyst to determine how the outcomes of these engagements respond to factors within decision makers control (aircraft design parameters such as thrust-to-weight ratio, RCS, tactics, etc.) and outside of decision makers control such as threat weapon capabilities and environmental factors.

3.2.1 Causal Diagrams

Systems dynamics is an emerging field devoted to the planning, design, and management of large-scale systems, that exploit the unique capabilities of computers to trace across many disciplines the implications of a variety of alternative designs, policies and strategies. The approach makes use of causal models which are designed to represent the effects on some variables caused by changes in others, thus enabling the engineer to define the consequences and evaluate large-scale alternative configurations. The modeling procedure is sequential and iterative starting with a mental model or verbal description of the problem, the expression of this mental picture in a graphical display called a causal diagram, and then the writing of the mathematical equations for the causal diagram.

The first step in developing the flow or causal diagram of the model is to identify the key variables which describe the problem situation and record the way the system to be analyzed works. These key variables which are deduced from the mental model or verbal description of the system, are arranged on a sheet of paper. Cause-effect relationships between pairs of variables are depicted by arrows in the second step. The third step in developing a causal

diagram is giving each link or arrow a plus or minus directional sign usually placed near the arrow head.

Thus, to begin the causal diagramming process, the key variables that describe the system behavior are identified from the verbal description of the problem. These key variables are then connected by arrows to show the cause-effect relationship. The variable at the tail of the arrow is the dependent variable; it affects the variable at the head of the arrow. The causal relationship can also be understood as the variable at the tail of the arrow "affecting or influencing" the variable at the head of the arrow depending upon the context. One point to be borne in mind is is that the pair-wise relationship is made under the assumption of "all other things being the same". The next step is to identify and mark the nature of the cause-effect relationship. If the relationship is one in which there is a direct proportionality between the two variables, then a plus sign is placed near the head of the arrow. This indicates an increase in the in the value of the variable at the tail of the arrow causes an increase in the value of the variable at the head of the arrow. A minus sign is placed at the head of the arrow when there is an inversely proportional relationship between the two variables, i.e., when an increase of the variable at the tail of the arrow causes the value of the variable at the head of the arrow to decrease.

There are two basic components of the structure of a system from the system dynamics perspective - flows and levels. Levels are state variables that represent the accumulation or build up of resources in the systems such as inventories of aircraft, ordnance, weapons, etc.. Rates of flow represent action in the system such as aircraft procurement and attrition. The flow can be categorized into two types: 1) physical flow and 2) information flow. Physical flows are causal relationships between a rate variable such as aircraft attrition (lost aircraft/day) and a level variable such as inventory (aircraft). Solid lines are used to indicate physical flows. The relationship between a level variable such as procurement and a rate variable such as procurement rate is an information flow. It is the information regarding the state of the inventory that influences the procurement rate. Such relationships depicting information flow are presented using dotted lines. Thus level variables will always appear at

the head of solid arrows and rate variables always appear at the tail of solid arrows. Any intermediate variable on the path from a level variable or exogenous input to a rate variable is called an auxiliary variable. Supplementary variables do not form part of the system itself, but merely indicate its performance and therefore appear always at the end of a dashed arrow, and having no arrows emanating from them. Exogenous inputs, have no arrows leading to them but have dashed arrows emanating from them implying that these constitute the boundaries of the model.

Fig. 3.1 depicts a causal diagram displaying the basic combat interactions between two opposing fighter aircraft fleets. The numbers of Carrier Based Fighters (CBF) and Aggressor Fighters (AGG) are level variables, aircraft attrition rates for CBF and AGG respectively are CBFKR and AGGKR are rate variables. Finally, sortie survivabilities, CBFSS and AGGSS, and aircraft lethalities, CBFL and AGGL, are treated as constants in this represention. The model in fact computes these lethalities in terms of the many disciplines that comprise complex modern warfare. The system depicted constitutes a second order positive feedback loop because the response of the system is unstable. In other words, if we were to perturb the original system by say introducing more aircraft on the CBF side this in turn would increase the attrition rate of the aggressor force (AGGKR) decreasing the aggressor force (AGG). Continuing around the loop, a decrease in AGG results in a decrease in the CBF aircraft attrition rate (CBFKR) which ultimately yields more CBF aircraft surviving the engagement. Clearly if one were to repeat this cycle for multiple sorties the aggressor fleet would eventually be annihilated. Thus the cycle is *vicious* in nature. Mathematically, positive feedback loops arise when the eigenvalues of the solution possess *positive* real parts. For the control engineer the roots would lie on the right hand side of the $s-plane$ thus implying a divergent solution. Negative feedback loops on the other hand arise when the eigenvalues of the solution display *negative* real parts and are characterized by their self compensation. An example of their benign behavior is the model of an oscillating pendulum with air resistance considered which eventually brings the system to a stop [Ogata, 1970]. Another example of a negative feedback loop and causal diagramming is shown in Fig. 3.2 where a simple air

vehicle speed control system is illustrated. The input to this system is a target velocity (VIN) to be achieved by the vehicle. The current vehicle velocity (VOUT) is added to VIN to appraise the differential speed between the desired and current value (DELTAV). Multiplying DELTAV by a suitable positive constant (GAIN) one obtains the rate of change in the throttle setting (TSSR) which affects the throttle setting (TSS) in some prespecified way. Once TSS is increased the thrust generated by the vehicle's powerplant increases thus resulting in a net acceleration (ACC) which in turn increases the vehicle speed (VOUT). Eventually, the actuating signal ε would be zero at the point when the target and current speeds coincide hence putting the system in equilibrium. The equivalent block diagram for this system is also shown in Fig. 3.2 to appreciate the similarities between causal diagramming and block diagrams. An important feature of causal diagramming is the fact that the system is described in words instead of transfer functions which make the interpretation of the interactions among the elements of the system easier.

3.2.2 System Dynamic Equations

Integration (or accumulation) is the basis of the level and rate structure used in systems dynamics. A level variable $L(t)$ denotes the accumulation of of some physical entity at time t. RI and RO represent the rate variables, rate-in and rate-out, denoting the change in the level variable over the interval from $t-1$ to t. The relationships between the level $L(t)$ and the rates can be expressed mathematically as,

$$L(t) = L(t-1) + \int_{t-1}^{t} (RI - RO)dt \qquad \{3.3\}$$

$$L.K = L.J + (DT)(RI.JK - RO.JK) \qquad \{3.4\}$$

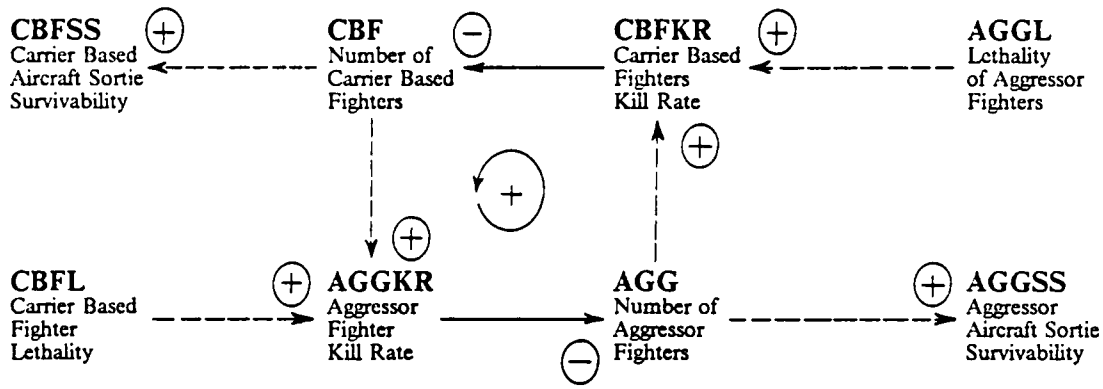
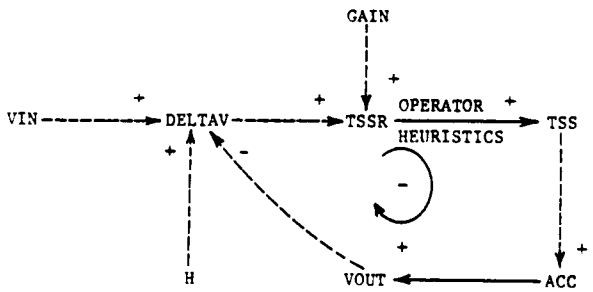
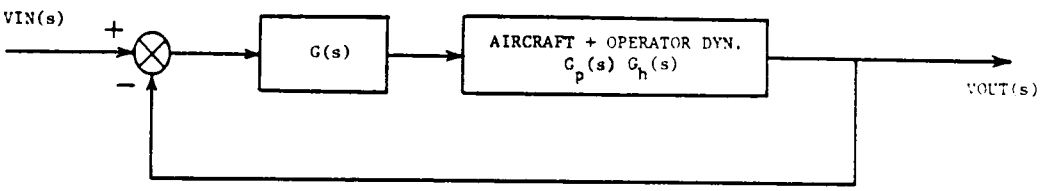


Figure 3.1 Basic Model Combat Interactions.



TSS - THROTTLE-SETTING
TSSR - THROTTLE SETTING RATE
DELTAV - SPEED DIFFERENTIAL
VIN - DESIRED SPEED
VOUT - ACTUAL SPEED
GAIN - FORWARD GAIN
H - FEEDBACK GAIN

CAUSAL DIAGRAM



H(s) = 1

VIN - DESIRED AIRCRAFT SPEED
VOUT - ACTUAL AIRCRAFT SPEED
H(s) - FEEDBACK GAIN
G(s) - FORWARD GAIN
$G_p(s)$ - AIRCRAFT TRANSFER FUNCTION
$G_h(s)$ - HUMAN OPERATOR TRANSFER FUNCTION

BLOCK DIAGRAM

Figure 3.2 Simple Vehicle Speed Control System.

In difference equation terminology, any level variable L_i is expressed as functions of rate variables R_j and the previous value of the level,

$$L_i(t) = L(t-1) + (dt)\sum_{j=1}^{n} R_j(t) \qquad i = 1,.....,m \qquad \{3.5\}$$

with the R_j is assumed to be constant over the interval from $t - dt$ to t. The rate variables are of the form

$$R_j(t) = f[L_i(t), E_k(t), A_{ij}(t), A_{kj}(t)] \qquad \{3.6\}$$

where E_k is the set of of exogenous inputs that affect R_j directly and A_{ij} and A_{kj} are the impacts of auxiliary variables in the causal streams from the *ith* level to the *kth* exogenous input, respectively. Since the exogenous inputs are known time functions or constants, if the initial values of the level variables are known, all other variables can be computed from them for that time. Then the new values of the level variables for the next point in time can then be found from the "level" equation 3.1.

DYNAMO (DYNAmic MOdels) is a computer program which compiles and executes system dynamic models. Because the inability of a computer language to handle subscripts, DYNAMO uses a postcript notation in which *.K* stands for the present time t, *.J* stands for the past time $t - dt$, and *.L* stands for the future time $t + dt$. As in all computer programming upper case letters are used and *DT* is called the simulation interval, the time between successive computations in the simulation. Since rate variables are assumed to be constant over *DT*, the double postcript is used., *.JK* for the rates on the right side of an equation and *.KL* for the rates on the left side [Drew, 1986].

3.2.3 DYNAMO Simulation Language

There are at least six well documented versions of DYNAMO [Pugh, 1983] and all of them support the basic functions to be described in the following paragraphs.

3.2.3.1 Logical Functions

DYNAMO supports logical functions similar in nature to those available in higher level languages such as FORTRAN and PASCAL. There are two types of conditional statements to compare two alternatives simultaneously. CLIP and FIFGE are used interchangeably though the former definition is used in the ASALT II model.

$$\text{CLIP(A,B,C,D) or FIFGE(A,B,C,D)} \quad \begin{cases} \text{A if } C \geq D \\ \text{B if } C < D \end{cases}$$

a special case of this rule is the comparison of the numerical value of a variable C with zero. This capability is achieved with either SWITCH or FIFZE functions as shown below.

$$\text{SWITCH(A,B,C) or FIFZE(A,B,C)} \quad \begin{cases} \text{A if } C = 0 \\ \text{B if } C \neq 0 \end{cases}$$

Another important pair of functions are MAX and MIN which select the largest and smallest of two given variables A and B.

$$\text{MAX(A,B)} \quad \begin{cases} \text{A if } A \geq B \\ \text{B if } A < B \end{cases}$$

$$\text{MIN(A,B)} \quad \begin{cases} \text{A if } A \leq B \\ \text{B if } A > B \end{cases}$$

furthermore, the function MAX can be used to compute the absolute value of a variable specifying the variable and its negative inside the two parenthesis positions.

MAX(A,-A)

3.2.3.2 *Table Functions*

A very important part of many simulation models is the use of tabular data, either empirically or theoretically derived. DYNAMO is capable to handle data by means of several types of table functions. TABLE, TABXT, TABHL, and TABPL are all invoked in the same manner though there are significant changes in their respective interpolating schemes. Two statements are required to describe a table function. The first one involves five ordered elements inside a parenthesis (see below) to specify the dependent variable name, the independent variable name, the lowest, highest values of the independent variable, and the interval between each independent variable. A general definition of a table is given below followed by a numerical example to help the understanding of this concept.

TABHL(Y-variable,x-variable,low x,high x,x-interval)
Y-variable=numerical values

Example 3.1

Suppose it is required to express in table form the installed engine thrust data of an aircraft as function of mach number given in Fig. 3.2.

This will be represented as follows, provided that THRUST and MACH are functions of time (i.e.noting the time subscripts).

THRUST.K=TABHL(THRUSTT,MACH.K,0,.6,.1)
THRUSTT=25000/24860/24690/24500/24000/23680/23400

where, THRUST is the installed engine thrust as a function of time, MACH represents the flight mach number under given atmospheric conditions also a function of time, and THRUSTT is the name of the table function containing the numerical values of the thrust function.

The main use of these table functions relies on the fact that every time the variable represented by the table function is invoked in the code the value of that variable will be interpolated or extrapolated from the known function values. TABLE, TABHL, and TABXT interpolate linearly between declared elements while TABPL performs cubic interpolation. TABHL upgrades TABLE by assigning the extreme point function values to the desired function

Variable	Mach Number						
Thrust (lbs.)	0 25000	.1 24860	.2 24690	.3 24500	.4 24000	.5 23680	.6 23400

Figure 3.3 Thrust Values for Example 3.1.

if extrapolation is required. TABXT performs linear extrapolation at the desired value of the function. A last remark in the definition of the numerical values for TABPL is the fact that a zero must be added for each numerical value defined for the Y-variable.

3.2.3.3 Delay Functions

A particularly useful feature of DYNAMO is the capability to introduce delays through the DELAY and SMOOTH functions. First and third order delays are readily available by the simple specification of these two functions. Higher-order delays can be achieved combining the functions already specified.The basic form of these delays is as follows:

DELAY1(I,D) or SMOOTH(I,D)
DELAY3(I,D)

where, I is the input to the delay and D is the average length of the delay.

3.2.3.4 Test Input Functions

Test functions allow the modeler to observe model response to outside influences. Six test functions are available in DYNAMO: PULSE, RAMP, NOISE, NORMRN, STEP, and SAMPLE. A typical example to use some of these functions would be to assess the dynamic response of a particular aircraft to external influences that could be modeled as a well defined train of impulses (using PULSE function or a sinusoidal function), or random behavior (using NOISE or NORMRN functions). The baseline model does not include any of these test functions since

the aircraft dynamics modeled are not detailed enough to be analyzed in this fashion. However, it is important to be aware of this language capability if tests are to be performed on other important variables.

3.2.3.5 *Trigonometric and Logarithmic Functions*

DYNAMO supports five elementary trigonometric functions. Exponential, natural logarithm, square root, sine and cosine are defined in the same way as in other higher-level computer languages. The following statements show the DYNAMO form for these functions.

EXP(A) LOGN(A) SQRT(A) SIN(A) COS(A)

In order to give more flexibility to the simulation language, user defined macros equivalent to subroutines in high-level languages are available. Macros are declared at the beginning of the code contrary to the FORTRAN practice and require two special declaration statements to begin and end the macro.

MACRO($x_1, x_2, \ldots\ldots, x_m$)
MEND

where, x_1, x_2 *etc.*. are dummy variables to be
replaced by the variables accompanying the macro variable in the code.

Another important feature of all DYNAMO versions is the external function capability which allows the linking of FORTRAN based structures to the main simulation. Without any doubt, the external function capability is one of the most powerful tools available of the language since many simulations require complex computations within every time interval. This is particularly important if an optimization subroutine is to be incorporated. The remainder of this chapter is devoted to a description of DYNAMO III (the version of the simulation language used in this research).

3.2.3.6 *DYNAMO III Functions*

The most notable difference between this version of DYNAMO and its predecessors is the incorporation of array capability as a built-in function. Arrays follow notation similar to that employed in FORTRAN. Parenthesis are used as subscripts and the initialization of each array dimension is performed at the beginning of the code with the use of a FOR statement. No closing statement is necessary for this FOR statement since all the "subscripted" variables will automatically be treated as arrays.

Manipulation of Arrays: The manipulation of arrays follows standard mathematical rules and the only cases where special notation is required are those when performing vector product (PRDV), scalar product (SCLPDR), summation of the elements of a vector (SUMV), and those of a matrix (SUM). The vector product function only quantifies the product between vector elements, for example if the vector product of elements x_n and x_p of vector V is desired then this is specified as follows.

A=PDRV(V,x_n,x_7) The scalar product (denoted by A) of two vectors (or matrices) V1 and V2 is computed as follows.

A=SCLPDR(V1,1st element of V1,last element of V1,V2,1st element of V2) Summation functions are of two classes depending on the type of variable dealt with. SUM is used to add all the elements of a matrix.

A=SUM(M) For a vector V (I.e. one-dimensional array) the summation of elements ranging from x_n to x_p is,

A=SUMV(V,x_n,x_p)

4.0 Mathematical Aspects of Survivability

Aircraft survivability is defined by Ball [1985] as the capability of an air vehicle to avoid or withstand the damaging mechanisms of a hostile man-made environment. In Chapter 1 of this dissertation it was pointed out that aircraft survivability encompassed five major areas of study: 1) susceptibility, 2) vulnerability, 3) lethality, 4) inventory, and 5) systems evaluation. The aim of this section is to provide some background on how the first three areas of survivability are generally evaluated. These three engineering oriented areas as it might be recalled are the principal focus of this research.

Aircraft susceptibility is the ease with which an aircraft is hit by a threat during an encounter. This variable is measured as the probability for the aircraft being hit by a propagator P_H and is a function of factors associated with the capabilities of the threat, the aircraft, and the scenario where the encounter takes place [Ball, 1985]. Typical areas covered in a susceptibility assessment are the threat performance capabilities such as radar and infrared detection mechanisms, weapons kinematic envelopes, tracking and fire control system limitations, etc. Also, aircraft performance parameters such as speed, altitude, specific excess power, maneuverability, use of passive and active countermeasures, aircraft infrared and radar signals, threat warning capability, etc. The scenario is usually defined in terms of tha definition of aircraft flight paths, lighting conditions, terrain modeling, etc. The

susceptibility assessment starts with the mechanisms that lead to the detection and tracking of the aircraft, continues with the launch of a weapon, weapon guidance, weapon detonation, and finalizes with the determination of the *miss* distance between the propagator and its target. Each one of the events just described can be modeled, in general, as probabilities conditioned to previous events. For example, the probability of weapons launch is conditioned to the probabilities of target detection and target in line of sight. Similarly, the probability of aircraft detection is, in general terms, conditioned to the event that the aircraft is within line of sight (this is not valid for the special case of beyond-the-horizon radar detection capability). Note that this modeling concept is a direct result of the multiplicatice theorem of conditional probabilities [Walpole and Myers, 1978]. Therefore, the probability of aircraft being hit can be represented as the product of the probabilities of aircraft in the line of sight (P_{LOS}), the probability of aircraft detection and tracking (P_D), the probability of weapons launch given aircraft detection and tracking, (P_L), the probability of weapons successful guidance given a weapons launch, (P_{SG}), and the probability of weapons detonation given that successful guidance has occurred, (P_{det}). In a true many-versus-many combat scenario (M on N) these probabilities will be functions of the geometry of the engagement and the type of weapons used. Letting M represent the number of aircraft in the engagement, N the number of threats, and L the number of weapons carried by each threat. The following expression is obtained for the probability that an aircraft i is hit by a weapon k launched from threat j.

$$P_{H\ ijk} = P_{LOS\ ij}\ P_{D\ ijk}\ P_{Lijk}\ P_{SGijk}\ P_{det\ ijk} \qquad \{4.1\}$$

where, $P_{LOS\ ij}$ the probability of the i th aircraft being in line-of-sight of the j th threat, $P_{D\ ijk}$ is the probability for the i th aircraft being detected by the j th threat with k detection mechanism (this assumes that each weapon has its own tracking and detection capability), $P_{L\ ijk}$ is the probability that the j th threat fires a k weapon to the i th aircraft, $P_{SG\ ijk}$ is the probability that a k th weapon fired by the j th threat is successfully guided to the vicinity of the i th aircraft, and $P_{det\ ijk}$ is the probability for the k th weapon launched by the j threat to detonate once it reaches the i th aircraft.

Aircraft vulnerability is generally interpreted as the capability of an aircraft to withstand various levels of damage. Mathematically vulnerability is expressed as the conditional probability that the aircraft is "killed" given a random hit $P_{K/H}$. Since aircraft are composed of many parts and systems subjected to damage it is possible to amplify the scope of the analysis by using a finite vulnerable element approach. Each aircraft component has its own vulnerability associated with and there might be overlap between components and redundancy of systems. If we assume that the aircraft is composed of n vulnerable, non-overlaping components then the total aircraft vulnerability for one random hit is [Ball, 1985],

$$P_{K/H} = \sum_{i=1}^{N} P_{K/HI} \qquad \{4.2\}$$

where, $P_{K/HI}$ represents the probability of kill of the i *th* component given a hit. If the analysis is extended to multiple hits and non-overlapping components, the probability of survival of the i component given M random hits is as follows,

$$P_{S/HI} = \prod_{k=1}^{M} P_{S/HI}^{(k)} \qquad \{4.3\}$$

where, $P_{S/HI}^{(M)}$ represents the probability of survival of the i *th* component given a random hit k. Since the probability of kill given a hit is just one minus the probability of survival given a hit then the probability of complete aircraft kill (i.e. N components) given M random hits becomes,

$$P_{K/H} = \sum_{i=1}^{N} \left[1 - \prod_{k=1}^{M} (1 - P_{K/HI}^{(k)}) \right] \qquad \{4.4\}$$

This approach is used in most vulnerability assessment models since a high resolution of the terminal effects of the threat on the target is needed to assess wether or not the target is killed given one or multiple hits. A vulnerability assessment starts at the end of the susceptibility phase once the miss distance from the threat to the target is known. The goal of this phase then is to estimate the potential damage caused by the weapon on the target. Notice that this analysis is still necessary for finite miss distances as externally detonated weapons (i.e. warheads that explode in the vicinity target) eject lethal fragments that might cause enough damage to the aircraft systems or crew to cause eventually complete loss of the aircraft (i.e. soft kill). In short aircraft vulnerability is a function of the geometry of the end-game and the lethality of the warhead. By lethality it is meant the destructive capability of a weapon.

Once vulnerability and susceptibility have been defined it is possible to completely estimate the aircraft survivability at the encounter level. Following standard notation [MIL-336-1, 1982; Ball, 1985] define the probability of aircraft kill , P_K, as the product of the probability of the aircraft being hit and the probability for the aircraft being killed given a hit,

$$P_K = P_H \; P_{K/H} \qquad \{4.5\}$$

Substituting Eq. 4.1 into 4.5 one obtains a general expression for the probability of aircraft kill in terms of the effectiveness mechanisms of the threat.

$$P_{K\ ijk} = P_{LOS\ ij} \; P_{D\ ijk} \; P_{Lijk} \; P_{SGijk} \; P_{\det\ ijk} \; P_{K\ i/H\ jk} \qquad \{4.6\}$$

where, $P_{K\ ijk}$ is the probability that aircraft i is killed by weapon k fired from threat j and $P_{K\ i/H\ jk}$ is the probability that aircraft i is killed given a hit with weapon k launched by threat j. All other terms being the same as before. At this point one can perceive intuitively the compound and dependent nature of the events occuring in both vulnerability and susceptibility assessments. It is easy to see that if an aircraft has been hit it is by no means guaranteed that it will killed since in some instances the warhead of the threat may not explode or the aircraft may have redundant systems to continue or abort its mission. From a modeling perspective this subdivision of phases is highly attractive since it allows one to perform the vulnerability and

susceptibility analyses in different time domains and still be able to combine their results to estimate aircraft survivability. For this reason it is not uncommon to represent vulnerability results in terms of average values for one or multiple aircraft aspect angles [Ball, 1985]. In this research vulnerability can also be expressed as the probability of single shot kill, P_{SSK} which can be interpreted as the lethality of the weapon in the vicinity of the target (i.e. within kill envelope). There seems to be some disagreement between members of the survivability community with respect to this term. Ball defines the single shot probability of kill to include guidance and fuzing (i.e. detonation) mechanisms in it [Ball, 1985]. He acknowledges, however, that the computational scheme for P_{SSK} and P_H is the same. The Military Handbook 336-1 on the other hand defines P_{SSK} more in terms of the terminal effects and damage mechanisms between threat and target [MIL-336-1, 1982]. This notion has already been used in this section to define the probability of the aircraft being hit where the guidance and detonation characteristics were included in P_H. The latter approach is opted in this research to differentiate more clearly between vulnerability and susceptibility contributions. Mathematically the probability that an aircraft survives F shots is given by,

$$P_{SSS} = \prod_{f=1}^{F} P_{SSS\,f} \qquad \{4.7\}$$

where, P_{SSS} is the probability that the aircraft survives F shots, $P_{SSS\,f}$ is the probability that the aircraft survives the *f* th shot. The probability of being *killed* by F shots (P_{SSK}) is then,

$$P_{SSK} = 1 - \prod_{f=1}^{F} P_{SSS\,f} \qquad \{4.8\}$$

which can also be expressed in terms of the probability of aircraft kill with the *f* th shot ($P_{SSK\,f}$),

$$P_{SSK} = 1 - \prod_{f=1}^{F}(1 - P_{SSK\,f}) \qquad \{4.9\}$$

This term then condenses the lethality capability of a weapon and measures its capability to destroy a target with K number of shots. It is possible to express the probability of survival of an aircraft at the encounter level by replacing $P_{K\,i/H\,jk)}$ in Eq. 4.6 by P_{SSK} of Eq. 4.9,

$$P_{K/E\ ijk} = P_{LOS\ ij}\ P_{D\ ijk}\ P_{L ijk}\ P_{SG ijk}\ P_{det\ ijk}\left[1 - \prod_{f=1}^{F}(1 - P^{(f)}_{SSS\ ijk})\right] \qquad \{4.10\}$$

where, $P_{K/E\ ijk}$ represents the i th aircraft kill probability per encounter with k weapon and from j threat, i differentiates between M aircraft, j among N threats, k between K weapons, and f refers to F shots fired during the encounter. The first four terms are usually referred as the threat system effectiveness, P_{TSE} because they represent the capability of the threat to inflict damage to the target aircraft.

$$P_{K\ ijk} = P_{TSE\ ijk}\left[1 - \prod_{f=1}^{F}(1 - P^{(f)}_{SSS\ ijk})\right] \qquad \{4.11\}$$

In order to estimate the probability of aircraft survival for an entire sortie one could expand previous equations to accommodate for E number of encounters per sortie per weapon [Ball, 1985].

$$P_{S/S\ ij} = \prod_{e=1}^{E_1}(1 - P_{K/Ee\ ij})\prod_{e=1}^{E_2}(1 - P_{K/Ee\ ij})\cdots\cdots\prod_{e=1}^{E_k}(1 - P_{K/Ek\ ij}) \qquad \{4.12\}$$

where, $P_{S/S\ ij}$ is the probability that aircraft i survives the sortie against the j threat, and weapon k. Similarly, $P_{K/E\bullet\ ij}$ is the probability that aircraft i is killed by weapon k launched from threat j. Although this last expression seems straightforward to solve for the particular case where $P_{K/E\bullet\ ij}$ being a constant this assumption is very unrealistic because the aircraft flight paths greatly influence the times in the firing envelope of a weapon and probability of aircraft kill per encounter ($P_{K/E\bullet\ ij}$).

4.1 Considerations in the Development of Survivability Models

There are several areas that need to be addressed in order to build a survivability/lethality assessment model. As may be recalled from Chapter 1 there is a survivability hierarchy which spans from the detailed analysis to estimate single shot kill probabilities (Level 1 in Table 1.3) to the macroscopic level of resource allocation tradeoffs (Level 6 in Table 1.3). Each of these levels of analysis poses its own challenges to the modeler since many inputs need to be synthesized in order to arrive at the desired survivability measure of effectiveness (MOE). It is observed from Table 1.3 that for Levels 2 and 3, areas where this research aims, the corresponding survivability effectiveness factors are the probability of the aircraft survival per encounter and per sortie, $P_{E/}$ and P_S, respectively. It should be understood that a sortie may be composed of one or more engagements thus corresponding to a higher level in the hierarchy.

The creation of scenario specific survivability models can be viewed as a three phase process where the physical characteristics of the combatants and the environment constitute the first building phase, the estimation of the survivability related variables is accomplished

in the second phase, and the selection of a suitable attrition law submodel corresponds to the third phase.

In the first phase three physical components need to be defined: 1) the environment where the encounters between the aircraft and the threat are to occur, 2) the aircraft characteristics necessary to estimate its susceptibility and vulnerability when confronted with a given threat, and 3) the threat characteristics that contribute to its susceptibility and vulnerability as well. These three model components then need to be combined in a rational fashion to estimate the "casualties" of each side at the end of the encounter. This is done by implementing an attrition model that reflects the type of interactions occuring during the duration of the engagement. Chapter 2 described several types of attrition models that have been in use through the years to describe the outcome of combat engagements while in previous section susceptibility and vulnerability assessment principles were given.

In this research the scenario models developed emphasize the susceptibility assessment for the simple reason that a vast amount of vulnerability data is available to the survivability community in classified form through SURVIAC [Vice, 1986] and thus can be readily implemented in these type of models. This is also compatible with the fact that these models are aimed at the conceptual design stage where vulnerability assessment can be somewhat unreliable due to the many unknowns about the exact internal aircraft configuration.

4.2 Attrition Equations and the Cokill Simulation Scheme

The form of the attrition equations adopted in a survivability assessment model greatly affect the outcome of the solution [Drew et al, 1986]. This complicates finding an appropriate model for each combat situation. In Chapter 2 some of the peculiar characteristic of Lanchester-type models were established and it was seen that in many cases the linear and square laws could be applied in particular cases. In this section we will discuss a particular

close form solution to the square law in order to point out some of the implications arising when simple aggregated model are solved. This particular model was chosen because it can be argued that in a perfect information aerial combat the aircraft participating will only fire shoots to surviving aircraft. That is, there is a concentration of force, or aimed fire, on the survivors. For identification purposes let X and Y represent two forces of M and N elements to be confronted. The attrition equations can be written as follows:

$$\dot{X}(t) = -Y(t)_{se}\, Y(t) \qquad \{4.13\}$$

$$\dot{Y}(t) = -X(t)_{se}\, X(t) \qquad \{4.14\}$$

where, X(t) and Y(t) represent the force sizes of two adversaries at time t, X_{se} and Y_{se} are system effectiveness parameters for the two adversary forces, respectively. These parameters are functions of the lethality of each system as previously be explained. Hence, it is clear that the attrition rate of a force is proportional to the product of the enemy force size and the effectiveness of this opposing force (i.e. lethality). A close form solution to this coupled equations can be found by the transition matrix method (i.e state space approach) for the special case of time-invariant attrition coefficients. Redefine the force sizes in terms of a single column vector $[X_1, X_2]^T$ where, X_1 and X_2 represent the X and Y forces, respectively. The second order homogeneous system is then written in state space form as follows,

$$\begin{bmatrix} \dot{X}(t)_1 \\ \dot{X}(t)_2 \end{bmatrix} = \begin{bmatrix} 0 & -Y_{se} \\ -X_{se} & 0 \end{bmatrix} \begin{bmatrix} X(t)_1 \\ X(t)_2 \end{bmatrix} \qquad \{4.15\}$$

which is in the standard form [Ogata, 1971],

$$\bar{\dot{X}}(t) = \bar{A}\ \bar{X}(t) \qquad \{4.16\}$$

notice that the bar on top of the variables simbolizes a matrix or a vector, transforming Eq. 4.16 into Laplace domain one obtains,

$$s\,\bar{X}(s) + \bar{X}(0) = \bar{A}\;\bar{X}(s) \qquad \{4.17\}$$

solving for $\bar{X}(s)$,

$$\bar{X}(s) = \;[s\,\bar{I} - \bar{A}]^{-1}\;\bar{X}(0) = \bar{\Psi}\;\bar{X}(0) \qquad \{4.18\}$$

where, $\bar{I}$ is the identity matrix, s is the Laplace scalar operator and $\bar{X}(0)$ is the initial condition column vector representing the forces on each side at time $t = 0$, and $\bar{\Psi}$ is the state transition matrix representing a transform matrix from initial conditions to any future time. The solution to this matrix is obtained by standard matrix inversion of $[s\,\bar{I} - \bar{A}]^{-1}$. The results are as follows,

$$[s\,\bar{I} - \bar{A}]^{-1} = \frac{ADJ\,[s\,\bar{I} - \bar{A}]}{\det\;[s\,\bar{I} - \bar{A}]} \qquad \{4.19\}$$

where, *ADJ* and det represent the adjoint matrix and the determinant of $\bar{\Psi}$, respectively.

$$ADJ\,[s\,\bar{I} - \bar{A}] = \begin{bmatrix} s & -X_{se} \\ -Y_{se} & s \end{bmatrix} \qquad \{4.20\}$$

and,

$$\det\;[s\,\bar{I} - \bar{A}] = s^2 - Y_{se}\;X_{se} \qquad \{4.21\}$$

therefore the transition matrix (Ψ) is just,

$$\bar{\Psi} = [s\,\bar{I} - \bar{A}]^{-1} = \begin{bmatrix} \dfrac{s}{s^2 - Y_{se}\,X_{se}} & \dfrac{-Y_{se}}{s^2 - Y_{se}\,X_{se}} \\ -\dfrac{X_{se}}{s^2 - Y_{se}\,X_{se}} & \dfrac{s}{s^2 - Y_{se}\,X_{se}} \end{bmatrix} \qquad \{4.22\}$$

retransforming this matrix to time domain the free response of the original system is obtained. Use a simple transformation of the type $a = \sqrt{Y_{se}\, X_{se}}$ to find the elements of $\overline{\Psi}$ in terms of the hyperbolic sine and cosine as follows,

$$\begin{bmatrix} X(t)_1 \\ X(t)_2 \end{bmatrix} = \begin{bmatrix} \cosh \sqrt{X_{se}\, Y_{se}}\, t & -\sqrt{\frac{Y_{se}}{X_{se}}} \sinh \sqrt{X_{se}\, Y_{se}}\, t \\ -\sqrt{\frac{X_{se}}{Y_{se}}} \sinh \sqrt{X_{se}\, Y_{se}}\, t & \cosh \sqrt{X_{se}\, Y_{se}}\, t \end{bmatrix} \begin{bmatrix} X(0)_1 \\ X(0)_2 \end{bmatrix} \qquad \{4.23\}$$

The previous solution can be extended to the case where the attrition coefficients vary with time. However, the transition matrix becomes difficult to evaluate even for the simplest linear systems where infinite exponential solutions for each of the matrix elements are generally obtained [Ogata, 1971]. Notice that the solution obtained in Eq. 4.23 for the time-invariant attrition coefficient case is amenable to aggregated forces where M and N represent the initial numbers of elements on each. Although a reasonable close form solution was obtained there is no explicit formulation of the characteristics of the combat elements to assess their individual effectiveness. This is particularly critical in aerial combat where multiple target engagements are possible with the use of active weapons (i.e. weapons with internal guidance and navigation capabilities). It is possible to define each element of each force as a state variable in the problem, however, this obviously imposes a large dimensionality burden if a close form solution is sought for even a small number of elements on each side. Moreover, the time -invariance constraint has not still been removed. An alternative method of solution to this system of equations is through the use of simulation where both, the aggregation and time-invariant constraints are removed from the problem. The number of combatants remaining at any instant in time on the two forces is given by the following two difference equations,

$$\overline{X}(t)_I = \overline{X}(t-1)_I + \dot{\overline{X}}(t)_I \qquad \{4.24\}$$

$$\overline{Y}(t)_j = \overline{Y}(t-1)_j + \dot{\overline{Y}}(t)_j \qquad \{4.25\}$$

with initial states $\overline{X}(t=0)_i = \overline{X}(0)_i$ and $\overline{Y}(t=0)_j = \overline{Y}(0)_j$ from where $\overline{X}(t)_i$ represents the friendly force attrition state vector at time t with i combat elements (e.g. aircraft). $\overline{X}(t-1)_j$ is the same vector at time $t = t-1$, and $\dot{\overline{X}}(t)_i$ is the friendly force attrition rate vector with similar dimensions as the former ones. Eq. 4.25 applies to the an enemy force with j elements.

As the simulation progresses, the levels of damage inflicted by the two forces are aggregated using Eqs. 4.24 and 4.25 to reflect the degradation in force sizes accordingly. The attrition rate vectors $\dot{\overline{X}}(t)_i$ and $\dot{\overline{Y}}(t)_j$ are functions of the time-varying systems effectiveness attrition coefficients of every element on each force and the number of adversaries.

$$\dot{\overline{X}}(t)_i = F\left[\overline{Y}(t)_{SE\,ji}\ \overline{Y}(t)_j\right] \qquad \{4.26\}$$

$$\dot{\overline{Y}}(t)_j = F\left[\overline{X}_{(t)}SE\,ij\ \overline{X}(t)_i\right] \qquad \{4.27\}$$

$\overline{Y}(t)_{SE\,ji}$ is the enemy system effectiveness matrix (n by m) containing the attrition coefficients from each j th combat element as it affects the i th combat element in the friendly force, $\overline{X}(t)_{SE\,ij}$ represents the time-varying friendly system effectiveness matrix (m by n) containing the attrition coefficients from each i th combat element as it affects the j th combat element in the enemy force, and $\overline{Y}_j$ and $\overline{X}_i$ are the attrition states of the forces at time t. These two matrices have a logical interpretation if one pictures M aircraft confronting N weapon sites each one having a shot opportunity at some instant in time. The total attrition experienced by an aircraft will be some function of the individual attritions inflicted by each site. Similarly, the total attrition of each site will be a function of the individual aircraft lethalities against a particular site. From here several attrition policies could be used in order to estimate numerically $\overline{Y}_j$ and $\overline{X}_i$. For example, assuming that the attrition rate for each element on each force is a linear combination of the individual attritions inflicted by each opponent one obtains,

$$\dot{\bar{X}}(t)_i = \sum_{j=1}^{n} \bar{Y}(t)_{SE\,ji}\ \bar{Y}(t)_j \qquad \{4.28\}$$

$$\dot{\bar{Y}}(t)_j = \sum_{i=1}^{m} \bar{X}(t)_{SE\,ij}\ \bar{X}(t)_i \qquad \{4.29\}$$

The point to be made here is that throughout the simulation all players are kept in the game though their numerical value is reduced according to the attrition rates experienced. The reasoning behind this is the fact that only an estimation of the probability of survival per sortie is wanted.

This particular approach is termed the "co-kill probability" scheme proposed by Hague [1979] and used in other studies. This approach offers the computational advantage over more traditional Monte Carlo simulation schemes were large number of encounters need to be simulated to draw definite conclusions [Hague, 1979]. Another study by Hague [1983] has suggested that the aggregation of levels of damage is reasonably precise for predicting outcomes at the M-on-N level and has even been correlated with engagements in an air combat range. The following is a brief explanation of the co-kill probability scheme as outlined by Hague [1979].

Suppose that two forces comprising M versus N aircraft are engaged. If vehicle i in the friendly force fires a weapon k with a kill probability $P_{K\,ij}$ to a vehicle j in the aggressor force at time t, the probability of vehicle j surviving the encounter at time of weapon impact, say $t + \delta t_1$, denoted $P_{S\,j}(t + \delta t_1)$ is given by,

$$P_{S\,j}(t + \delta t_1) = P_{S\,j}(t) - P_{K\,ij}(t) \qquad \{4.30\}$$

where δt_1 represents the delay allowed for missile time of flight. Similar results can be easily extended for the j th vehicle firing an l weapon upon a vehicle i on the friendly force at a time

$t + \delta t_2$ and weapon impact time $t + \delta_3$. Denoting the probability of survival of the i th aircraft as $P_{t+\delta t_3}$ at the time of impact one obtains,

$$P_{S\,i}(t + \delta t_3) = P_{S\,i}(t + \delta_2) - P_{S\,j}(t + \delta_2)\ \ P_{K\,ji}(t + \delta t_2) \qquad \{4.31\}$$

where, $P_{K\,ji}(t + \delta t_2)$ is the probability that aircraft j kills aircraft i at the time of launch $t + \delta_2$, $P_{S\,j}(t + \delta_2)$ is the probability of the j th aircraft survival at time of launch This implies that an aircraft whose probability of survival has been reduced below the initial unity value has less opportunity to destroy enemies as the engagement progresses. Using this approach the equations of motion can be written in differential form just as the equations of motion of the aircraft and integrated simultaneously to give a better assessment of the combat scenario through time. This application will become clearer in the next chapter which is devoted to the explanation and construction of specific scenario models.

5.0 Scenario Specific Tradeoff Models

5.1 Introduction

The purpose of this chapter is to fully describe the program logic and assumptions made in the creation of the scenario-specific tradeoff models. The particular missions to be described in this chapter have already been defined in Section 1.5 of this dissertation and the first objective is to define some of the specifics of the environmental setting where an air superiority and ground attack (or surface attack) mission take place. In subsequent paragraphs these models will be simply referred to as ASALT I and ASALT II acronyms derived from Aircraft Survivability and Lethality Tradeoffs Model.

5.2 *Air Superiority Mission Model*

5.2.1 Combat Scenario

The combat scenario used in this model tries to capture the essential elements of a typical air superiority mission where the main goal is to deny partial or complete control of the airspace to an enemy. The model in its nominal setting addresses a typical fighter sweep mission as it might occur prior to a strike mission to a heavily defended inland target. The fighter sweep could also be cataloged as a remore escort mission where a force consisting of M friendly fighters deny the use of airspace to N enemy aircraft (aggressors) thus allowing the strike attack to be conducted immediately after (or simultaneously) the air-to-air engagement as shown in Fig. 5.1.

The carrier-based fighter fleet (friendly forces) comprise a number of twin-engined, high thrust-to-weight ratio fighters similar in performance to the F/A-18 "Hornet". Each aircraft is armed with 8 air-to-air missiles (4 long range, 2 medium range, and 2 short range) and a cannon. These aircraft have installed a high performance radar and a sophisticated avionics suite with real time data link between the aircraft and an airborne early warning command system aircraft (AWACS). The electronic countermeasure capabilities of the aircraft (ECM) allow the use of either passive and active systems. In the former group expendables, such as IR flares and chaff cartridges are used, while the later group includes self-screen and stand-off jammers.

The aggressor fleet consists of N high performance, 25-ton class interceptors with powerful augmented engines. The aggressors also have a long range capability radar though not as powerful as that of the CBF fleet. The weaponry of the aggressors comprises 8 air-to-air missiles (similar mix as that of CBF aircraft) with more limited kinematic envelopes and a cannon as well. ECM equipment is also provided.

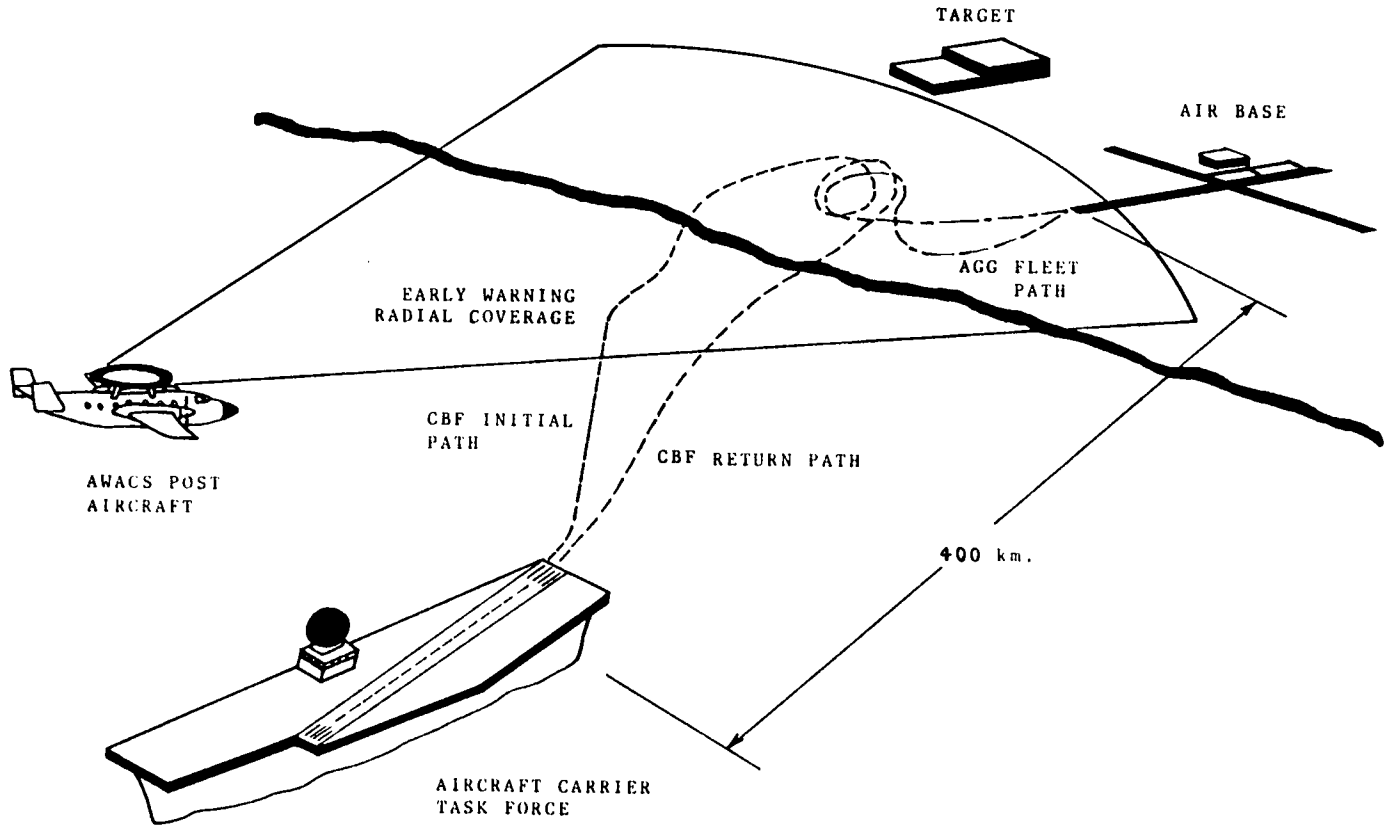


Figure 5.1 Independent Fighter Sweep Scenario.

The CBF fleet performs a remote escort mission prior to the main strike to suppress the air defense capabilities of the enemy and thus increase the chances of strike success. The simulation starts with both fleets already in the air, presumedly in the neighborhood of their respectively bases, accelerating towards an engagement area whose location is dictated by the initial aircraft states. The nominal model assumes a distance of 400 km. from the carrier battle group (CBG) to the primary target position and 250 km. from the CBG to the enemy airfield.

CBF initial vectoring takes place via a data link between the fighters and the AWACS aircraft. The aggressors are assumed to have limited ground control intercept capability (GCI). The engagement becomes "active" when the target acquisition takes place on either side of the combatant forces or an oncoming weapon is detected by any aircraft in a fleet. Engagement steering commands are assigned to each aircraft according to the opponent aircraft states (i.e., position, velocity, etc.) and the engagement progresses through a series of four well defined phases. At each phase several aircraft functions such as target detection, identification, weapons launch, guidance, and detonation are assessed on both force sides to estimate the levels of damage of each aircraft and hence evaluate the probability of survival at each point in the mission.

The mission concludes with the return of the surviving forces (on both sides) to their respective bases. The rules of disengagement are functions of the aircraft fuel, weapon status, and opponent's condition.

The model then addresses the fighter sweep as an independent scenario where enemy aircraft engage the sweeping naval fighters (called carrier based fighters-CBF) at some point between the carrier task force and an enemy inland airfield as depicted in fig. 3.1. The main purpose of the fighter sweep will be to degrade enemy air forces to ensure the use of the airspace by the friendly attacking force and escorts [Shaw, 1986]. Let the friendly and enemy forces be composed of M and N aircraft, respectively. The engagement then takes place in the airspace between the enemy airfield and the aircraft carrier provided that the minimum safe

distance form the carrier is not violated. The effect of a Forward Air Control Post (FACP) is modelled to provide initial vectors to the CBF force towards their enemies in the engagement.

Four phases are distinguished during the engagement: 1) initial phase, 2) beyond visual range (BVR), 3) close-in and air combat maneuvering (ACM), and 4) disengagement and return phase, as shown in Fig. 5.2. The geometry of the engagement, weapon status, fuel allowances, etc. dictate the transitions from one zone to another in the model, as will be explained later in the section describing the portion of air-to-air interactions. The model can be divided into three main components: 1) air-to-air interactions, 2) aircraft system effectiveness, and 3) vehicle characteristics and performance. Though not considered as a separate entity, there is a large section at the beginning of the code devoted to the model macros. These macros constitute subroutine blocks used throughout the entire program.

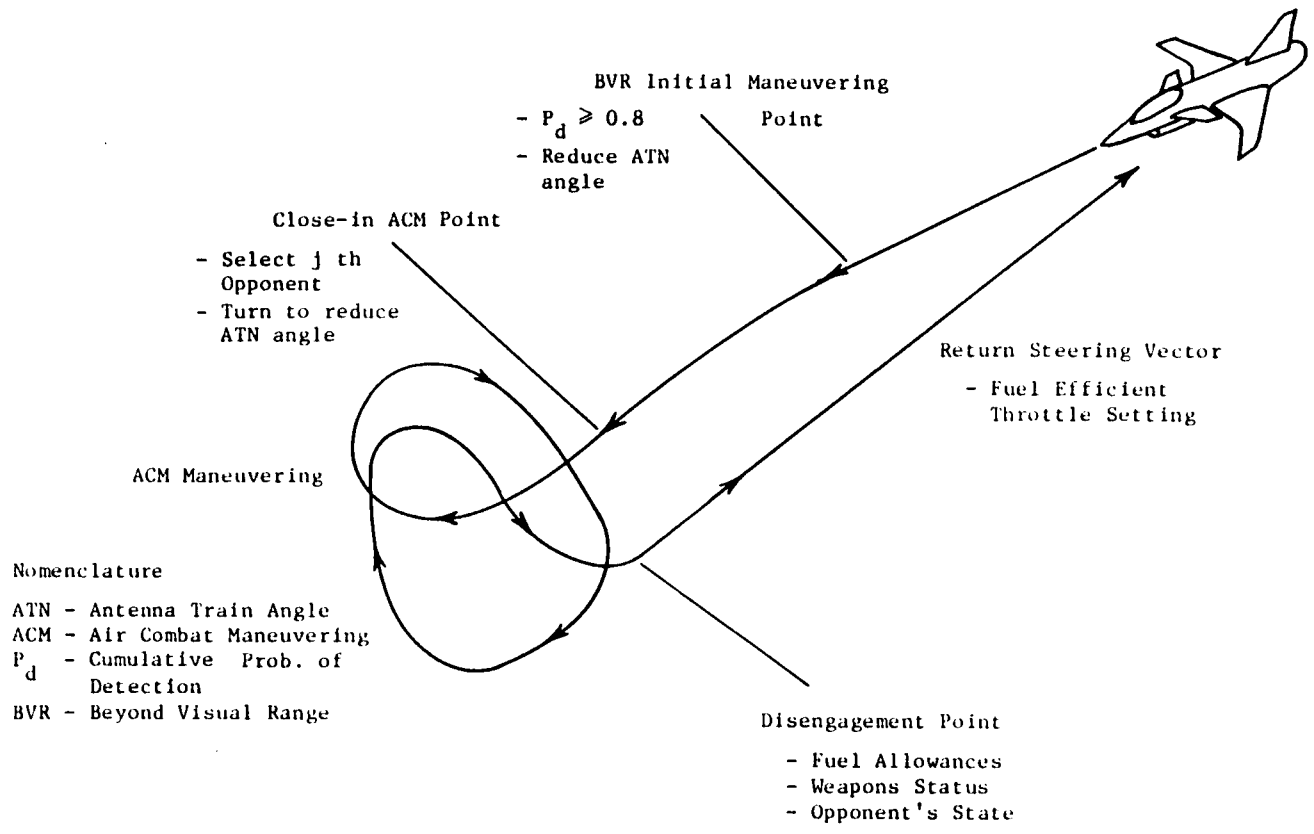


Figure 5.2 Air Combat Phases.

5.2.2 Model Inputs and Outputs

The model inputs can be classified into six broad categories: 1) aerodynamic data, 2) propulsion characteristics, 3) sensor data, 4) aircraft signatures, 5) engagement initial conditions, and 6) weapon kinematic envelopes. These categories encompass most of the assumed parameters in the model that can easily be modified in reruns in order to perform sensitivity analyses.

5.2.2.1 Aerodynamic Data

This comprises basic geometric properties of the aircraft such as wing area (S), wing aspect ratio (AR), wing effectiveness factor (e), as well as the particular drag characteristics of each aircraft and their weapons. These aerodynamic characteristics constitute a simple set of parameters that are known at the conceptual design stage and from which preliminary vehicle performance can be readily extracted as depicted in Fig. 5.3.

The propulsion data is simplified to two sets of curves: 1) thrust vs. mach number and 2) specific fuel consumption (SFC) curves. These two sets also constitute minimum requirements to predict vehicle fuel state conditions (very important in air combat) and also to complement the data base used in the assessment of vehicle performance. Fig. 5.3 illustrates the typical behavior of this curve for a high performance low by-pass ratio engine. These parameters are typically known for most U.S. and foreign engines.

5.2.2.2 Sensor Characteristics

In this group radar, infrared, and ECM sensor data are provided. Typical radar characteristics include average power, antenna size, search volume, noise temperature,

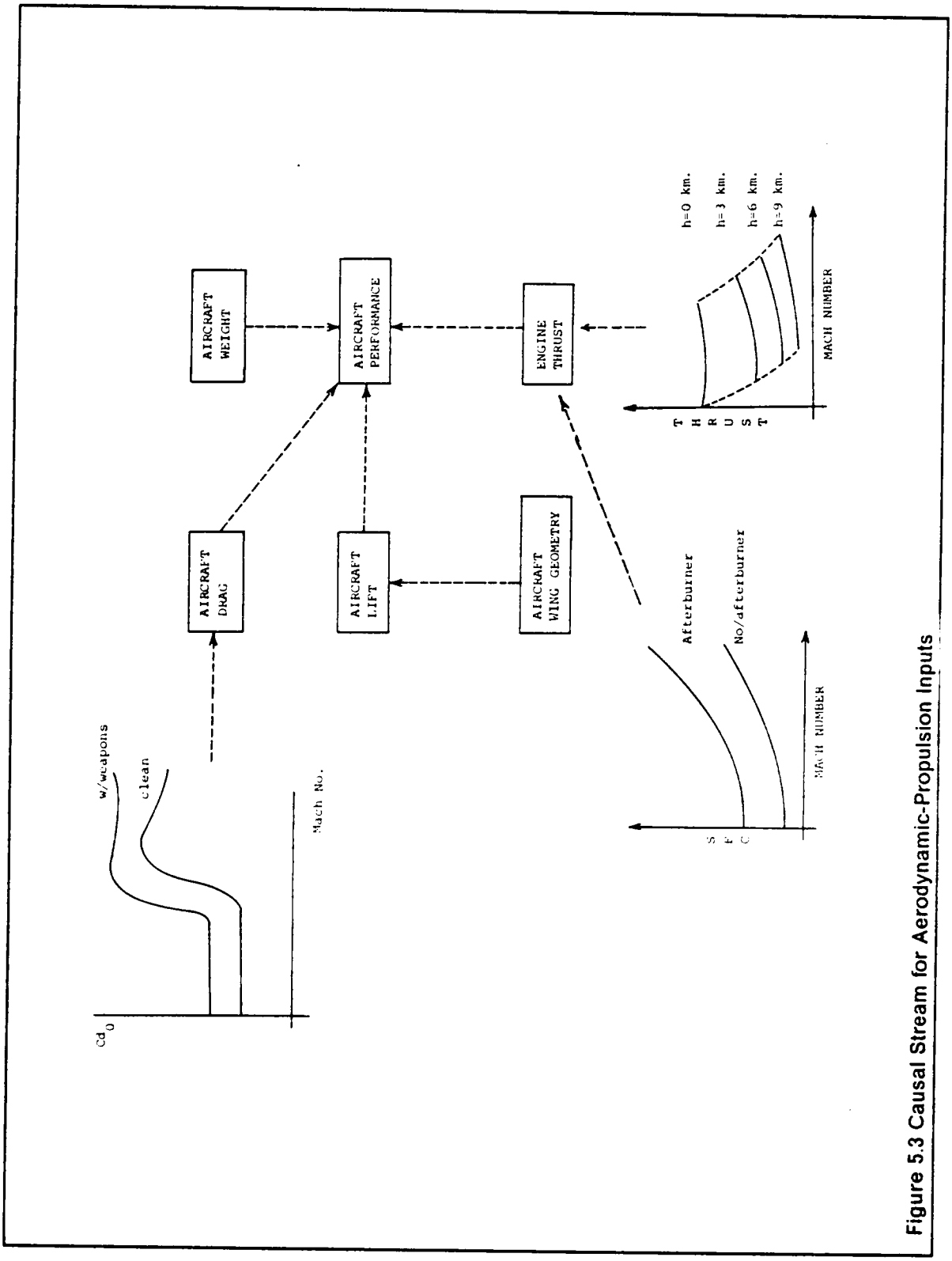


Figure 5.3 Causal Stream for Aerodynamic-Propulsion Inputs

system losses, etc. Infrared (IR) characteristics include the noise equivalent irradiance of the sensor (NEI) and the spectral boundaries of the radiation to be measured. The ECM portion of the model requires basic jammer characteristics such as power, gain, and bandwidth. Two switch statements have been incorporated into the model to allow the user the selection of no jamming, self-screen jamming, and stand-off jamming. Also some parameters of the radar warning receiver (RWR) are exogenous inputs to the model (i.e. power, gain, losses, etc.). Fig. 5.4 summarizes this.

5.2.2.3 *Aircraft Signatures*

Aircraft Signatures are implemented as table functions since these vary according to azimuth aspect angle. Fig. 5.5 exemplifies the data typically needed. Notice that the weapons contribution to signatures is accounted independently in order to simplify sensitivity analysis since the bookeeping task of assessing the number of weapons at any point in time is built into the model. The IR signatures data deals with the aircraft engine emission patterns and temperatures. The input parameters are: number of engines (NE), engine exhaust area (AE), and equivalent exhaust surface contours.

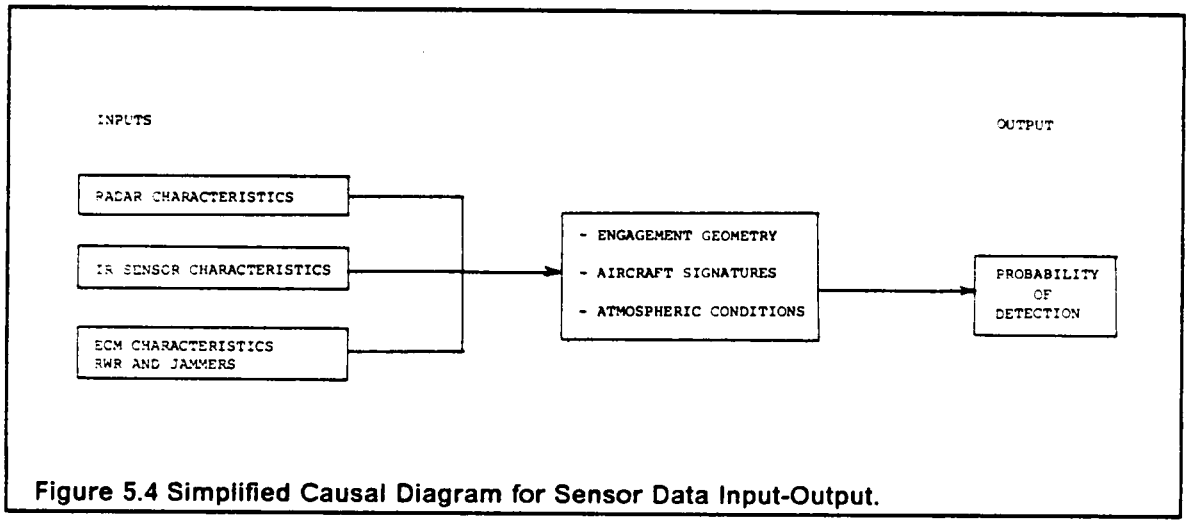


Figure 5.4 Simplified Causal Diagram for Sensor Data Input-Output.

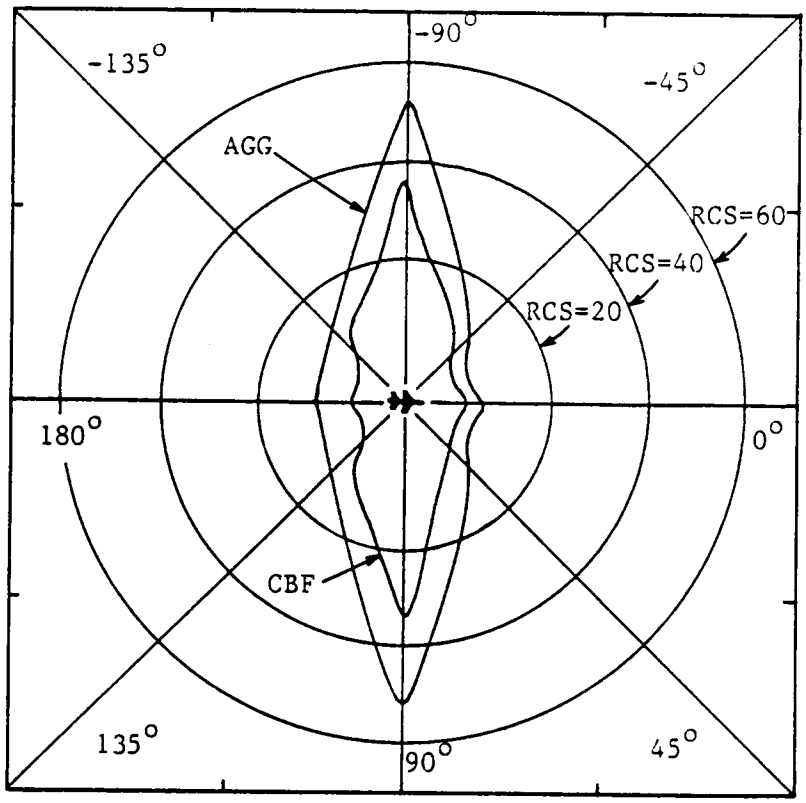


Figure 5.5 Typical Radar Signatures Modeling Curves.

5.2.2.4 *Engagement Initial Conditions*

The input necessary to establish the initial geometry of the engagement is an initial heading angle. The idea behind this is to simulate the condition of receiving vector information from an AWACS aircraft as explained before. Another important user input is the initial number of aircraft on both fleets as well as their initial positions and speeds. Fig. 5.6 summarizes this in a simple diagram.

5.2.2.5 *Weapons Kinematic Envelopes*

Inputs for the kinematic envelopes constitute: 1) a baseline value corresponding to the maximum range of the weapon in a frontal hemisphere attack for a non-maneuvering target, and 2) 3 multipliers (in the form of table function) to correct the maximum range due to off-boresight launch conditions, platform launch speed, and launch altitude. Fig. 5.7 illustrates a typical shape of the non-maneuvering envelope. Also, a minimum range firing envelope is given as a function of the maximum range envelope to avoid launches at very close range were realistically fuzing characteristics would constraint an actual launch.

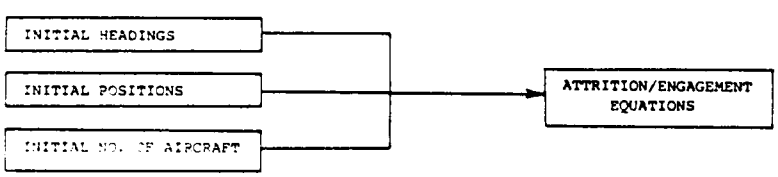


Figure 5.6 Engagement Inputs.

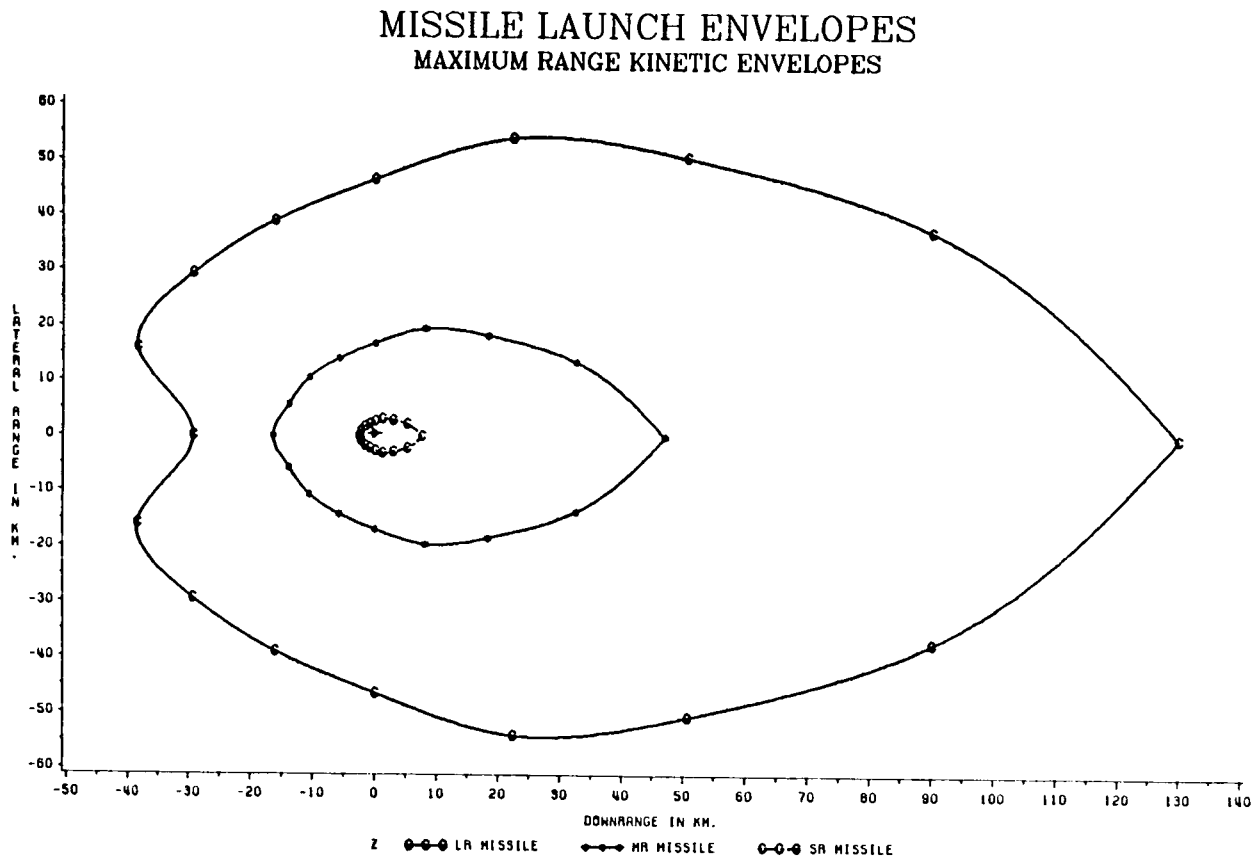


Figure 5.7 Typical Weapons Kinematic Non-maneuvering Envelopes.

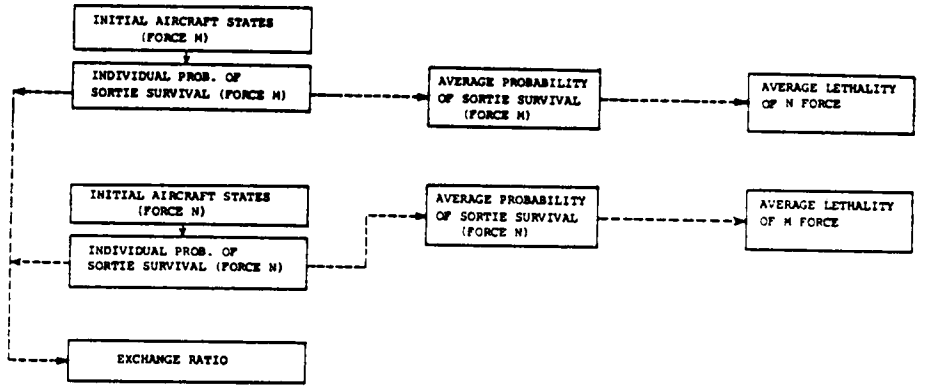


Figure 5.8 Model Output Diagram.

5.2.2.6 *Model Outputs*

The main output parameter of this model is the aircraft survivability per sortie ($P_{S/S}$). Each aircraft is assumed to have a probability of sortie survival of unity at the beginning of the simulation. The value of $P_{S/S}$ is reduced according to to the attrition equations developed in Section 5.1 using the co-kill probability scheme. A secondary indicator of the effectiveness of a force composed of M aircraft is the average probability of survival per sortie of the fleet, $Pav_{S/S}$. Similarly the lethality of the force can be assessed by summing the number of aircraft killed in the opposing force. Finally, the exchange ratio is also evaluated as an indicator of force effectiveness (Fig. 5.8).

5.2.3 Model Macros

DYNAMO III, the computer simulation language associated with the systems dynamics methodology employed in this research, has the capability of implementing subroutines with a minimum of effort. These subroutines are denoted "macros" and since they are extensively

used in the model it is necessary to understand their function. There are twenty eight macros used and each one will be fully described in the subsequent paragraphs.

5.2.3.1 Macro ARCSIN

As its name implies this macro computes the arc sine of an angle provided that cartesian coordinates of two points in space designated (X1,Y1) and (X2,Y2) are given. A fifth input is required in this macro and corresponds to the hypotenuse (HY) of the triangle formed by the two points and the imaginary perpendicular to the horizontal axis of the earth-fixed coordinate system chosen as reference for aircraft positions in the model. Fig. 5.9 illustrates the geometry of this axis system.

The full description of the two points of interest (X1,Y1) and (X2,Y2) avoids the ambiguities in determining the quadrant where these points are located, thus simplifying subsequent angular computations. Eqs. 5.1 through 5.11 depict the DYNAMO III macro implementation for ARCSIN. Notice that two checks are necessary to assess the relative positions of the two points of interest (i.e., two aircraft positions in an engagement) and thus to determine the quadrant corresponding to those instantaneous aircraft positions. Also, it is noted that the values for the macro ARCSIN are divided into two groups to avoid large inaccuracies in the neighborhood of $\pi/2$ and $3\pi/2$ where small changes in the argument (Y1-Y2)/(HY+1E-6) yield considerable variations in the arc sine function. In this respect, an argument cutoff point selected arbitrarily at 0.925 (i.e., 67.67 deg.) seemed to yield good results without an excessive computational burden.

In summary, the approximation of the arc sine function with a linear piecewise function yields results within one degree of the exact value for near perpendicular aircraft angle-off conditions and this suffices for the accuracy of this simulation. The accuracy of this method was weighted against a third order Newton polynomial interpolation method (3 interpolating segments per $\pi/2$) with similar CPU time requirements on an IBM 3090 mainframe computer.

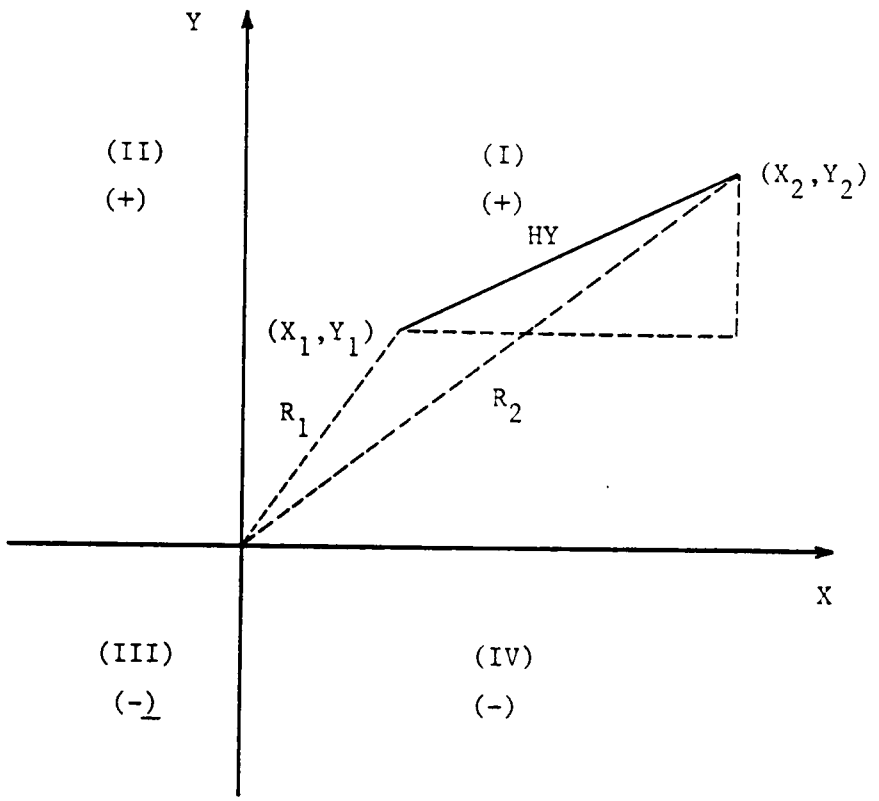


Figure 5.9 Macro ARCSIN Geometry Convention.

A final word about this macro is the inclusion of a small constant in the denominator (1 E-6) to avoid division by zero. This would tend to occur when the distance between two or more vehicles becomes very small.

```
MACRO   ARCSIN(X1,Y1,X2,Y2,HY)
A       ARCSIN=CLIP($SIN2.K,$SIN1.K,Y1.K,Y2.K)                                  5.1
A        $SIN2.K=CLIP($SIN3.K,$SINIV.K,X1.K,X2.K)                               5.2
A          $SIN3.K=CLIP($SIN1I.K,$SIN2I.k,.925,MAX(Y1.K-Y2.K,-Y1.K+Y2.K)
X            /(HY.K+1E-6))+180                                                  5.3
A          $SINIV.K=CLIP($SIN22.K,$SIN12.k,.925,MAX(Y1.K-Y2.K,-Y1.K+Y2.K)
X            /(HY.K+1E-6))+180                                                  5.4
A        $SIN1.K=CLIP($SINII.K,$SINI.K,X1.K,X2.K)                               5.5
A          $SINII.K=CLIP($SIN12.K,$SIN22.k,.925,MAX(Y2.K-Y1.K,-Y2.K+Y1.K)
X            /(HY.K+1E-6))                                                      5.6
A          $SIN12.K=TABHL(TS1II,MAX(Y2.K-Y1.K,-Y2.K+Y1.K)/(HY.K+1E-6)
X            ,.925,1.0,.00375)                                                  5.7
A          $SIN22.K=TABHL(TS2II,MAX(Y2.K-Y1.K,-Y2.K+Y1.K)/(HY.K+1E-6)
X            ,0.0,.925,.025)                                                    5.8
A        $SINI.K=CLIP($SIN1I.K,$SIN2I.k,.925,MAX(Y2.K-Y1.K,-Y2.K+Y1.K)
X          /(HY.K+1E-6))                                                        5.9
A          $SIN1I.K=TABHL(TSIN1I,MAX(Y2.K-Y1.K,-Y2.K+Y1.K)/(HY.K+1E-6)
X            ,0.0,.925,.025)                                                    5.10
A          $SIN2I.K=TABHL(TSIN2I,MAX(Y2.K-Y1.K,-Y2.K+Y1.K)/(HY.K+1E-6)
X            ,.925,1.00,.00375)                                                 5.11
MEND
```

The numerical values of the invoked tables TS1II, TS2II, TSIN1I, and TSIN2I are given in eqs. 5.12 through 5.15.

```
T       TSIN1I=0/1.43/2.87/4.30/5.74/7.18/8.63/10.08/11.54/13.00/14.48
X        /15.96/17.46/18.97/20.49/22.02/23.58/25.15/26.74/28.36/30.31
X        /33.37/35.10/36.87/38.68/40.54/42.45/44.42/46.47/48.59/50.81
X        /53.13/55.59/58.21/61.05/64.15/67.7                                    5.12

T       TSIN2I=67.67/68.24/68.82/69.43/70.05/70.69/71.35/72.04/72.75
X        /73.5/74.26/75.07/75.93/76.84/77.82/78.88/80.06/81.40/82.98
X        /85.04/90                                                              5.13

T       TS1II=112.3/111.76/111.2/110.6/110/109.3/108.7/108/107.3/106.5
X        /105.7/104.9/104.1/103.2/102.2/101.1/100/98.6/97/95/90                 5.14

T       TS2II=180/178.57/177.1/175.7/174.3/172.8/171.4/169.9/168.5/167
X        /164/162.5/161/159.5/158/156.4/153/154/152/150/148.3/146.6/145
X        /143.1/141/139.5/137.6/135.6/133.5/131/129/126.9/124/121.8/119
X        /115.8/112.3                                                           5.15
```

5.2.3.2 *Macros SSOUND, TEM, PRATIO, and SIGM*

These set of subroutines compute the speed of sound, temperature, pressure ratio, and density ratio at any specified altitude, respectively. An approximation of the standard atmosphere (ICAO and U.S., 1962) is used in accordance to the equations provided by Roskam and Lan [1981]. Starting with SSOUND, the DYNAMO equations are shown in 5.16 and 5.17.

```
MACRO SSOUND(ALT)
A       SSOUND.K=CLIP(295.2,TABHL(AT,ALT.K,0,12200,1525),ALT.K,12200)      5.16
MEND

T       AT=340.5/334.5/328.4/322.34/315.85/309.8/303.0/296.6/295.2         5.17
```

Similarly, TEM computes the atmospheric temperature at altitude according to the constant temperature lapse rate model previously mentioned (i.e., -6.5 deg C per 1000 meters). This is shown in eq. 5.18.

```
MACRO TEM(ALT)
A       TEM.K=CLIP(216.7,T0-.0065*ALT.K,ALT.K,11000)                       5.18
MEND
```

SIGM computes the density ratio at altitude as the ratio of pressure ratio (DELTA) and temperature ratio (THETA). The dummy argument DELTA is used as input although it is equivalent to the output of PRATIO as seen in eq. 5.19.

```
MACRO SIGM(DELTA,THETA)
A       SIGM.K=DELTA.K/THETA.K                                             5.19
MEND
```

Finally, macro PRATIO computes the air pressure ratio at a given altitude (ALT). Eq. 5.20 incorporates a CLIP function to differentiate between the two layers of pressure variation assumed in the standard model. These layers correspond to typical troposphere and stratosphere altitude bands for medium latitudes [Roskam and Lan, 1981].

```
MACRO PRATIO(ALT)
A       PRATIO.K=CLIP(.2234*EXP(-(ALT.K-11000)/6340.64),
```

```
X       (TEM(ALT.K)/T0)**5.2561,ALT.K,11000)                    5.20
MEND
```

Note that all four macros express altitude above mean sea level in meters.

5.2.3.3 *Macro DIREC*

Throughout this model there are instances when is necessary to estimate return vectors for each aircraft once certain fuel, weapons, and opponent conditions are met. The macro DIREC estimates the angle formed by the aircraft velocity vector and the return-home position vector given the aircraft present heading (HEAD), the direction of the vector line-of-sight (VLOS) from "home" to the present aircraft position, and the ordinates of the aircraft position (YCOMP1) and that of the home base (YCOMP2). The first CLIP statement indicates the position of the aircraft with respect to the base. The dummy variables in 5.21, $DIR12 and $DIR34, stand for directions in quadrants I and II or III and IV, respectively. The angular difference between the present heading angle (HEAD) and VLOS is compared with either 180 or -180 depending upon the previously determined quadrant, to compute the angular difference between HEAD and VLOS. Fig. 5.10 depicts this graphically. All inputs to DIREC are in degrees.

```
MACRO DIREC(HEAD,VLOS,YCOMP1,YCOMP2)
A       DIREC.K=CLIP($DIR12.K,$DIR34.K,YCOMP1.K,YCOMP2.K)                          5.21
A       $DIR34.K=CLIP(HEAD.K-VLOS.K,(HEAD.K-VLOS.K)-360,180,HEAD.K-VLOS.K)        5.22
A       $DIR12.K=CLIP(360+(HEAD.K-VLOS.K),HEAD.K-VLOS.K,-180,HEAD.K-VLOS.K)       5.23
MEND
```

5.2.3.4 *Macro YAW*

This macro simply limits the value of the heading angle (ψ) within $0 \leq \psi \leq 2\pi$. Eqs. 5.24 through 5.26 easily achieve this.

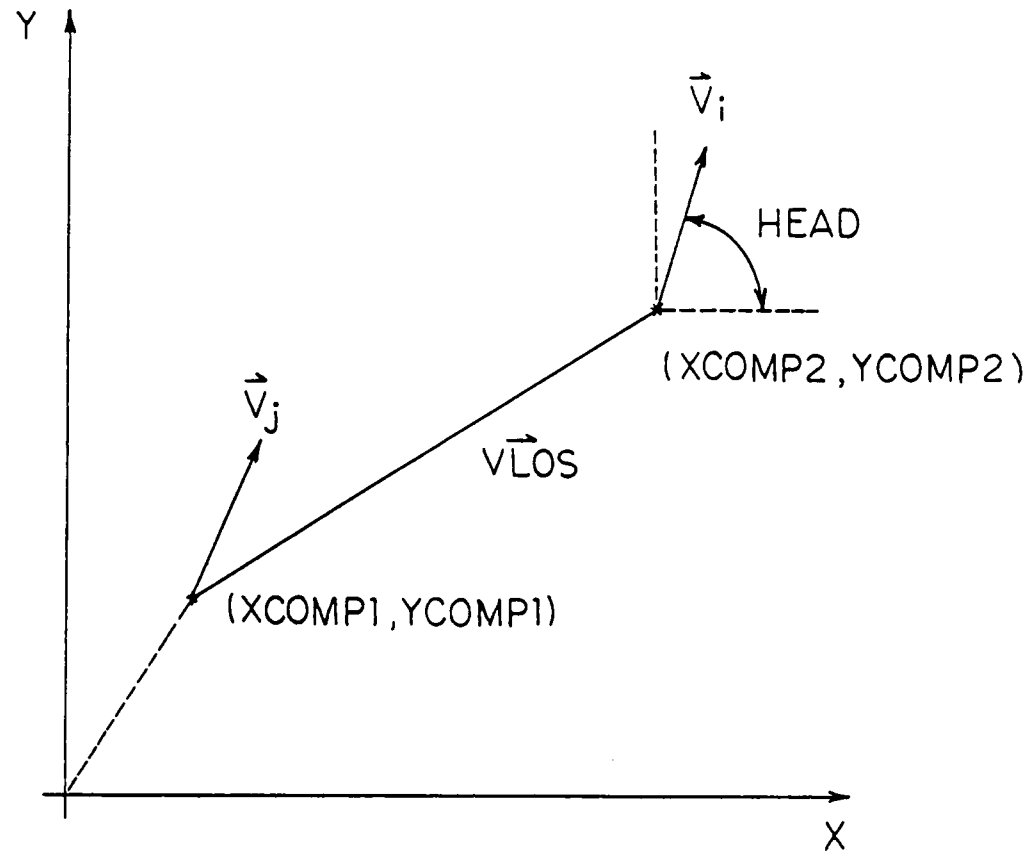


Figure 5.10 Notation for Macro DIREC.

```
MACRO YAW(ANGLE)
A       $NUM.K=ANGLE.K/360                                              5.24
A       YAW.K=CLIP($YAWPO.K,$YAWNE.K,$NUM.K,0)                          5.25
A       $YAWPO.K=CLIP($N1P.K,$N036.K,$NUM.K,1)                          5.25.1
A       $N036.K=ANGLE.K                                                 5.25.2
A       $N1P.K=CLIP($N2P.K,$N3672.K,$NUM.K,2)                           5.25.3
A       $N3672.K=ANGLE.K-360                                            5.25.4
A       $N2P.K=CLIP($N3P.K,$N7210.K,$NUM.K,3)                           5.25.5
A       $N7210.K=ANGLE.K-720                                            5.25.6
A       $N3P.K=CLIP($N4P.K,$N1014.K,$NUM.K,4)                           5.25.7
A       $N1014.K=ANGLE.K-1080                                           5.25.8
A       $N4P.K=CLIP($N5P.K,$N1418.K,$NUM.K,5)                           5.25.9
A       $N1418.K=ANGLE.K-1440                                           5.25.10
A       $N5P.K=CLIP($N6P.K,$N1821.K,$NUM.K,6)                           5.25.11
A       $N1821.K=ANGLE.K-1800                                           5.25.12
A       $N6P.K=ANGLE.K-2160                                             5.25.13
NOTE
A       $YAWNE.K=CLIP($N1N.K,$NN036.K,-1,$NUM.K)                        5.26
A       $NN036.K=360+ANGLE.K                                            5.26.1
A       $N1N.K=CLIP($N2N.K,$NN367.K,-2,$NUM.K)                          5.26.2
A       $NN367.K=720+ANGLE.K                                            5.26.3
A       $N2N.K=CLIP($N3N.K,$NN721.K,-3,$NUM.K)                          5.26.4
A       $NN721.K=1080+ANGLE.K                                           5.26.5
A       $N3N.K=CLIP($N4N.K,$NN101.K,-4,$NUM.K)                          5.25.6
A       $NN101.K=1440+ANGLE.K                                           5.26.7
A       $N4N.K=CLIP($N5N.K,$NN141.K,-5,$NUM.K)                          5.26.8
A       $NN141.K=1800+ANGLE.K                                           5.26.9
A       $N5N.K=CLIP($N6N.K,$NN181.K,-6,$NUM.K)                          5.26.9
A       $NN181.K=2160+ANGLE.K                                           5.26.10
A       $N6N.K=2520+ANGLE.K                                             5.26.11
MEND
```

5.2.3.5 *Macro SPECTR*

SPECTR finds the relative infrared energy radiated by a black body whose spectral bandwidth lies between two known points, MULOW and MUHIGH, in the infrared spectrum. Fig. 11 shows the universal blackbody curves [Hudson, 1969] direct result of Planck's radiation law. The curve on the left represents the relative spectral radiant emittance while the right one is the relative energy below a certain cutoff wavelength argument μT, where μ is the radiation wavelength and T is the temperature in degrees absolute. Eqs. 5.27 through 5.31 depict the actual implementation of these universal curves in the macro SPECTR.

```
MACRO SPECTR(EGT,MUHIGH,MULOW)
A       SPECTR.K=$ENHIGH.K-$ENLOW.K                                     5.27
A       $ENHIGH.K=TABHL(ENERGY,$LTHIGH.K,1000,15000,1000)               5.28
A       $ENLOW.K=TABHL(ENERGY,$LTLOW.K,1000,15000,1000)                 5.29
A       $LTLOW.K=MULOW*EGT.K                                            5.30
```

```
A       $LTHIGH.K=MUHIGH*EGT.K                                    5.31
MEND
```

Engine exhaust temperature (EGT) and the two spectral bandwidth limiting values (MULOW and MUHIGH) represent inputs to this macro. Dummy variables $LTLOW and $LTHIGH compute the lower and upper boundary values of μT to be used in the universal radiation curves (fig. 11). The curve of interest to us is the cumulative radiant energy curve (A) which is implemented as a TABLE function (see Section 2.3) denoted ENERGY. Two other dummy variables, $ENHIGH AND $ENLOW, are necessary to find the values of the relative energies comprising the infrared (IR) radiation spectrum of interest. The difference between these two energy levels constitutes the desired value of IR radiating energy denoted SPECTR.

5.2.3.6 *Macro IRDET*

This macro finds the cumulative probability of infrared detection of a target for a false alarm rate of 1E-8. This cumulative probability of detection is implemented as a simple table function called IRDT dependent upon the signal-to-noise ratio (SNOISE) as shown in eq. 5.32. Eq. 5.32 invokes the table function shown in 5.33 to get the actual value of the cumulative probability of detection.

```
MACRO IRDET(SNOISE)
A       IRDET.K=TABHL(IRDT,SNOISE.K,2,7,.2)                       5.32
MEND

T       IRDT=0/.01/.02/.03/.04/.05/.08/.11/.21/.33/.45/.56/.65/.73
X         /.81/.87/.93/.96/.975/.983/.988/.993/.996/.998/.999/1   5.33
```

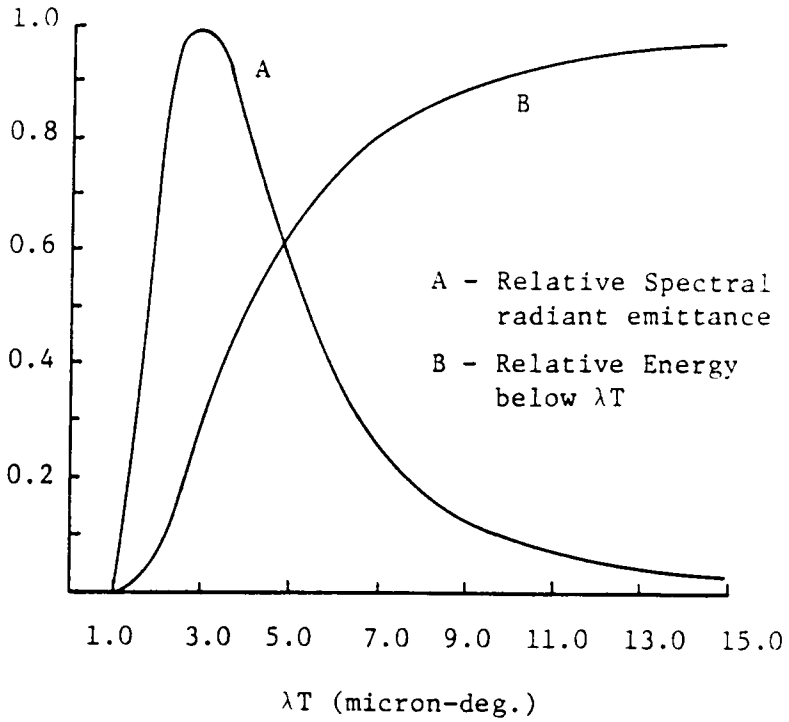


Figure 5.11 Universal Radiation Curves for a Black Body (adapted from Hudson, 1969)

5.2.3.7 *Macro ALPH*

ALPH finds the value of a parameter α used in the computation of the ratio of atmospheric transmittance (τ). τ is modelled as a linear function with altitude (ALT) which constitutes the only input required in this macro (eqs. 5.34 and 5.35).

```
MACRO ALPH(ALT)
A       ALPH.K=TABHL(ALPTT,ALT.K,0/15000,3000)                    5.34
MEND

T       ALPTT=.04/.031/.0225/.0137/.005/.003                      5.35
```

5.2.3.8 *Macro AF*

AF represents a correction factor applied to the infrared emission values in order to account for target aspect angle variations typically encountered during an air combat engagement. The target aspect angle (ATN) represents the only input to the macro as seen in eqs. 5.36 and 5.37.

```
MACRO AF(ANGLE
A       AF.K=TABHL(AFT,MAX(ATN.K,-ATN.K),0,180,20)                5.36
MEND

T       AFT=.15/.17/.20/.25/.32/.39/.50/.62/.75/1.0               5.37
```

Fig. 5.12 depicts the geometry convention used to define the target aspect angle (ATN). For the aggressor fleet a similar arrangement is used except that the variable name is denoted by TAA. Note that ATN and TAA vary from 0 to π and take either sign as will be explained in Section 5.2.4.3. The absolute value of ATN is used as independent variable in the table function AFT to find the desired value of the emission multiplier. Fig. 5.13 shows the numerical values of AFT in graphical form.

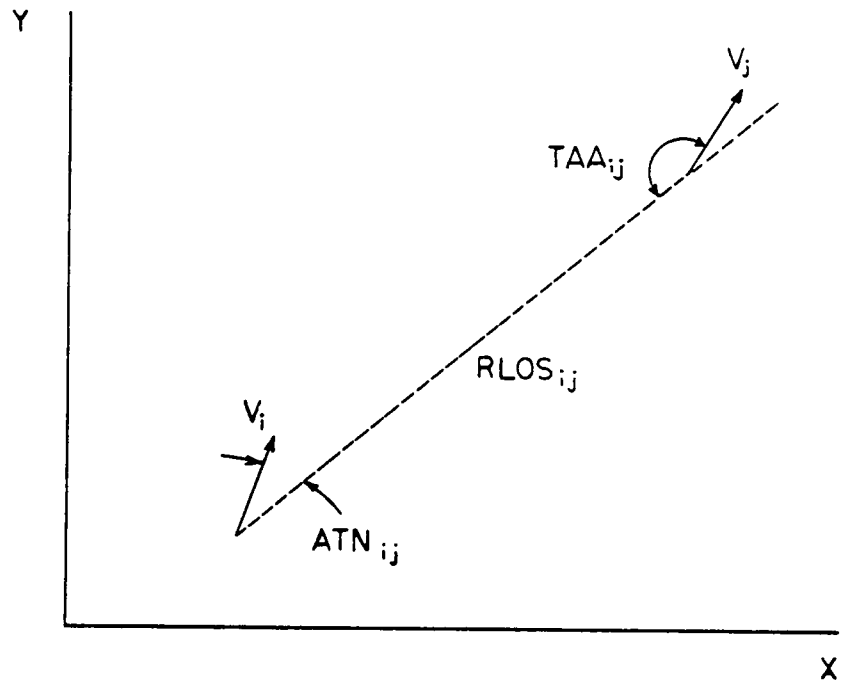


Figure 5.12. Target Aspect Angle Convention.

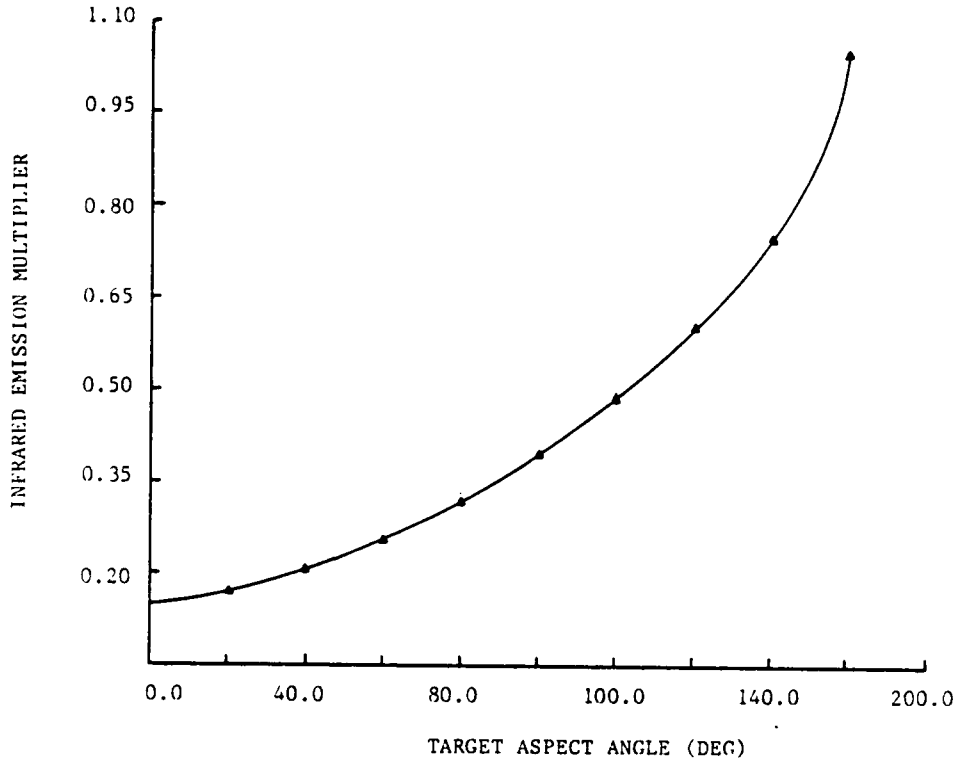


Figure 5.13. Emission Multiplier Variation with Target Aspect Angle.

5.2.3.9 *Macro LOS*

LOS is used to estimate wheter or not a target is within line of sight of an attacker knowing the altitude (ALTD) at which the engagement takes place and the line of sight range between the two (RLOS). Table function ALOST represents the minimum altitude at which an aircraft is within LOS of an observer at a distance RLOS/2 standing on a perfectly spherical terrain. This condition also ensures that another aircraft or target flying at near the same altitude could also be able to establish LOS contact with the previous aircraft an observer. Tabular values for ALOST and RLOS values are given in meters (Eq. 5.40).

```
MACRO LOS(ALTD,RLOS)
A       LOS.K=CLIP(1,0,ALTD.K,$ALOS.K)                          5.38
A         $ALOS.K=TABLE(ALOST,RLOS.K/2,0,3E5,2E4)               5.39
MEND

T       ALOST=0/9.63/38.5/86.55/153.90/240.45/346.3/471.31/615.95
X       /780/962/1164.1/1385.4/1628.1/1885.98/2164.6            5.40
```

5.2.3.10 *Macros RCSAGM and RCSAAM*

Just as aspect angle affects the "viewed" infrared emission pattern of an air vehicle, it also affects its radar signatures (RCS). RCSAGM and RCSAAM are multipliers or correction factors to account for the large azimuthal variations in aircraft signatures. Note that the radar signatures particular to each fleet aircraft are incorporated independently following the original "role disaggregation" established in the overall model among the combatant fleets. This also gives versatility to introduce dissimilar aircraft (i.e., with different radar and IR signatures) within a given force. Eqs. 5.41 and 5.42 accomplish this introducing two table functions representing the radar cross section "footprint" in azimuth of the aircraft modeled in the nominal model. The tabular values are incorporated in eqs. 5.43 and 5.45 and depicted graphically in Fig. 5.14.

```
MACRO RCSAGM(ATN)
A       RCSAGM.K=TABHL(RCSAGT,MAX(ATN.K,-ATN.K),0,180,22.5)          5.41
MEND
MACRO RCSAAM(TAA)
A       RCSAAM.K=TABHL(RCSAAT,MAX(TAA.K,-TAA.K),0,180,22.5)          5.42
MEND

T       RCSAGT=1/.85/1.3/2.5/5.5/3.8/3.0/1.8/1.6                     5.43
T       RCSAAT=1/.88/1.5/3.3/5.7/3.9/2.3/1.8/1.5                     5.44
```

5.2.3.11 *Macro MRBSM*

This macro evaluates a multiplier used to correct the weapons (i.e., air-to-air missiles) maximum nominal range due to off-boresight conditions. As will it become clear in Section 5.4.3 the missile kinematic envelopes are defined as nominal values for both, the CBF and AGG aircraft corrected by three multipliers to account for azimuth, aircraft speed, and aircraft altitude. A single input is required in MRBSM as only the target aspect angle, denoted by the dummy variable AA, is used to correct the kinematic envelopes due to azimuthal (target-off) variations. Notice from eqs. 5.45 and 5.46 that variations in AA are bounded between $0 \wedge \pi$. Tabular values for the CBF are shown in eq. 5.46 while those for the AGG are those of eq. 5.45A in Appendix A of this dissertation. Fig. 5.15 depicts the trend of the multiplier in graphical form. It is realized that the use of this multiplier results in symmetrical weapon envelopes which further need to be corrected for maneuvering targets.

```
MACRO MRBSM(AA)
A       MRBSM.K=TABHL(MRBSMT,MAX(AA.K,-AA.K),0,180,22.5)             5.45
MEND

T       MRBSMT=1/.75/.55/.50/.45/.417/.40/.375/.375/.35              5.46
```

5.2.3.12 *Macro MICF*

The missile intercept confidence factor (MICF) is a subjective parameter used to estimate the probability of weapons launch to a target depending upon the relative states of the target

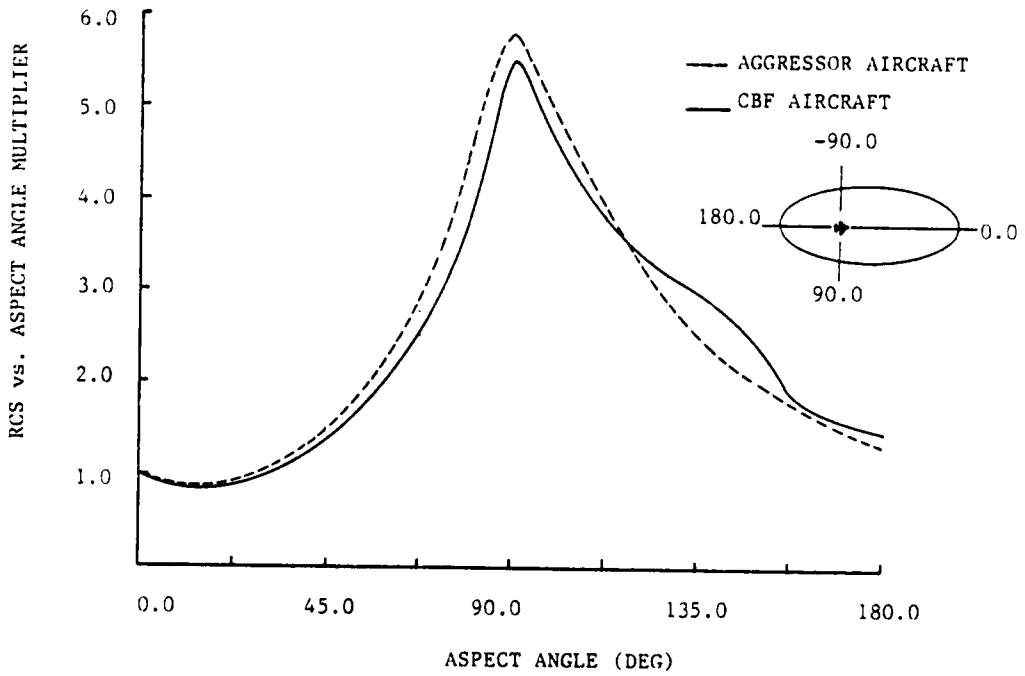


Figure 5.14. Aircraft Cross Sectional Area Footprint in Azimuth.

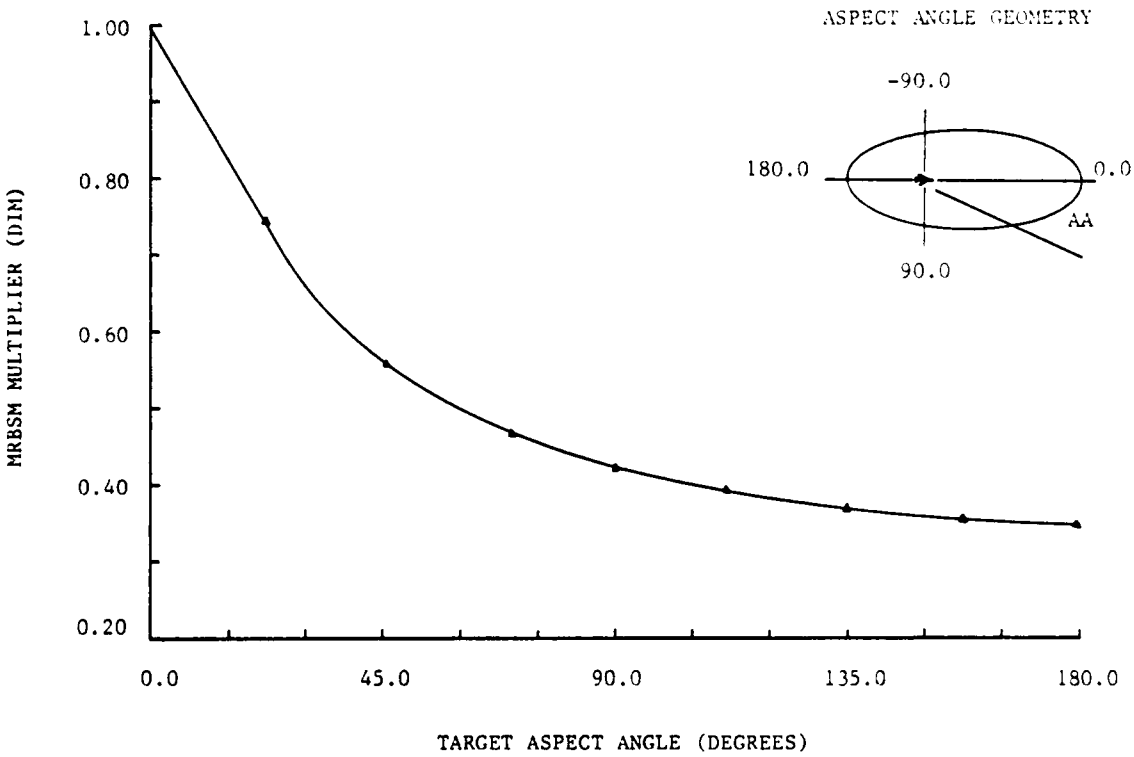


Figure 5.15. Air-to-Air Weapon Range Off-boresight Multiplier.

and attacking aircraft as well as the known kinematic envelopes of the weapons carried [Scott, 1979 and Lutter, 1981]. Eqs. 3.47 through 5.49 show this macro.

```
MACRO MICF(R,RMAX,RNE,RMIN)
A       MICF.K=CLIP(0,$MICF1.K,R.K,RMAX.K)                                  5.47
A       $MICF1.K=CLIP((RMAX.K-R.K)/(RMAX.K-RNE.K),$MICF2.K,R.K,RNE.K)       5.48
A       $MICF2.K=CLIP(1,0,R.K,RMIN.K)                                       5.49
MEND
```

Four pieces of information are required to evaluate MICF. These are: 1) The slant range (R) from the attacker to the target, 2) the maximum steady-target kinematic range for the i th weapon (RMAX) in question (corrected by aircraft speed, altitude, etc.), 3) the so-called never escape range (RNE) which represents the maximum range at which the missile and "always" hit a maneuvering target, and 4) the minimum steady-target kinematic envelope (RMIN) which in general is a function of fuzing characteristics.

As it can be seen from Eqs. 5.47 through 5.49 MICF represents a linearly varying factor with range having a unity value at the never escape missile kinematic boundary (R=RNE) and zero at the maximum range boundary (R=RMAX) for a nonmaneuvering target. Dummy variables $MICF1 and $MICF2 are used to transfer control to the proper algebraic expression for MICF depending upon the value of R.

5.2.3.13 Macro BINARY

Binary simply assigns a value of 0 if the input DIST is greater or equal than MLE or 1 if this condition is not satisfied. This macro is used to test physically if an intruder is or is not within the firing envelope of an attacking aircraft as seen in Eq. 5.50.

```
MACRO BINARY(DIST,MLE)
A       BINARY.K=CLIP(0,1,DIST.K,MLE.K)                                     5.50
MEND
```

5.2.3.14 *Macro MABSLA*

This macro computes a multiplier that corrects target detection due to azimuthal beam shape losses typical of radar antennas. Eqs. 5.51 through 5.53 show this macro which requires to inputs: the target aircraft aspect angle (AA) and the antenna maximum train angle (THETA) which limits physically the motion of the antenna platform or the radar control system. Fig. 5.16 shows the actual table function assumed in the nominal model for MABSLA.

```
MACRO MABSLA(AA,THETA)
A       MABSLA.K=TABHL(DELAT,$DELAZ.K,0,60,10)                    5.51
A       $DELAZ.K=(THETA.K/2)-MAX(AA.K,-AA.K)                      5.52

T       DELAZ=1/.96/.93/.90/.85/.80/.75                           5.53
MEND
```

5.2.3.15 *Macros RATINV and DBINV*

RATINV converts the ratio of two numbers (i.e., range information) to decibels. The only input to the macro is the quantity denoted as A which represents the ratio to be converted to decibels, as shown in Eq. 5.54.

```
MACRO RATINV(A)
A       RATINV.K=10*(LOGN(MAX(.001,A.K))/LOGN(10))                5.54
MEND
```

Notice that a MAX function is used to avoid the computation of log (0) and a cutoff value of -30 db. (.001) has been chosen without introducing significant errors, as it will become clear later.

DINV is used to convert decibels to an argument that could represent a ratio of two quantities. Again, only a single input is required and this represents the number of decibels to be converted to an argument. Eq. 3.55 shows the simple equation to accomplish this inversion.

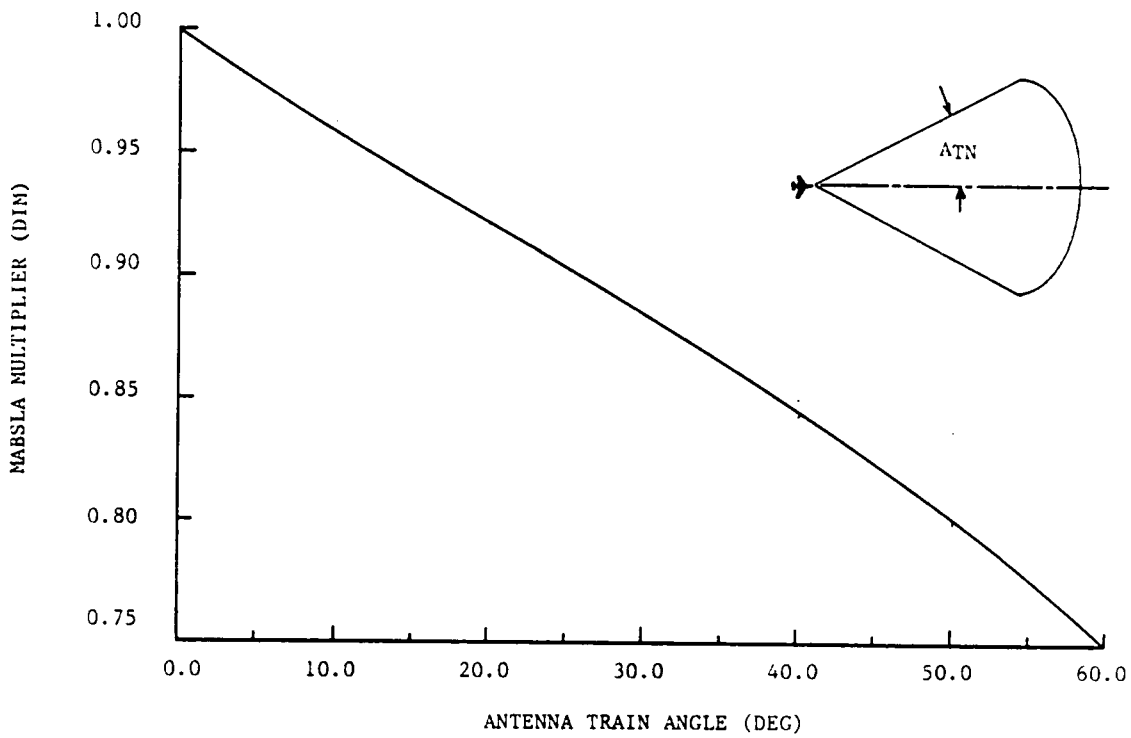


Figure 5.16. Azimuthal Beam Shape Loss Multiplier and Geometry.

```
MACRO DINV(A)
A       DINV.K=10**(A.K/10)                                    5.55
MEND
```

The implementation of these two macros is necessary to aid in the computation of the cumulative probability of radar detection as it will be explained in a subsequent section.

5.2.3.16 *Macro INTRP*

The extensive use of table look-ups through the model is based on a linear interpolation algorithm (INTRP). Fig. 5.17 represents a graphical depiction of the interpolation problem. Suppose that the linear segments H and I are given in the problem and represent piecewise approximations to a set of curves (i.e., thrust vs. mach number curves). These curves can be easily implemented in DYNAMO as sets of table functions (points A, B, C, and D). Since point (Xn,Yn) is the point of interest, DYNAMO III automatically finds the values of E and F from the specified table functions for I and H. Knowing the value of the curve J it is possible to find point G (Xn,Yn) according to 5.56.

```
MACRO INTRP(E,F,H,I,J)
A       INTRP.K=E.K+((F.K-E.K)*(J.K-H.K)/(I.K-H.K)              5.56
MEND
```

5.2.3.17 *Macro LOADF*

This macro evaluates the maximum allowable load factor, in G's, that an aircraft can tolerate structurally, constrained by thrust, or due to crew tolerances. The computation of load factor is of primary importance in determining the maneuvering capabilities of the aircraft. Eqs. 5.57 through 5.62 show the computational scheme used in this macro. Input parameters

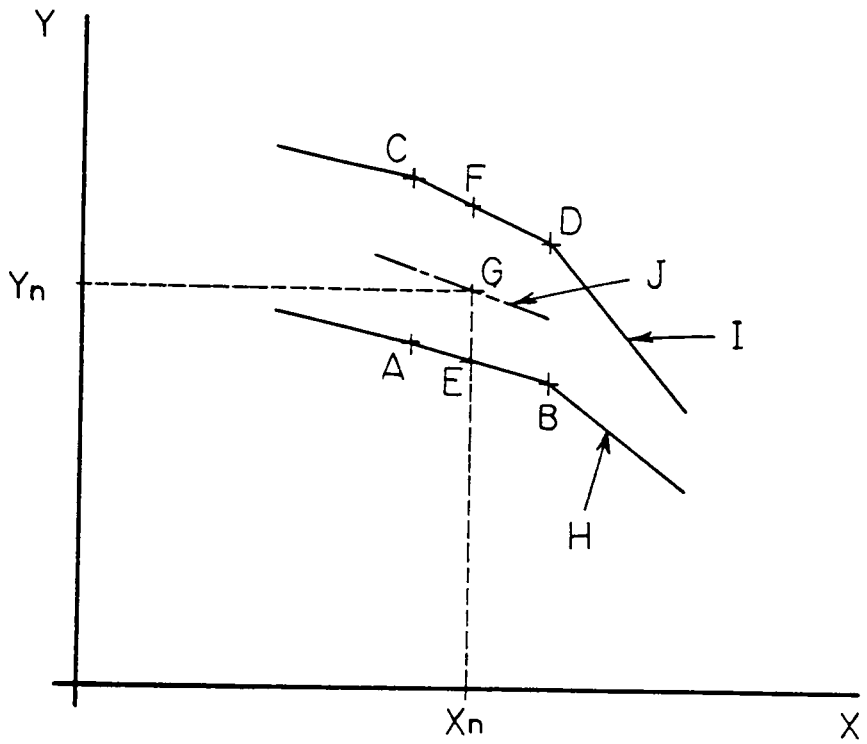


Figure 5.17. Linear Interpolation Geometry.

are: dynamic presure (Q), aircraft weight (WEIGHT), efficiency factor (K), maximum available thrust (THRUST), wing area (WAREA), zero lift coefficient (CD0), and structural limitations (NSTRUC).

```
MACRO LOADF(Q,WEIGHT,K,THRUST,WAREA,CDO,NSTRUC)
A          LOADF.K=MIN($NTRUS.K,MIN(NSTRUC,$NCREW))                    5.57
A           $NTRUS.K=CLIP((WAREA*Q.K/(WEIGHT.K))*SQRT($THIRD.K),1
X           ,$FIRST.K-$SECON.K,0)                                      5.58
A             $THIRD.K=ABS($FIRST.K-SECON.K)                           5.59
A             $SECON.K=CDO.K/K                                         5.60
A             $FIRST.K=THRUST.K/(K*Q.K*WAREA)                          5.61
A          $NCREW.K=7.5                                                5.62
MEND
```

Dummy variables $FIRST, $SECON, and $THIRD are used to compute lumped terms inside of another macro defined variable $NAERO which evaluates the thrust/drag limited sustained load factor in a steady turn according to 5.63.

$$N_t = \frac{Q}{WEIGHT/WAREA}\sqrt{\frac{THRUST}{K\,Q\,WEREA} - \frac{CDO_o}{K}} \qquad 5.63$$

Eq. 5.57 just selects the minimum between the structural load factor, the crew tolerances (NCREW) and the thrust limited load factor (NTRUS) computed in 5.58. This value will later on be compared with the load factor limited by maximum lift capabilities (CLMAX) to determine the useful sustained load factor which ultimately dictate the sustained turn rate capability of the aircraft. This is covered extensively in Section 5.2.7 of this dissertation.

5.2.3.18 Macro YAWRTE

Once the maximum sustainable, or available, load factor has been evaluated it is possible to estimate the maximum available sustained turn rate ($\dot{\psi}$) using in Eq. 5.64. The information necessary to compute this macro is the maximum allowable load factor (LOAD) and the aircraft speed (SPEED).

```
MACRO YAWRTE(LOAD,SPEED)
```

```
A       YAWRTE.K=G*SQRT(LOAD.K**2-1)/SPEED.K                    5.64
MEND
```

5.2.3.19 *Macro TFLY*

Its purpose is to estimate the time-of-flight (TOF) of an air-to-air weapon to reach a non-maneuvering target if a direct collision course is established form the attacker to the target. Known variables in the problem are the line-of-sight range (RLOS), missile speed (MSPEED), target speed (ASPEED), and the launch target aspect angle (ATNTAA) which are used according to Eq. 5.65.

```
MACRO TFLY(RLOS,MSPEED,ASPEED,ATNTAA)
A       TFLY.K=RLOS.K/(ASPEED.K*COS(ATNTAA.K/57.29)+MSPEED.K)   5.65
MEND
```

5.2.3.20 *Macro STAT*

This is a general purpose macro which estimates the mean, variance, and standard deviation of any variable (X) in the model. Output variables of the macro constitute MEAN, VAR, and STD with X as the sole input (see Eqs. 5.66 through 5.74).

```
MACRO STAT(X,MEAN,VAR,STD)
A       STAT.K=X.K(DT)                                          5.66
L       $CUMX.K=$CUMX.J+(DT)(X.J)                               5.67
N       $CUMX=0                                                 5.68
A       MEAN.K=$CUMX.K/$TTIME.K                                 5.69
A       $TTIME.K=TIME.K+$ITIME+1E-15                            5.70
N       ITIME=TIME                                              5.71
L       $CUMX2.K=$CUMX2.J+(DT)(X.J**2)                          5.72
N       $CUMX2=0                                                5.73
A       VAR.K=($CUMX2.K/$TTIME.K)-MEAN.K**2                     5.73
A       STD.K=SQRT(VAR.K)                                       5.74
MEND
```

5.2.3.21 *Macro TIMER*

The purpose of this macro is to accumulate elapsed times for each one of the combat phases identified in Section 5.2.4.6. Eq. 5.75 initializes the times to zero while Eq. 5.76 physically aggregates the value of the dummy variable RATE through the simulation. The conditional values of RATE will become clear in Section 5.4.5 when the control variables are treated in more detail.

```
MACRO TIMER(RATE)
L           TIMER.K=TIMER.J+(DT)(RATE.J)                    5.75
N           TIMER=0                                         5.76
MEND
```

5.2.3.22 *Macro DTECT*

DTECT contains the universal cumulative probability of detection curves (radar). These curves adapted from Brookner [1978] use twelve dummy variables to cover a large db spectrum required in the computation of radar detection and tracking using a Swerling I target model [Stimpson, 1985]. Eqs. 5.77 through 5.107 represent a series of dummy variables (12) used to estimate the location of the desired cumulative probability of detection curve among the several curves shown in Fig. 5.18. Tabular values corresponding to those curves shown in Fig. 18 are separately contained in Eqs. 5.108 through 5.117 and placed outside the section devoted to the macros in the code. These numerical values are retrieved within the macro by means of dummy variables P5T, P75T, P9T, etc. Input parameters are: 1) The distance traveled by the target between radar scans (DR), 2) radar nominal detection range (R0), 3) range from aircraft to the target at which the cumulative probability of detection is sought, and 4) the tabular values for the cumulative probability of detection (PT5, P75T, etc.).

```
MACRO DTECT(DR,R0,RC,P5T,P75T,P9T,P10T,P13T,P15T,P175T,P20T,P22T,P24T)
A           DTECT.K=CLIP($PD5.K,$PDT1.K,5.0,$R0DR.K)        5.77
```

```
A       $PD5.K=TABHL(P5T,0-$RCR0.K,2.5,9,0.5)                                  5.78
A       $PDT1.K=CLIP($P575.K,$PDT2.K,7.5,$R0DR.K)                              5.79
A       $P575.K=INTRP($PD5.K,$PD75.K,5.0,7.5,$R0DR.K)                          5.80
A       $PD75.K=TABHL(P75T,0-$RCR0.K,2.25,8.75,0.5)                            5.81
A       $PDT2.K=CLIP($P759.K,$PDT3.K,9.0,$R0DR.K)                              5.82
A       $P759.K=INTRP($PD75.K,$PD9.K,7.5,9,$R0DR.K)                            5.83
A       $PD9.K=TABHL(P9T,0-$RCR0.K,2,8,0.5)                                    5.84
A       $PDT3.K=CLIP($P910.K,$PDT4.K,10,$R0DR.K)                               5.85
A       $P910.K=INTRP($PD9.K,$PD10.K,9,10,$R0DR.K)                             5.86
A       $PD10.K=TABHL(P10T,0-$RCR0.K,2,7,0.5)                                  5.87
A       $PDT4.K=CLIP($P1013.K,$PDT5.K,13,$R0DR.K)                              5.88
A       $P1013.K=INTRP($PD10.K,$PD13.K,10,13,$R0DR.K)                          5.89
A       $PD13.K=TABHL(P13T,0-$RCR0.K,1.75,5.25,0.5)                            5.90
A       $PDT5.K=CLIP($P1315.K,$PDT6.K,15,$R0DR.K)                              5.91
A       $P1315.K=INTRP($PD13.K,$PD15.K,13,15,$R0DR.K)                          5.92
A       $PD15.K=TABHL(P15T,0-$RCR0.K,1.5,4.5,0.5)                              5.93
A       $PDT6.K=CLIP($P1517.K,$PDT7.K,17.5,$R0DR.K)                            5.94
A       $P1517.K=INTRP($PD15.K,$PD175.K,15,17.5,$R0DR.K)                       5.95
A       $PD175.K=TABHL(P175T,0-$RCR0.K,1.25,3.75,0.5)                          5.96
A       $PDT7.K=CLIP($P1720.K,$PDT8.K,20,$R0DR.K)                              5.97
A       $P1720.K=INTRP($PD175.K,$PD20.K,17.5,20,$R0DR.K)                       5.98
A       $PD20.K=TABHL(P20T,0-$RCR0.K,1,3,.25)                                  5.99
A       $PDT8.K=CLIP($P2022.K,$PDT9.K,22,$R0DR.K)                              5.100
A       $P2022.K=INTRP($PD20.K,$PD22.K,20,22,$R0DR.K)                          5.101
A       $PD22.K=TABHL(P22T,0-$RCR0.K,.75,2.75,.25)                             5.102
A       $PDT9.K=CLIP($P2224.K,$PD24.K,24,$R0DR.K)                              5.103
A       $P2224.K=INTRP($PD22.K,$PD24.K,22,24,$R0DR.K)                          5.104
A       $PD24.K=TABHL(P24T,0-$RCR0.K,.75,2.5,.25)                              5.105
A       $R0DR.K=RATINV(R0.K/DR.K)                                              5.106
A       $RCR0.K=RATINV(RC.K/R0.K)                                              5.107

T       PD5T=0/.1/.22/.33/.42/.51/.59/.65/.72/.77/.81/.85/.87/.89              5.108
T       PD75T=0/.16/.32/.46/.58/.69/.78/.85/.89/.93/.95/.97/.98/.99            5.109
T       PD9T=0/.15/.34/.5/.65/.76/.84/.90/.94/.96/.98/.99/1.0                  5.110
T       PD10T=0/.22/.41/.6/.75/.86/.92/.96/.98/.99/1.0                         5.111
T       PD13T=0/.3/.54/.72/.85/.93/.98/1                                       5.112
T       PD15T=0/.28/.57/.80/.95/.98/1.0                                        5.113
T       PD175T=0/.3/.61/.86/.97/1                                              5.114
T       PD20T=0/.17/.34/.50/.69/.83/.94/.98/1.0                                5.115
T       PD22T=0/.1/.3/.5/.67/.83/.93/.99/1.0                                   5.116
T       PD24T=0/.21/.44/.66/.83/.94/.99/1.0                                    5.117
```

The mechanics of this macro are as follows: The values of DR and R0 are used as inputs and their ratio in decibels is computed (R0/DR) in Eq. 3.106. Using the third input RC, the ratio RC/R0 is evaluated and converted to decibels in Eq. 5.107. Now, a two dimensional search takes place within the set of curves shown in Fig.3.19 to estimate the point corresponding to the intersection of R0/DR and RC/R0. The macro INTRP is invoked to interpolate within the set of curves corresponding to values of R0/DR. Example 5.1 illustrates the use of this macro.

Example 5.1

An aircraft flies over hostile territory at 800 knots and at an altitude of 15000 ft. (AGL). At a given instant is located at 5 km. from a radar that has a baseline range (R0) of 25 km. and time between scans of 12 seconds. Find the aircraft cumulative probability of detection at that particular instant.

Solution.

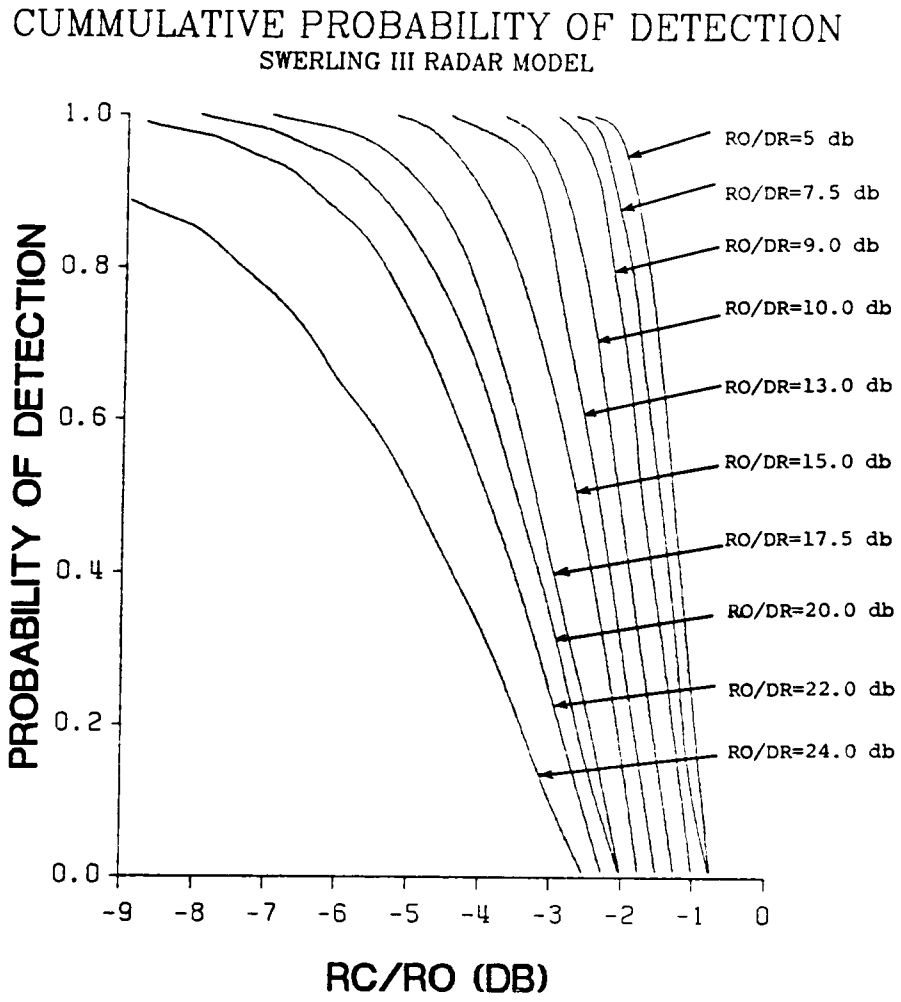


Figure 5.18. Cumulative Probability of Detection Curves.

It is necessary to quantify the distance covered in one time radar

It is necessary to quantify the distance covered in one time radar antenna scan (DR), referred as delta range; the ratio of the downrange distance from primary target to aircraft (RC) and the baseline range (R0) called RCR0, and finally the ratio of R0 to DR (R0DR). These values are quantified in the main program and they constitute the macro inputs to quantify the cumulative probability of radar detection (PDRF).

From the data given,

V= 800 knots = 411.56 m/sec.
t= 12 sec.
DR=[V][t] = [411.56 m/sec][12 sec] = 4939 m.
since R0 = 25 km., then
R0DR = R0/DR = [{25 km.}{1000 m/km}/4939 m] = 5.062

converting to decibels (see macro RATINV),

R0DR = 10[log{5.062}] = 7.04 db.

RCR0 = RC/R0 = [5 km.]/[25 km.] = .20

also converting to decibels,

RCR0 = 10[log{.2}] = -6.99 db.

Fig. 5.15 shows the region in the cumulative probability of detection curves where the search and interpolation take place. In this case only the curves for R0DR values of 5 and 7.5 db are shown since the manual computations show values of 7.04 db. and -6.99 db. for R0DR and RCR0, respectively.

Eq. 5.77 starts the search for the closest two R0DR curves to the actual value of R0DR to be interpolated (i.e., 7.04 db. in this example). Since 7.04 is greater 5.0 (first CLIP statement) then DTECT takes the value of $PDT1 (Eq. 5.79) where the next comparison is made. Since 7.04 is less than the next R0DR curve (i.e., 7.5 db.) then $PDT1 takes the value $P575 corresponding to the first option in the CLIP statement of Eq. 5.79. $P575 (Eq. 5.80) uses the macro INTRP to linearly interpolate between the values of the curves R0DR=5 db. and R0DR=7.5 db. as explained previously. Notice that the first two terms inside INTRP (see Eq. 5.80) are in fact table functions defined in 5.78 and 5.81. These table function equations perform another interpolation using RCR0 as independent variable to locate points E and F shown in Fig. 5.17 using the numerical values for the R0DR curves defined in 5.108 and 5.109. The values A, B, C, and D are obtained using the built-in table function capability of Dynamo III and hence E and F can be readily found.

The ordinate values of the linear segments defining R0DR=5 db. between -6.5 and -7 db. values of RCR0 (abscissa in Fig. 5.17) are: A=.77 and B=.72 (ninth and tenth numerical values of PD5T in Eq. 5.108). Similarly, C=.95 and D=.93 define a linear segment of the 7.5 db. R0DR level curve between -6.75 and -7.25 db. RCR0 values (Fig. 5.17). Linear interpolation yields: E=.769 and F=.9396 from where the ordinate value of G is computed according to INTRP macro (Eq. 5.55).

G = E + [{F-E}{J-H}/{I-H}]

where J=7.04, H=5.0, and I=7.5 in db.

therefore,

G = .769 + [{.9396-.769}{7.04-5}/{7.5-5}] = .9082

which represents the cumulative probability of radar detection for this particular example.

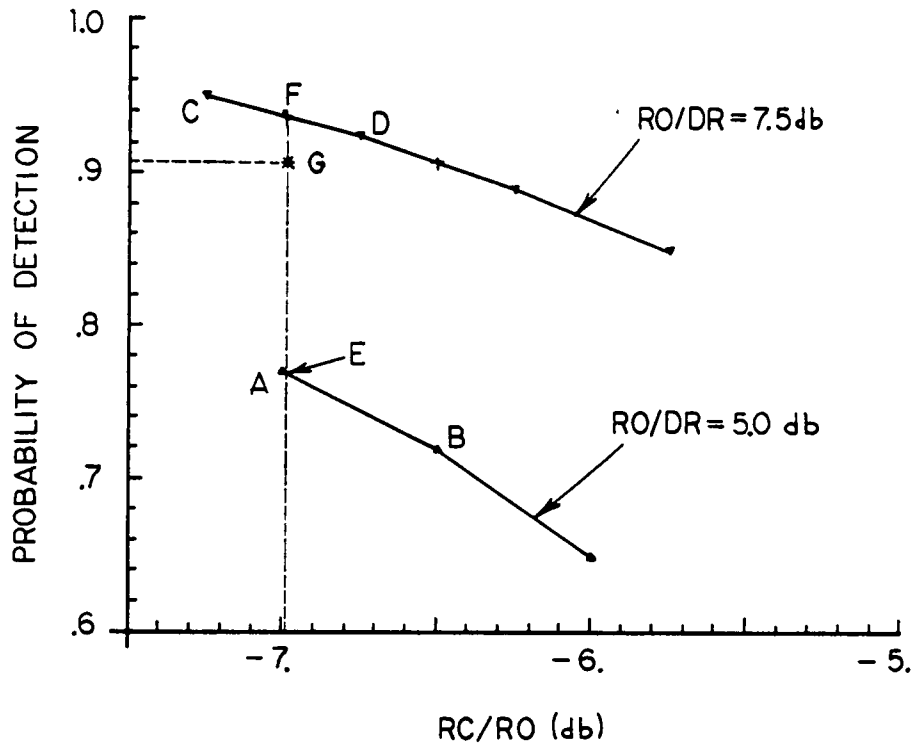


Figure 5.19 Cumulative Probability of Detection Curves for Example 5.1.

This concludes a brief explanation of the model macros. Now our attention will be devoted to the description of the air-to-air interactions.

5.2.4 Air-to-Air Interactions

This portion encompasses the real essence of the model. First, the general attrition equations are described and certain restrictions imposed on them outlined. Second, a full description of the geometry of the engagement is given including coordinate and angular conventions. Third, the combat engagement phases are described and the context of phase timers introduced. Finally, state and control variables are explained in detail as well as their time variations within each combat phase.

5.2.4.1 General Attrition Equations

The attrition equations used in the model bear some resemblance characteristic of a Lanchester's square model, where there is a concentration of force, or aimed fire, on the survivors. For identification purposes throughout this dissertation let CBF and AGG represent two forces of M and N aircraft to be confronted. The attrition equations can be written as follows:

$$\frac{dCBF(t)}{dt} = -AGG(t)_{se}\,AGG(t) \qquad 5.118$$

$$\frac{dAGG(t)}{dt} = -CBF(t)_{se}\,CBF(t) \qquad 5.119$$

where, CBF(t) and AGG(t) represent the number of friendly and aggressor aircraft at time t, CBF_{se} and AGG_{se} are aircraft system effectiveness parameters for friendly and aggressor

forces, respectively. These parameters are functions of the lethality of each aircraft as will be explained in Section 5.6 of this dissertation. Hence, it is clear that the attrition rate of a force is proportional to the product of the enemy force size and the effectiveness of this opposing force (i.e., lethality).

The number of aircraft remaining at any instant in time on the two forces is given by the following two difference equations,

$$CBF_t = CBF_{t-1} + \dot{CBF}_t\, dt \qquad 5.120$$

$$AGG_t = AGG_{t-1} + \dot{AGG}_t\, dt \qquad 5.121$$

with initial states $CBF_{t=0} = CBF_o$ and $CBF_{t=0} = CBF_o$.

As the simulation progresses, the levels of damage inflicted by the two forces are aggregated using Eqs. 5.120 and 5.121 to reflect the degradation in force sizes accordingly. This approach described in Section 4.2 of this dissertation resulted in co-kill equations such as 5.122 to estimate the probability of survival of an aircraft (i) when fired upon a threat *j*.

$$P_{S\,i}(t + \delta_1) = P_{S\,i}(t) - P_{S\,j}(t)\, P_{K\,ji}(t) \qquad \{5.122\}$$

where, $P_{S\,i}(t + \delta_1)$ is the probability of survival of aircraft *i* at weapon impact time $t + \delta_1$, $P_{S\,i}(t)$ is the probability of survival of aircraft *i* at weapons launch (*t*), $P_{S\,j}(t)$ is the probability of survival of threat *j* at time of weapons launch (t), and $P_{K\,ji}(t)$ is the probability of kill of aircraft *i* due to a weapon launch at time *t*.

5.2.4.2 *Array Convention in the Model*

An integral part of the attrition mechanism and also present in the model is the incorporation of array variables to differentiate between the friendly and aggressor aircraft

as well as to differentiate between their weapons as well as the functions performed throughout the simulation. Table 5.1 summarizes the convention used.

The adoption of this notation allows a natural distinction between the activities performed by the two opposing forces. It also gives flexibility to the type and number of weapons used in the air-to-air engagement. Finally, the same array notation allows the user to easily introduce dissimilar aircraft in the simulation.

5.2.4.3 *Geometry of the Engagement*

Section 5.2 has been descriptive of the combat scenario being portrayed by the model. Now, we focus on the specific geometric considerations necessary to describe a coplanar intercept (2-dimensional) problem with (M + N) participants. Fig. 5.20 depicts a graphical representation of the geometry used. For the sake of simplicity a 2 vs. 1 aerial engagement is shown.

An earth-fixed orthogonal axes system centered at the carrier battle group (CBG) location was chosen. The relatively slow mobility of the CBG with respect to the aircraft speeds and considering a typical duration time of an air superiority mission of 30 minutes seems to justify previous assumption. Aircraft positions are referred to this earth-fixed axes system as depicted in Fig.3.20 by R_1, R_2 , and R_3. Moreover, the position changes are given in terms of the heading angle (ψ) and the magnitude of the aircraft velocity vector (V) which assumed to be aligned with the plane of symmetry of the aircraft (Eqs. 5.123 and 5.124).

$$\frac{dX}{dt} = V\cos\psi \qquad 5.123$$

$$\frac{dY}{dt} = V\sin\psi \qquad 5.124$$

Table 5.1 Model Variable Array Convention.

Subscript	Number	Remarks
I	N.A.	Carrier Based Fighter (CBF)
J	N.A.	Aggressor Fighter (AGG)
K	N.A.	CBF Fighter Weapons
L	N.A.	AGG Fighter Weapons
Subscript	**Number**	**Aircraft Weapons**
K or L	1	Long Range Air-to-Air Missile (LRAAM)
K or L	2	Medium Range Air-to-Air Missile (MRAAM)
K or L	3	Short Range Air-to-Air Missile (SRAAM)
K or L	4	Gun/Cannon

Eqs. 5.123 and 5.124 are equivalently represented in DYNAMO III for the CBF aircraft as follows:

```
L     X.K(I)=X.J(I)+(DT)(V.J(I)*COS(SAI.J(I)/57.29)                    5.125
N     X(I)=XN(I)                                                       5.126
T     XN(*)=0/500/1000/1500                                            5.127
L     Y.K(I)=Y.J(I)+(DT)(V.J(I)*SIN(SAI.K(I)/57.29)                    5.128
N     Y(I)=YN(I)                                                       5.129
T     YN(*)=0/0/0/0                                                    5.130

NOTE  X     - DOWNRANGE (METERS)
NOTE  Y     - LATERAL RANGE (METERS)
NOTE  V     - AIRCRAFT BODY/WIND AXES VELOCITY VECTOR (METERS/SEC)
NOTE  XN    - INITIAL AIRCRAFT DOWNRANGE POSITION (METERS)
NOTE  YN    - INITIAL AIRCRAFT Lateral DOWNRANGE POSITION (METERS)
NOTE  SAI   - AIRCRAFT HEADING ANGLE (DEGREES)
```

Notice that the addition of four extra equations (Eqs. 5.126, 5.127, 3.129, and 5.130) are necessary to define the initial aircraft positional states.

The aggressor force position states follow a similar treatment with different variable names. XAG and YAG are used to represent the cartesian positions of each aggressor aircraft. The initial positions (in meters) are indicated in Eqs. 5.131 through 5.136. Note the differentiation between the array notation for CBF and AGG aircraft (I and J labels).

```
L     XAG.K(J)=XAG.J(J)+(DT)(VAG.J(J)*COS(SAIG.J(J)/57.29)             5.131
N     XAG(I)=XAGN(I)                                                   5.132
T     XAGN(*)=2.5E5/2.505E5/2.51E5/2.515E5                             5.133
L     YAG.K(J)=YAG.J(J)+(DT)(VAG.J(J)*SIN(SAIG.J(I)/57.29)             5.134
N     YAG(I)=YAGN(I)                                                   5.135
T     YAGN(*)=0/0/0/0                                                  5.136
```

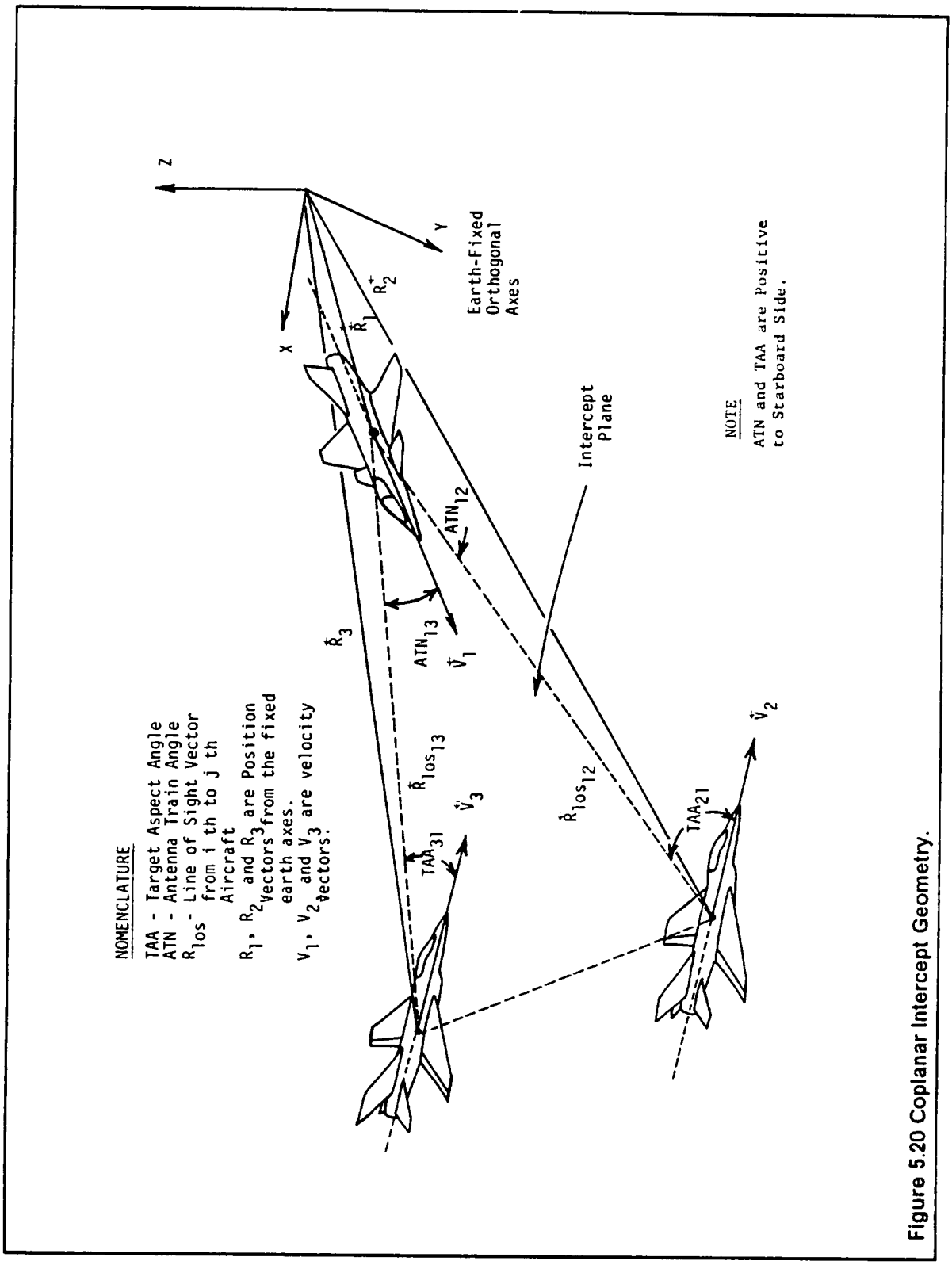


Figure 5.20 Coplanar Intercept Geometry.

```
NOTE    YAG     - AGGRESSOR AIRCRAFT LATERAL RANGE (METERS)
NOTE    VAG     - AGG AIRCRAFT BODY/WIND AXES VELOCITY VECTOR (METERS/SEC)
NOTE    XAGN    - INITIAL AGG AIRCRAFT DOWNRANGE POSITION (METERS)
NOTE    YAGN    - INITIAL AGG AIRCRAFT Lateral DOWNRANGE POSITION (METERS)
NOTE    SAIG    - AGG AIRCRAFT HEADING ANGLE (DEGREES)
```

The convention for the heading angle (ψ) follows the traditional trigonometric tradition with 0 and 90 degrees representing west-east directions, respectively. Notice that this differs by -90 from the standard used by aviators and air traffic controllers.

Another important angular convention is that adopted for the target aspect angle (AA). AA is the angle subtend by an aircraft velocity vector (V) and the line of sight vector to a target (RLOS). For the sake of clarity in this treatment the target aspect angle as measured from any CBF aircraft is denoted as ATN (antenna train angle) while that associated with any aggressor is referred as TAA (target aspect angle). This notation is consistent with that used by Shaw [1986]. ATN and TAA are bounded within 0 and π (in radians). In order to avoid confusion between targets to the port and starboard sides of an aircraft a sign convention has been adopted. Positive values represent targets on the starboard side while negative values are used for targets to port side. Fig. 3.21 further illustrates this point.

```
A       ATN.K(I,J)=DIREC(SAI.K(I),DIRLOS.K(I,J),Y.K(I),YAG.K(J))        5.137
A       TAA.K(I,J)=DIREC(SAIG.K(J),DIRGOS.K(I,J),YAG.K(J),Y.K(I))       5.138

NOTE    ATN     - TARGET ASPECT ANGLE MEASURED FROM CBF VELOCITY VECTOR (DEG)
NOTE    TAA     - TARGET ASPECT ANGLE MEASURED FROM AGG VELOCITY VECTOR (DEG)
```

Eqs. 5.137 and 5.138 show the DYNAMO III equations for ATN and TAA. An important point to be noticed is the bi-dimensionality of the arrays containing values for ATN and TAA. This is so because ATN and TAA are angles measured from the i th to the j th thus resulting in a M by N angular description matrix for both sides. This implies that the model keeps track of N angular measurements from each i aircraft and M are computed for each j vehicle. Eqs. 5.137 and 5.138 also show the use of macro DIREC described in Section 5.3.3. In this particular case DIREC finds the angle between the heading angle (SAI) and the direction of the vector line of sight from the aircraft to the target (DIRLOS). It also checks for the relative magnitudes of the ordinate components of the aircraft positions to assign the proper sign to the target aspect

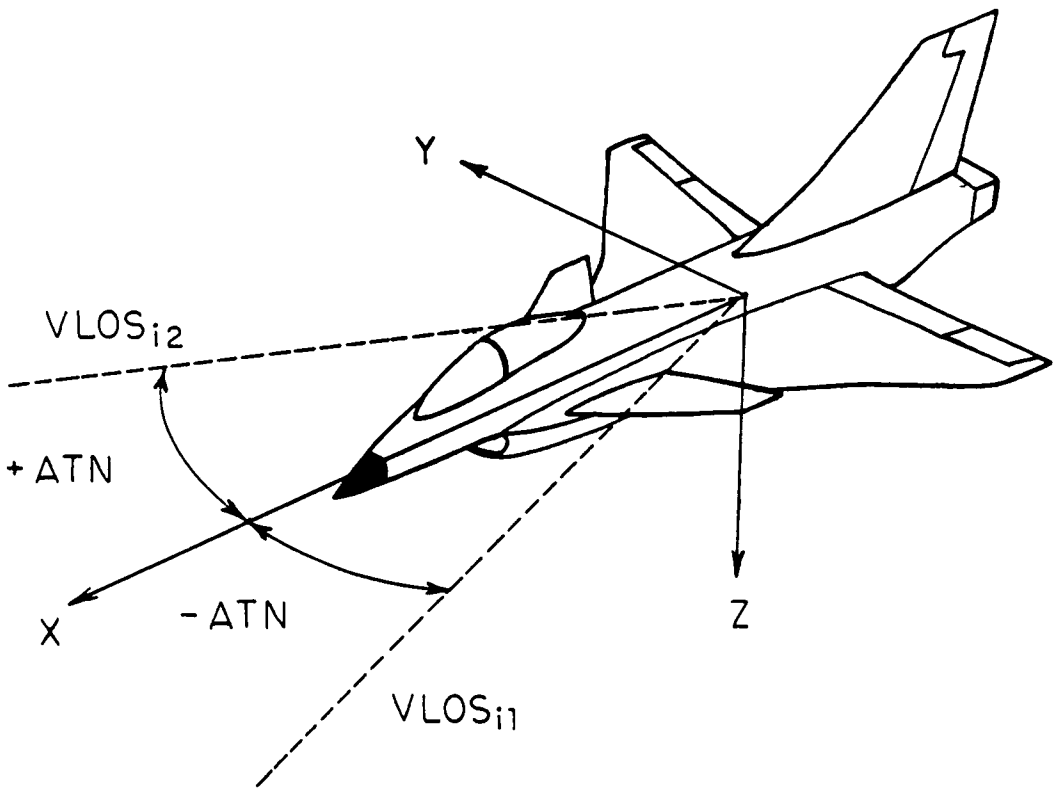


Figure 5.21 Target Aspect Angle Sign Convention.

angle. Eq. 5.138 is the equivalent of 5.137 though it refers to the aggressor force aircraft. DIRGOS stands for the direction of the vector line of sight as measured from an aggressor to a CBF. Fig. 5.22 graphically describes these subtle differences.

5.2.4.4 *State Variables*

In the previous section reference was made to the aircraft positions with respect to an earth-fixed set of axes. These positions (X,Y) and (XAG,YAG) represent only part of the variables necessary to completely describe the state of each aircraft at any point in time. In this section other variables such as heading angle, aircraft velocity, and fuel status are examined.

The heading angle (SAI, SAG) is the angle formed by the aircraft velocity vector (V) and the horizontal projection of the earth-fixed axes moving with the aircraft. Sustained changes in heading ($\dot{\phi}$) are in general functions of bank angle (ϕ) assuming standard, coupled aerodynamic control aircraft configurations are analyzed. ϕ is further limited by load factor constraints imposed by the structural integrity of the aircraft aerodynamic limitations, and human tolerances or a combination of these. Eqs. 5.139 through 5.141 are used to compute the heading angle (SAI) for the CBF force.

```
A     SAI.K(I)=YAW(SAIA.K(I))                                                    5.139
L     SAIA.K(I)=SAIA.J(I)+(DT)(RSAIA.J(I))                                       5.140
A     RSAIA.K(I)=RSAI1.JK(I)+RSAI2.JK(I)+RSAI3.JK(I)+RSAI4.JK(I)                 5.141

NOTE  SAI    - YAW ANGLE (HEADING ANGLE)
NOTE  YAW    - MACRO TO COMPUTE COMPUTE YAW ANGLES OVER 360 DEGREES AND
NOTE           BELOW ZERO DEGREES
NOTE  RSAIA  - INSTANTANEOUS YAW RATE (DEG/SEC)
NOTE  RSAI1  - YAW RATE IN THE INITIAL COMBAT PHASE (DEG/SEC)
NOTE  RSAI2  - YAW RATE IN BVR PHASE (DEG/SECOND)
NOTE  RSAI3  - YAW RATE IN ACM ENGAGEMENT (DEG/SEC)
NOTE  RSAI4  - YAW RATE IN DISENGAGEMENT/RETURN COMBAT PHASE (D/SEC)
```

The first equation in this sequence (Eq. 5.139) invokes the macro YAW, described in Section 5.3.4, to constrain the value of the heading angle (SAI) between 0 and 2π. Eq. 5.140 represents the physical accumulation of the heading angle with time (a level variable) subjected to a rate

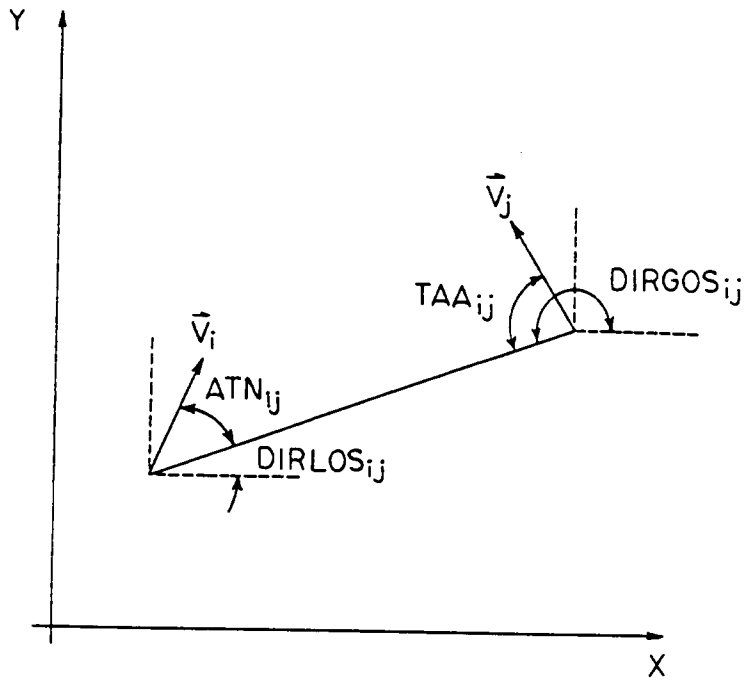


Figure 5.22 Line of Sight Vectors Convention.

of change RSAIA ($\dot{\phi}$). This rate of change in in the yaw angle is modeled as an auxiliary variable with four rates, RSAI1 through RSAI4 corresponding to each one of the phases in the combat. This modeling scheme permits more flexibility allowing independent pursuit strategies to be used at each stage. The initial values of the heading angle (ψ) are specified in Eqs. 5.142 and 5.143.

```
N       SAIA(I)=SAIAN(I)                                          5.142
T       SAIAN(*)=45/45/46/47                                      5.143

NOTE    SAIN    - INITIAL HEADING ANGLE (DEGREES)
NOTE    SAIA    - CBF HEADING ANGLE (DEG.)
```

Another state variable constitutes the aircraft speed. The speed of the aircraft is a function of the acceleration parameter which is a lumped term containing the engine thrust (T), aircraft mass (WK), drag (D), angle of attack (ALPHA), and thrust offset angle (SIGMA). Since the motion is constrained to two dimensions, the acceleration along the flight path is given as follows:

$$\frac{dV}{dt} = \frac{T\cos(\alpha+\sigma) - D}{m} \qquad 5.144$$

where, V is the aircraft velocity, T the thrust developed (τT), α the angle of attack, σ the thrust offset angle, D the aircraft total drag, and m the aircraft mass.

```
L       V.K(I)=V.J(I)+(DT)(ACC.JK(I))                             5.145
N       V(I)=VN(I)                                                5.146
T       VN(*)=260/260/260/260                                     5.147
R       ACC.KL(I)=((T.K(I)*COS(ALP.K(I)+SIGMA(I))-D.K(I))/WK.K(I) 5.148

NOTE    V       - CBF AIRCRAFT VELOCITY VECTOR MAGNITUDE (M/SEC)
NOTE    VN      - INITIAL SPEED FOR CBF AIRCRAFT (M/SEC)
NOTE    ACC     - INSTANTANEOUS LONGITUDINAL ACCELERATION OF CBF AIRCRAFT
NOTE              (M/SEC-SEC)
NOTE    T       - AIRCRAFT THRUST (NEWTONS)
NOTE    ALP     - AIRCRAFT ANGLE OF ATTACK (RADIANS)
NOTE    SIGMA   - LONGITUDINAL THRUST OFFSET ANGLE (RADIANS)
NOTE    D       - AIRCRAFT TOTAL DRAG FORCE (NEWTONS)
NOTE    WK      - AIRCRAFT MASS (KGS.)
```

Notice the similarities in the implementation of throttle setting and yaw angle variations. The mass of the aircraft, WK, is another state variable which depends upon the engine fuel

consumption (FFLOW) the weapons carried (ATAAWW), and the mass of expandables (WEEXP). Due to the length of a typical air superiority mission of 30-50 minutes the mass variations are large and thus need to be accounted for. In fact, one of the most important limitations of an air engagement is the fuel state at the point of disengagement. The mass of the aircraft (WK) is modeled as a level variable (WK) incorporating three rates out to account for the engine fuel consumption (FFLOW), weapons delivery, and used expendables. These two last terms use the scalar product multiplication available in DYNAMO III. The initial aircraft mass is computed in accordance to Eq. 3.151 which sums the payload (PYL), empty mass (EM), and the initial fuel onboard (FUELN). PYL is evaluated as the scalar product of the initial number of air-to-air weapons (ATAWN) and the mass of each weapon (ATAAWW), a second term (MEECM) accounts for the external ECM carried, and a third term (WEXP) accounts for those expendables inside the airframe. The empty mass is expressed as the product of an empty baseline mass value (EMB) and a multiplier to account for potential engine modifications (MEIM) that in the nominal case is set to unity (i.e., no effect on EM). This multiplier should be ideally derived from a powerplant-airframe sensitivity analysis to validate the changes in structural mass necessary to accommodate scaled engines. The initial fuel (FUELN) is an input from the user and its relevance lies in the fact that fuel status is used as decision parameter in the simulation to start a disengagement. This simple form allows the user to explore the effect of fuel allowances in a typical engagement and its effect on survivability. The number of weapons also constitutes part of the overall aircraft states although their definition and implementation will be left for a later section of this dissertation.

```
L     WK.K(I)=WK.J(I)-(DT)(FFLOW.JK(I)+SCLPRD(ATAWR.JK(I,*),1,4
X       ,ATAAWW.K(*),1))                                          5.149
N       WK(I)=IM(I)                                               5.150
N         IM(I)=EM(I)+PYL(I)+FUELN(I)                             5.151
N         EM(I)=EMB(I)*MIEM(I)                                    5.152
T           EMB(*)=14000/14000/14000/14000                        5.153
T           MIEM(*)=1/1/1/1                                       5.154
N         PYL(I)=SCLPRD(ATAWN(I,*),1,KK,ATAAWW(*),1)
X         +WEECM(I)+WEXP(I)                                       5.155
N           WEECM(I)=NEECM(I)*WECMU(*)                            5.156
T             NEECM(*)=0/0/0/0                                    5.157
T             WECMU(*)=250/250/250/250                            5.158
T             WEXP(*)=300/300/300/300                             5.159

NOTE    IM          -  INITIAL MASS (KG.)
```

```
NOTE    EM      - EMPTY MASS (KG.)
NOTE    EMB     - BASELINE EMPTY MASS (KG.)
NOTE    MIEM    - MASS INCREASE VS. ENGINE MODIFICATION (KG.)
NOTE    PYL     - PAYLOAD (KG.)
NOTE    FUELN   - INITIAL FUEL MASS (KG.)
NOTE    CBFWN   - INITIAL NO. OF AA WEAPONS (UNITS)
NOTE    CBFAWW  - AIR-TO-AIR WEAPON MASS (KGS.)
NOTE    MEECM   - MASS OF EXTERNAL ECM EQUIPMENT (KG.)
NOTE    NEECM   - NO. OF ECM EXTERNAL PODS (UNITS)
NOTE    WECMU   - WEIGHT OF EXTERNAL ECM POD (KG.)
```

Summarizing, the main variables defining the aircraft state are shown in mathematical form in Eqs. 5.160 through 5.164.

$$\frac{dX}{dt} = V\cos\psi \qquad 5.160$$

$$\frac{dY}{dt} = V\sin\psi \qquad 5.161$$

$$\frac{dV}{dt} = \frac{T\cos(\alpha+\sigma) - D}{m_a} \qquad 5.162$$

$$\frac{dm_a}{dt} = -cT - m_w w_{lr} \qquad 5.163$$

and

$$\frac{d\psi}{dt} = \frac{T\sin(\alpha+\sigma) - D}{m_a V}\sin(\phi) \qquad 5.164$$

where, X and Y are position coordinates, V is the aircraft velocity, ψ is the heading angle, T is the installed thrust, D the total aircraft drag, m_a is the aircraft mass, m_w the particular masses of the weapons, *wl* the weapon load (units), *c* is the specific fuel consumption, α is the angle of attack, σ the thrust offset angle, and ϕ the bank angle.

5.2.4.5 *Control Variables*

Two control variables are addressed in this model to achieve motion in a horizontal plane. These are bank angle (ϕ) and throttle setting (TS). However, ϕ is only implicitly modeled as result of the close relationship between load factor (n) and bank angle (Eq. 165).

$$n = \frac{1}{\cos \phi} \qquad 5.165$$

Load factor is relevant in this context because aircraft aerodynamic and structural limitations are expressed in the same units (G's). Load factor is constrained by the structural integrity of the aircraft (NSTRUC), the thrust available to sustain a desired turn rate (NTRUST), crew limitations (NCREW), and maximum angle of attack limitations (N1). In this simulation it is assumed that all aircraft perform hard but coordinated turns without sideslip in the pursuit of an adversary. It should be realized that n acts as path guidance parameter and thus necessitates some feedback information concerning the relative states of the targets to be pursed. This implies that n is adjusted according to heading changes during the engagement. More insight to the previous statement can be gained from the basic relationship between load factor and yaw rate (Eq. 5.166).

$$\dot{\psi} = \frac{g\sqrt{n^2 - 1}}{V} \qquad 5.166$$

the computation scheme to estimate the desired heading changes varies according to the engagement phase due to the differences in goals particular to each one. This will become clear in the next section where the combat phases are detailed.

The second control variable is the throttle setting (TS) which regulates the acceleration of the aircraft, ultimately controlling speed (recall that the motion is restricted to the horizontal plane). Throttle setting is constrained to vary from zero to unity. The upper ten percent of the operational TS band is reserved for afterburning use while the remaining 90 percent is used

in the no-reheat mode. As in the case of load factor TS changes are performed from phase to phase according to prespecified heuristics which will be explained in the next section.

5.2.4.6 *Engagement Phases and Control Scheduling*

In order to describe the phases of the air engagement it is necessary to understand several assumptions made.

1) The entire air combat simulation is divided into four phases. A) initial, B) beyond visual range, C) close-in and air combat maneuvering, and D) disengagement and return phase.

2) Each phase is characterized by particular tactics centered around manipulation of the controls ϕ and TS. These controls obey simple heuristic rules to position and aircraft in the best state for weapon delivery with respect to an opponent.

3) A pure pursuit guidance scheme is used in the program as pursuit strategy among combatants. In this scheme a pilot tries to maintain its aircraft velocity vector aligned with its target.

4) There is no role determination between the participants in this model. Aggressive tactics are used on both sides in the sense that maximum available turn rate capability is used to gain position advantage to launch an attack.

5) Several parameters dictate the transition points between the phases of the engagement: fuel status, weapons, probability of detection, etc.

A series of timers are used to keep track of transition times for each aircraft between phases as well as to estimate the elapsed times spent on each phase. This could later be used to establish more realistic limitations on the use of certain strategies such as

reheat use in close combat. The use of these timers or counters is also associated with the need to update guidance and control laws specific to each aircraft. Timers constitute simple level equations initialized to zero by the macro TIMER and activated/deactivated when certain conditions are satisfied as depicted in Eqs. 5.167 through 5.180.

```
A       T1.K(I)=TIMER(RTT1.K(I))                                                    5.167
A       T2.K(I)=TIMER(RTT2.K(I))                                                    5.168
A       T3.K(I)=TIMER(RTT3.K(I))                                                    5.169
R        RTT1.KL(I)=RT1.K(I)*SWITCH(1,0,RTT2.JK(I))*SWITCH(RTT3.JK(I))              5.169.1
R        RTT2.KL(I)=RT2.K(I)*SWITCH(1,0,RTT3.JK(I))                                 5.169.2
R        RTT3.KL(I)=RT3.K(I)                                                        5.169.3
A        RT1.K(I)=CLIP(1,0,RT11.K(I)+RT12.K(I),1)                                   5.170
A        RT11.K(I)=CLIP(1,0,SUMV(PGRD.K(I,*),1,JJ)/JJ,.8)                           5.171
A        RT12.K(I)=CLIP(0,RT13.K(I),FAW.K,.98)                                      5.172
A          FAW.K=SUM(AGAW.K)/SUM(AGAWN)+1.0E-6)                                     5.172.1
A        RT13.K(I)=CLIP(1,0,SUMV(RWRA(I,*),1,JJ)/JJ,
X        SUMV(RLOS.K(I,*),1,JJ)/JJ                                                  5.173
R        RT2.KL(I)=CLIP(1,0,20000,SUMV(RLOS.K(I,*),1,JJ)/JJ)                        5.174
R        RT3.KL(I)=CLIP(1,0,RT31.K(I)+RT32.K(I),1)                                  5.175
A          RT31.K(I)=CLIP(1,0,FUELAC,FUELR.K(I))                                    5.176
A          RT32.K(I)=CLIP(1,0,WEAPAC,AVWEAP.K(I))                                   5.177
A          AVWEAP.K(I)=SUMV(CBFW.K(I,*),1,KK)//(SUMV(CBFWN(I,*),1,KK)
X          +1.0E-6)                                                                 5.178
C          FUELAC=.4                                                                5.179
C          AVWEAP=.1                                                                5.180

NOTE    TIMER    - MACRO TO INITIALIZE AND UPDATE COMBAT TIMES
NOTE    T1       - TIMER THAT TRIGGERS BVR ENGAGEMENT
NOTE    T2       - TIMER THAT TRIGGERS ACM ENGAGEMENT
NOTE    T3       - TIMER THAT TRIGGERS DISENGAGEMENT-RETURN PHASE
NOTE    RTT1,..  - CHANGES IN TIMERS (RATE VARIABLES)
NOTE    RT1,..   - CHANGES IN TIMERS (AUXILIARY EQUATIONS)
NOTE    WEAPAC   - WEAPON STATUS FRACTION USED TO INITIALIZE DISENGAGEMENT
NOTE               TIMER
NOTE    FUELAC   - FUEL FRACTION USED AS CUTOFF FOR DISENGAGEMENT
NOTE    AVWEAP   - AVERAGE WEAPONS REMAINING IN AN AIRCRAFT
NOTE    FAW      - AVERAGE FRACTION OF WEAPONS REMAINING IN THE AGGRESSOR FLEET
NOTE    FUELR    - FUEL FRACTION REMAINING ON EACH CBF AIRCRAFT
```

T1 corresponds to the time transition between the initial and beyond visual range (BVR) stages. The rate variable RTT1 associated with T1 is activated (i.e., the counting process begins) when the sum of variables RT11 and RT12 is greater or equal to 1 (Eq. 5.170). This statement in fact is equivalent to an OR gate structure where three conditions are evaluated as follows: Eq. 5.173 checks if the average distance from the i aircraft is less than the maximum range of the CBF radar warning receiver (RWRA). If this condition is met a one is assigned to RT13, zero otherwise. Mathematically this expression is equivalent to,

$$RT13.K(I) = \begin{cases} 1 \text{ if } \frac{1}{jj}\sum_{j=1}^{jj} RWRA_{ij} \geq \frac{1}{jj}\sum_{j=1}^{jj} RLOS_{ij} \\ 0 \text{ if } \frac{1}{jj}\sum_{j=1}^{jj} RWRA_{ij} < \frac{1}{jj}\sum_{j=1}^{jj} RLOS_{ij} \end{cases}$$

where jj stands for the number of aggressor aircraft at the begining of the simulation. Next, the number of weapons on the aggressor force (FAGAWR) is checked in Eq.3.172 to see if a launch has occurred an event that is conditioned by the result of RT13. If a launch in fact has occurred and if the CBF radar warning receiver (RWR) is within detection range of the launching aggressor a unit value is assigned to RT12 which in turn drives RT11 to unity indicating a transition to BVR engagement phase (i.e., activating T1).

Independently of previous results, the early detection of aggressors by radar or infrared methods can also start the preparation of an attack from the friendly aircraft force. RT11 models this by setting an averaged cumulative probability of detection threshold of the aggressor force (PGRD) at 0.8. Fig. 5.23 depicts a functional diagram illustrating the events considered to switch from initial to BVR engagement phase.

During the BVR phase the aim of the each aircraft (CBF or AGG) is to "collectively" pursue the adversary aircraft. That is, the adversary fleet is seen as a single target with an averaged target aspect target angle as aiming point. As resolution of targets improves the second transition point takes place and it is assumed that the new guidance scheme of each aircraft switches to a one-to-one mode. This does not imply that weapons are aimed at a particular target as all aspect missile capabilities might propiciate their use against multiple targets at medium and short distances (20000-6000 m.).

The second transition point in the engagement occurs at a fixed slant range from the opposing fleet. The idea behind this simplified rationale is as follows: It might be expected from an advanced fighter aircraft to have available several radar modes of operation to be used during a typical engagement (pulse doppler search, range-while-scan, track-while-scan, etc.). Ultimately, each aircraft will resort to some sort of single tracking mode once range considerations allow. It has been assumed that ranges on the order of 15 to 20 km. would be typical for entering the air combat maneuvering (ACM) phase and thus were selected as

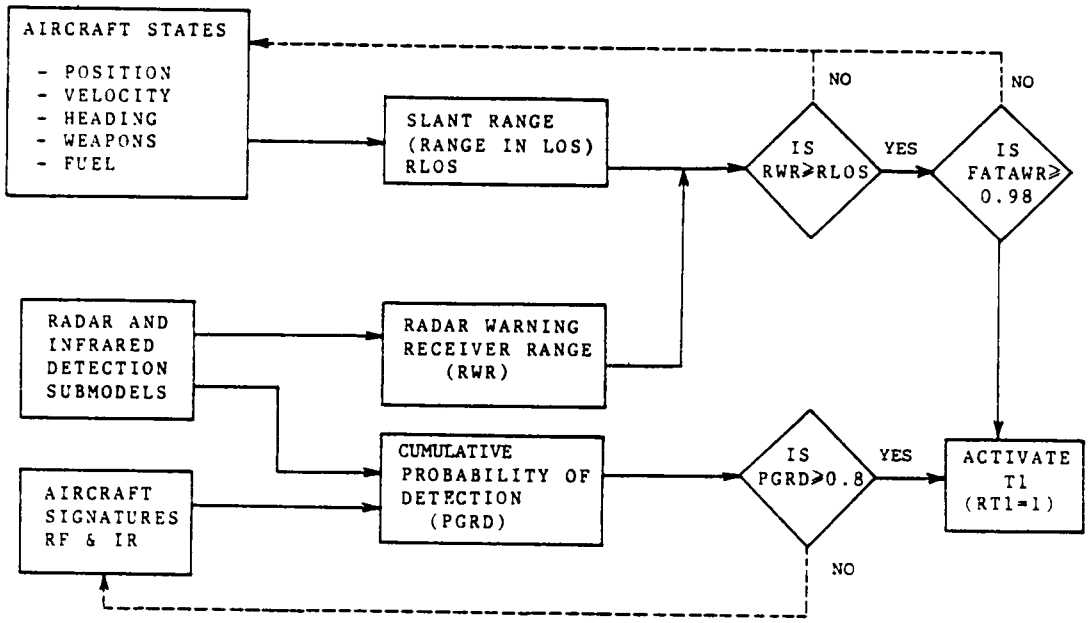


Figure 5.23 Functional Diagram for First Engagement Transition Point.

nominal transition values. Eq. 5.175 shows the activation of RTT2 as unity once the line of sight range (RLOS) from the "bogies" reaches the threshold mark.

The third transition point marks the point of disengagement and return to carrier or land base for the CBF and AGG fleets, respectively. This transition is a function of the weapons and fuel status of each aircraft. Another OR gate structure is used to verify when the fuel ratio (FUELR) and the fraction of weapons remaining (FAW) are below certain thresholds, FUELAC and WEAPAC, respectively. Eqs. 5.179 and 5.180 show the nominal values chosen for these disengagement parameters. It should be realized that a disengagement fuel fraction of 0.4 implies a compromise in speed for the return leg.

Once the timers have been described in some detail the focus now is in the specific events taking place in the engagement phases and their effect on the control variables described in Section 5.2.4.5.

5.2.4.7 Initial Phase

The initial phase starts the simulation and tries to capture a period of no direct detection, between the fighters in both fleets, where vectors can be transmitted to the opposing forces by an airborne early warning post (AWACS) or a ground control intercept post (GCIP). It has been said that, as part of the state variable initialization process, an initial heading is given to the aggressor and friendly aircraft. These initial headings would in fact be responsible, coupled with the throttle settings chosen, for the initial intercept paths to be followed. Further a yaw rate variable denoted as RSAI1 is incorporated to modify the initial vector according to some prespecified law. For the nominal model this rate of change has been set to zero as shown in Eq. 5.181. Notice that single enumeration of RSAI1 is possible if heading changes are to be done independently for each aircraft.

R	RSAI1.K(I)=0		5.181
NOTE	RSAI1	- YAW RATE IN THE INITIAL COMBAT PHASE (DEG/SEC)	

In this initial phase the throttle control rate (TSR1) is specified as zero implying that no throttle changes are made. The aircraft in fact will usually be accelerating or decelerating depending upon the initial velocity assigned to each aircraft. Eqs. 5.145 through 5.148 depicted the velocity vector initialization (VN) and acceleration along the flight path (ACC).

```
L     V.K(I)=V.J(I)+(DT)(ACC.JK(I))                                          5.145
N     V(I)=VN(I)                                                             5.146
T     VN(*)=260/260/260/260                                                  5.147
R     ACC.KL(I)=((T.K(I)*COS(ALP.K(I)+SIGMA(I))-D.K(I))/WK.K(I)              5.148

NOTE  V      - CBF AIRCRAFT VELOCITY VECTOR MAGNITUDE (M/SEC)
NOTE  VN     - INITIAL SPEED FOR CBF AIRCRAFT (M/SEC)
NOTE  ACC    - INSTANTANEOUS LONGITUDINAL ACCELERATION OF CBF AIRCRAFT
NOTE           (M/SEC-SEC)
NOTE  T      - AIRCRAFT THRUST (NEWTONS)
NOTE  ALP    - AIRCRAFT ANGLE OF ATTACK (RADIANS)
NOTE  SIGMA  - LONGITUDINAL THRUST OFFSET ANGLE (RADIANS)
NOTE  D      - AIRCRAFT TOTAL DRAG FORCE (NEWTONS)
NOTE  WK     - AIRCRAFT MASS (KGS.)
```

Eqs. 5.182 through 5.187 show the throttle setting modeled as a level variable with four rates (TSR1, TSR2, TSR3, and TSR4) corresponding to throttle variations through each one of the combat phases. Notice that throttle setting is initialized to 0.8 for each aircraft in the CBF fleet in the model nominal case. The rate of change of throttle control during the initial combat phase (TSR1) is set to zero implying that no throttle changes are made as depicted in Eqs. 5.186 and 5.187.

```
L     TS.K(I)=TS.J(I)+(DT)(TSR.J(I))                                         5.182
N       TS(I)=TSN(I)                                                         5.183
T       TSN(*)=.8/.8/.8/.8                                                   5.184
A     TSR.K(I)=TSR1.JK(I)+TSR2.JK(I)+TSR3.JK(I)+TSR4.JK(I)                   5.185
R       TSR1.KL(I)=TSR1C(*)                                                  5.186
T       TSR1C(*)=0/0/0/0                                                     5.187

NOTE  TS     - CBF AIRCRAFT THROTTLE SETTING (DIM)
NOTE  TSR    - CBF AIRCRAFT THROTTLE SETTING RATE OF CHANGE (DIM)
NOTE  TSN    - INITIAL CBF AIRCRAFT THROTTLE SETTING (DIM)
NOTE  TSR1   - TS RATE OF CHANGE DURING INITIAL COMBAT PHASE (DIM)
NOTE  TSR2   - TS RATE OF CHANGE DURING BVR COMBAT PHASE (DIM)
NOTE  TSR3   - TS RATE OF CHANGE DURING ACM COMBAT PHASE (DIM)
NOTE  TSR4   - TS RATE OF CHANGE DURING DISENGAGEMENT COMBAT PHASE (DIM)
NOTE  TSR1C  - NUMERICAL VALUE OF TSR1 DURING INITIAL COMBAT PHASE (DIM)
```

5.2.4.8 *Beyond Visual Range (BVR)*

BVR starts with either side of the combatant forces launching a weapon or else detected by any electronic means. In this phase the aircraft that has detected "bogies" maneuvers according to a pure pursuit strategy placing its velocity vector aligned with an averaged target aspect angle (AVATN) as shown in Fig. 5.24. In other words, the attacker aims towards the "centroid" of the opposing fleet in this stage where little radar discrimination can be achieved among a closely compact group of targets. The load factor becomes the heading control variable as expressed in Eq. 5.166. The computation of load factor, however, is constrained by thrust, aerodynamics, crew tolerance, and structural integrity as it will be shown later.

```
R       RSAI2.KL(I)=SWITCH(0,RSAI2A.K(I),RTT1.JK(I))                          5.188
A         RSAI2A.K(I)=CLIP(-AVATN.K(I)/DT,RSAI2B.K(I),SAI1M.K(I)*DT           5.189
X         ,MAX(AVATN.K(I),-AVATN.K(I)))                                       5.190
A         RSAI2B.K(I)=CLIP(-SAI1M.K(I),SAI1M.K(I),AVATN.K(I),0)               5.191
A           AVATN.K(I)=SUMV(ATN.K(I,*),1,JJ)/JJ                               5.192

NOTE    RSAI2    - HEADING ANGLE RATE OF CHANGE IN BVR PHASE (DEG/SEC)
NOTE    AVATN    - AVERAGE ANTENNA TRAIN ANGLE (DEG)
NOTE    ACMT     - ACM TURNING VECTOR (DEG)
NOTE    ATNP     - MATRIX CONTAINING POSITIVE VALUES OF ATN (DEG)
NOTE    ATNN     - MATRIX CONTAINING NEGATIVE ATN VALUES (DEG)
```

Eq. 5.188 computes the rate of change in heading ($\dot{\psi}$) in the BVR phase (RSAI2). Note that only one SWITCH statement is used to avoid initialization of RSAI2 when the rates RTT2 and RTT3 are not zero which would correspond to the ACM and disengagement combat phases, respectively. Also notice the sequencing of auxiliary equations RSAI2A through RSAI2C to obtain intermediate steps to ultimately obtain the desired value of RSAI2. Eq. 5.192 computes the value of AVATN (see. Fig. 5.26) as follows:

$$AVATN_i = \frac{1}{jj}\sum_{j=1}^{jj} ATN_{ij} \qquad 5.193$$

Following the order of execution of this set of equations RSAI2C decides whether a turn should be executed to the left or to the right of the i th aircraft. SAI1M stands for the maximum

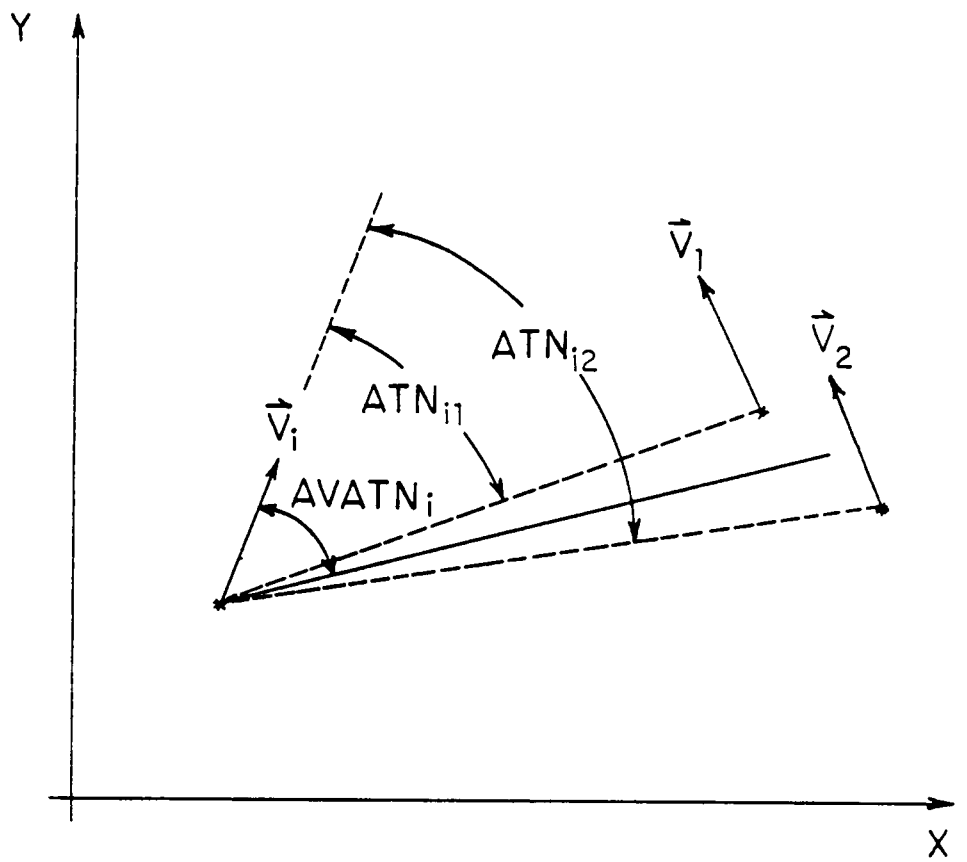


Figure 5.24 Average Target Aspect Angle Guidance in BVR.

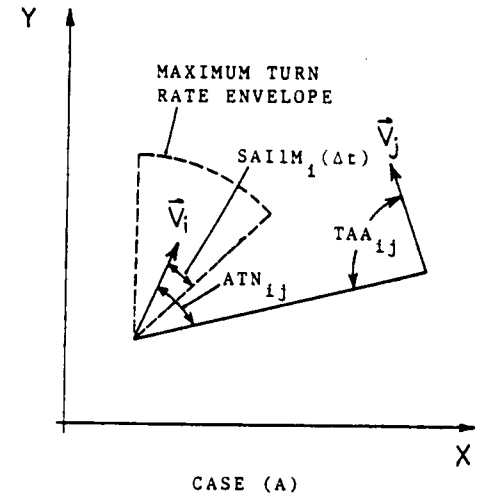
available sustained turn rate. AVATN follows the same sign convention used for ATN and TAA, that is, positive for targets on the starboard side of the attacker. Then if $AVATN \geq 0$ a command is schedule to reduce the heading angle by SAI1M (deg/sec). Otherwise, an increase in SAI1M is commanded (Eq. 5.191). Eq. 5.190 constitutes another check to find out if the product of the maximum available turn rate (SAI1M) and the simulation time interval (δt) exceed the absolute value of the averaged target aspect angle (AVATN). This procedure is reduce the overshooting of target at small target angles. Fig. 5.25 is a graphic representation of what Eq. 5.190 accomplishes in the pursuit control law.

In both cases the maximum sustained turn rate envelopes are shown. Notice that these envelopes are the product of SAI1M and DT and represent the sustained turn rate capture envelopes of a particular aircraft. Case (A) represents a large target aspect angle (ATN) condition where the i th aircraft heading change is restricted to $SAI1M \times DT$ and thus it is not possible to achieve a zero ATN in one simulation interval. Contrary to this, case (B) depicts a small angle-off geometry where it is possible for aircraft i to reach a zero target aspect angle provided that the target does not maneuver. In this example a one-on-one engagement has been assumed for illustrative purposes. In a true M-on-N environment the issue is handled in a similar fashion once a target has been selected. By the same token in the BVR phase ATN should be replaced by AVATN which becomes the target aspect angle of interest.

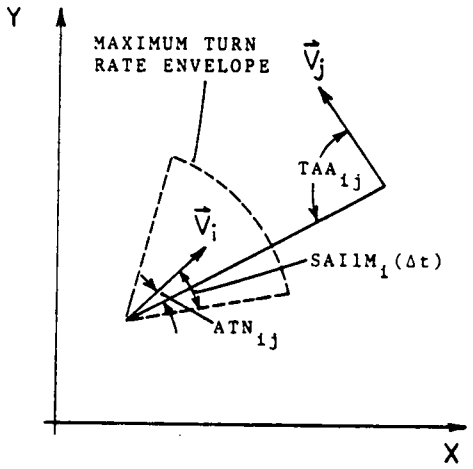
```
R       TSR2.KL(I)=CLIP(0,TSR2A.K(I),0,T1.K(I))                          5.194
A        TSR2A.K(I)=CLIP(TSR2B.K(I),0,0,T2.K(I))                         5.195
A          TSR2B.K(I)=CLIP(0,TSR2C(I),TS.K(I),.90)                       5.196
T            TSR2C(*)=.005/.005/.005/.005                                5.197

NOTE    TSR2     - THROTTLE SETTING RATE OF CHANGE DURING BVR PHASE (DIM)
NOTE    T1       - TIMER TO START THE BVR COMBAT PHASE
NOTE    T2       - TIMER TO START THE ACM COMBAT PHASE
NOTE    TS       - CBF AIRCRAFT THROTTLE SETTING (DIM)
NOTE    TSR2A, TSR2B, .. ARE INTERMEDIATE DUMMY VARIABLES
```

Typical of any interception, the BVR phase is characterized by an aircraft acceleration in order to reach a high energy state before the close combat maneuvering (ACM). The throttle setting control is increased at a constant pace (TSR2) which for the nominal model it is assumed to be 3 percent of the maximum value per simulation interval until reaching 90



CASE (A)



CASE (B)

NOTES:

SAIlM$_i$ - Maximum Sustained Turn Rate (Deg/sec)

ATN$_{ij}$ - Target Aspect Angle Measured from i th Aircraft

TAA$_{ij}$ - Target Aspect Angle Measured from j th Aircraft

V_i - i th Aircraft Velocity Vector

V_j - j th Aircraft Velocity Vector

Δt - Simulation Interval (sec)

Figure 5.25 Sustained Turn Rate Capture Envelopes.

percent of the maximum allowable setting which corresponds to maximum military power (no reheat). Eqs. 5.194 and 5.195 perform the routinely checks for T1 active corresponding to BVR phase. Eq. 5.196 limits the value of throttle setting to 0.9 as previously explained. Three observations that can be made about the increase in speed derived from the incremental throttle setting are the following: 1) the increased speed limits the turn rate capability of an attacker according to Eq. 5.166. However, even small sustained turn rates allow a large frontal hemisphere coverage if the distance from the target is large as in the case of BVR engagements. 2) The speed increase reduces the exposure of the attacker to the enemy radar (i.e., reducing the cumulative probability of detection) and therefore increases the chances of a surprise attack. The effect of speed though can be detrimental in frontal attacks and similar weapon capabilities where a small F-pole is usually achieved unless high speed maneuverability is readily available. 3) The launch envelope of a weapon is greatly enhanced if the speed of the launching platform is increased. It seems then justifiable to increase the throttle setting to accelerate the aircraft in this phase as it has been extensively documented in the literature [Herbst, 1983; Shaw, 1986; Imado and Susumu, 1986].

5.2.4.9 Close Air Combat Maneuvering (ACM)

It has been said that this phase starts at a fixed range between the opposing forces. The guidance algorithm for this phase is again, based upon the maximum sustained turn rate capabilities of each aircraft though differ from those used in previous phase in the sense that a single target is aimed at instead of a cluster of targets. The first part in determining the heading rate of change in the ACM phase (RSAI3) is to check whether or not timer T2 has been activated. This is accomplished in Eqs. 5.198 and 5.199 where RSAI3 is set to zero if T2 is zero or if $T3 \geq 0$. This last condition implies that that a disengagement has occurred. The guidance scheme used in the ACM phase directs each aircraft towards a target presenting the minimum aspect angle (ATN or TAA whichever side you are in) so that minimum heading changes are

required from the original paths. The direction of turn represents a quandary that needs to be resolved since there is always a possibility of having targets to either side of the aircraft (i.e., positive and negative ATN's). To help determining the turning directions in the ACM phase two variables ATNP and ATNN are defined such that ATNP contains all positive values of the target aspect angle matrix (ATN) and ATNN contains all negative values of ATN. Notice that if ATN is an $M \times N$ matrix then ATNP and ATNN are also of the same order as seen in Eqs. 5.203 and 5.204. Notice that 5.203 defines ATNP as ATN except for negative values which are substituted by an arbitrarily large number (i.e., 1000) so that all elements in ATN are real positive numbers. Similarly, ATNN is defined as $-ATN$ except for the positive values which are also assigned a large numerical value (1000). The idea is to decompose ATN into two matrices containing only positive numbers from which the minimum is to be selected as the immediate target to be pursued. Fig. 5.26 illustrates a numerical example of an arbitrary ATN matrix decomposition for a hypothetical 3 vs. 4 engagement.

```
R     RSAI3.KL(I)=CLIP(0,RSAI3A.K(I),0,T2.K(I))                                  5.198
A       RSAI3A.K(I)=CLIP(RSAI3B.K(I),0,0,T3.K(I))                                5.199
A       RSAI3B.K(I)=CLIP(-ACMT.K(I)/DT,RSAI3C.K(I),SAI1M.K(I)*DT
X       ,MINATN.K(I))                                                            5.200
A         RSAI3C.K(I)=CLIP(-SAI1M.K(I),SAI1M.K(I),ACMT.K(I),0)                   5.201
A       ATNP.K(I,J)=CLIP(ATN.K(I,J),1000,ATN.K(I,J),0)                           5.202
A         ATNN.K(I,J)=CLIP(1000,-ATN.K(I,J),ATN.K(I,J),0)                        5.203
A       MNATNP.K(I)=MIN(ATNP.K(I,1),MIN(ATNP.K(I,2),MIN(ATNP.K(I,3)
X       ,ATNP.K(I,4))))                                                          5.204
A       MNATNN.K(I)=MIN(ATNN.K(I,1),MIN(ATNN.K(I,2),MIN(ATNN.K(I,3)
X       ,ATNN.K(I,4))))                                                          5.205
A       MINATN.K(I)=MIN(MNATNP.K(I),MNATNN.K(I))                                 5.206
A         ACMT.K(I)=CLIP(-MINATN.K(I),MINATN.K(I),MNATNP.K(I)                    5.207

NOTE    RSAI3    - HEADING RATE OF CHANGE IN ACM ENVIRONMENT (DEG/SEC)
NOTE    ACMT     - ANGULAR CHANGE TO PURSUIT A TARGET (DEGREES)
NOTE    SAI1M    - MAXIMUM SUSTAINED TURN RATE (DEG/SEC)
NOTE    ATN      - TARGET ASPECT ANGLE MEASURED FROM CBF VELOCITY VECTOR (DEG)
NOTE    ATNP     - MATRIX CONTAINING POSITIVE VALUES OF ATN (DEG)
NOTE    ATNN     - MATRIX CONTAINING NEGATIVE ATN VALUES (DEG)
NOTE    MNATNP   - MINIMUM POSITIVE ATN FROM I TH AIRCRAFT TO JTH AIRCRAFT
NOTE               (USED TO KEEP UP WITH THE DIRECTION TO WHICH THE AIRCRAFT
NOTE               SHOULD TURN TO MAINTAIN LOS ALIGNMENT WITH TARGET)
NOTE    MNATNN   - ABSOLUTE VALUE OF MINIMUM ELEMENT IN ATNN MATRIX FROM
NOTE               I TH TO J TH AIRCRAFT
```

Once the matrices ATNP and ATNN are determined it becomes necessary to know the minimum value of ATN for each attacker. This is accomplished using Eqs. 5.204 and 5.205 which compute the minimum values of ATNP and ATNN and assigns them to two vectors

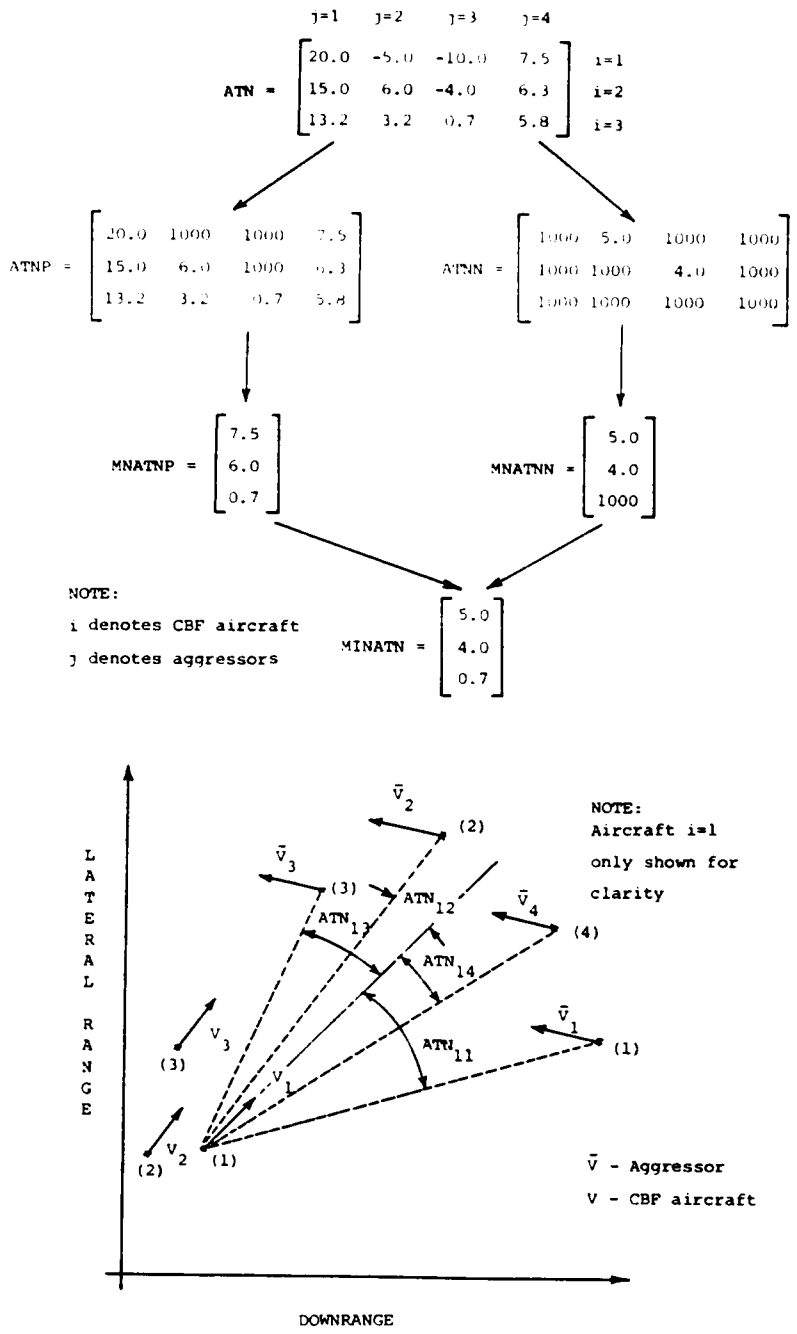


Figure 5.26 Decomposition of ATN Matrix and Geometry.

denoted by MNATNP and MNATNN (see Fig. 26). These two vectors are further compared to select the smallest among the row elements of them (i.e., for each i aircraft). The result is a vector MINATN computed in Eq.3.206. Notice that this results dictates the heading changes for each i aircraft and thus the array subscript of MINATN needs necessarily to be one dimensional. The direction of the turn required to pursue a single target is assessed in Eq. 5.207 and its magnitude denoted ACMT. A negative is assigned to MINATN if the minimum target aspect is an element of the vector MNATNN (i.e.$MNATNN \geq MNATNP$) also implying that a left turn is to be commanded in the pursuit of the target. A positive value of MINATN would command a right turn.

At this point the attacker knows the direction and desired magnitude of the turn in order to follow a given target. However, sustained aircraft performance needs to be incorporated before the heading rate control parameter (RSAI3) is updated since ultimately the aircraft is bounded by its maximum sustained turn rate envelope. Eq. 5.200 compares the product of the maximum sustained turn rate (SAI1M) and the simulation interval (DT) with the minimum of the target aspect angle previously obtained (MINATN). If the target is within the maximum turn rate envelope (Fig. 5.25) then the heading rate of change commands a turn of magnitude (ACMT), otherwise the maximum sustained performance is exploited to reduce the target aspect angle. This treatment is similar to that used in the BVR phase except for the fact that a single target is pursued instead of the centroid of the opposing fleet. Fig. 5.26(B) depicts a schematic of a 3 vs. 4 engagement showing the target aspect angles as measured from aircraft i in the CBF fleet. The geometry approximately corresponds to the numerical values shown in (A) and it is observed that $ATN_{i=1/i=2}$ is a minimum for this particular aircraft. Target aspect radials for vehicles 2 and 3 in the CBF fleet are not shown for the sake of clarity.

```
R       TSR3.KL(I)=CLIP(0,-TSR3A.K(I),0,T2.K(I))                    5.208
A         TSR3A.K(I)=CLIP(TSR3B.K(I),0,0,T3.K(I))                   5.209
A           TSR3B.K(I)=CLIP(TSR3C(I),-TSR3C(I),V.K(I),VC.K(I))      5.210
T             TSR3C(*)=.0008/.0008/.0008/.0008                      5.211

NOTE    TSR3      - THROTTLE SETTING RATE OF CHANGE IN ACM COMBAT PHASE
NOTE    TSR3A, TSR3B, .. ARE INTERMEDIATE DUMMY VARIABLES
NOTE    T2        - TIMER TO START ACM PHASE
NOTE    T3        - TIMER TO INITIATE DISENGAGEMENT COMBAT PHASE
NOTE    V         - CBF AIRCRAFT SPEED (M/SEC)
```

```
NOTE      VC        - CBF AIRCRAFT CORNER SPEED (M/SEC)
```

The throttle control setting variations in the ACM phase are shown in Eqs. 5.208 through 5.211. The first two statements perform the check for T2 active and T3 inactive implying ACM phase is in effect. The third statement, Eq. 5.210, bounds the value of speed (V) to a value near the corner speed (VC) so that the aircraft decelerates before the short range maneuvering starts. It is assumed that during the ACM portion of the simulation pilots would want to fly at near corner speeds (VC) in order to achieve maximum turning performance capability. This in fact could translate into more firing opportunities, yet retaining reasonable energy levels for the disengagement. The nominal model shows a gradual reduction of TS rate in order to decelerate near VC as seen in Eq. 5.211.

5.2.4.10 Disengagement Phase

This phase starts with the activation of timer T3 which occurs when either the fuel fraction (FUELR) or the fraction of weapons remaining (AVWEAP) reach a certain threshold. Fig. 27 shows a functional diagram illustrating the decisions involved in the process.

Once the activation of T3 takes place each aircraft is commanded to fly a "pursuit path" towards the aircraft carrier or the enemy base depending upon the particular case. For this purpose a "return" vector is computed, denoted STCBF, from each aircraft position to the desired return point. Eq. 5.218 checks T3 active to start the return sequence.

```
R       RSAI4.KL(I)=CLIP(0,RSAI4A.K(I),0,T3.K(I))                          5.212
A         RSAI4A.K(I)=CLIP(-STCBF.K(I)/DT,RSAI4B.K(I),SAI1M.K(I)*DT
X         ,ABS(STCBF.K(I)))                                                5.213
A           RSAI4B.K(I)=CLIP(-SAI1M.K(I),SAI1M.K(I),STCBF.K(I),0)          5.214

NOTE    RSAI4     - HEADING RATE OF CHANGE IN DISENGAGEMENT PHASE (DEG/SEC)
NOTE    RSAI4A, RSAI4B,.. INTERMEDIATE RSAI4 COMPUTATION VARIABLES
NOTE    SAI1M     - MAXIMUM SUSTAINED TURN RATE (DEG/SEC)
NOTE    T3        - TIMER TO START THE DISENGAGEMENT PHASE
NOTE    STCBF     - ANGULAR DIFFERENCE BETWEEN SAI VECTOR AND RETURN STEERING
NOTE                VECTOR (DEGREES)
```

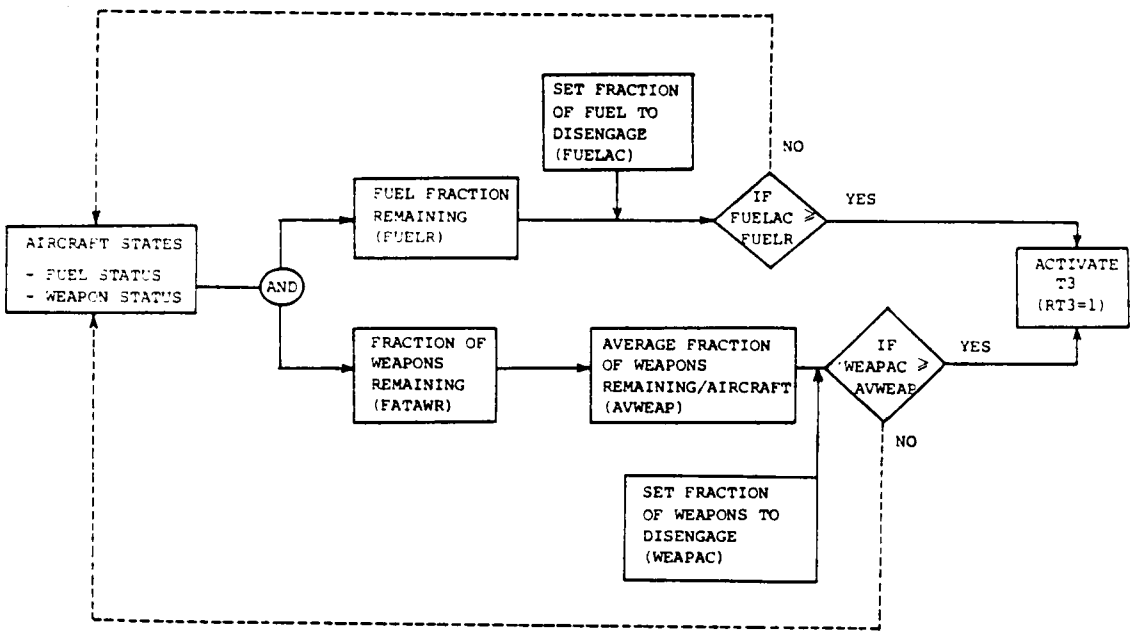


Figure 5.27 Functional Flow Diagram to Activate T3.

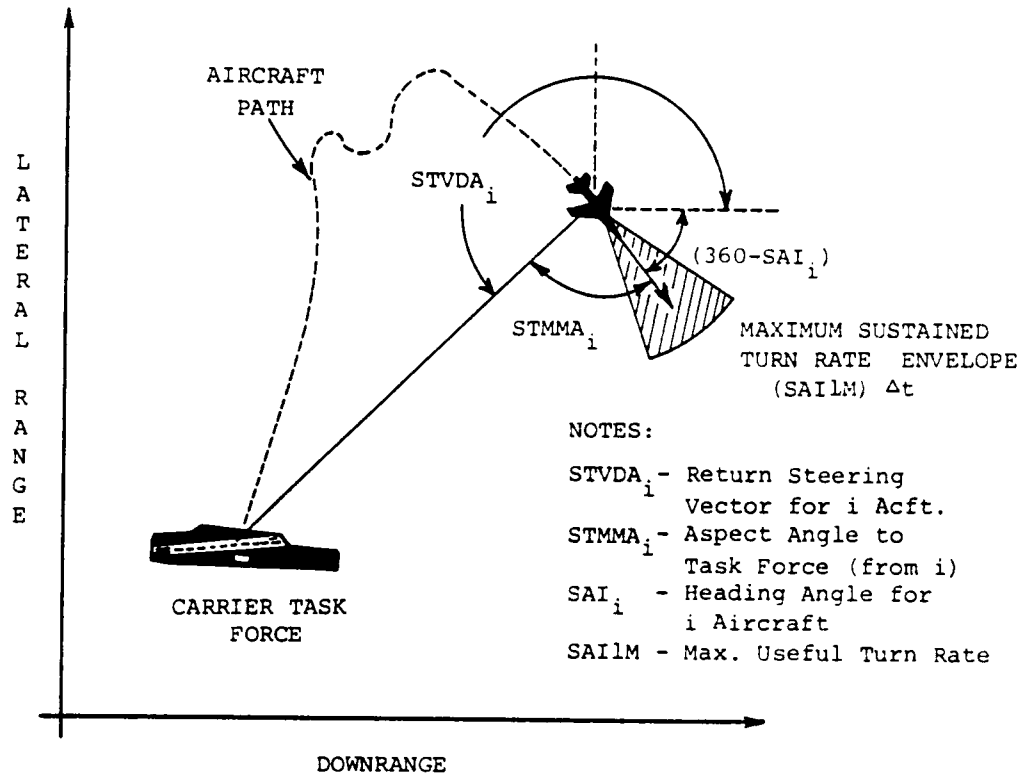


Figure 5.28 Geometry of Return Steering Vector.

Fig. 5.28 depicts the geometry of the return phase. A general aircraft path is shown in dotted lines while the solid line represents the return steering vector as measured from the set of body fixed axes moving with the vehicle. STVDA, the direction of the return vector, is defined in Eq. 5.216. Notice the use of macro ARCSIN where the cartesian coordinates of the aircraft (X,Y) and the carrier battle group (XN,YN) are provided. Also, the magnitude of the return steering vector, STVMA, is an input to ARCSIN (Eq. 5.216). The guidance algorithm, however, requires the aspect angle between the direction of the aircraft velocity vector (SAI) and STVDA. The resulting angle, denoted STCBF, is computed in Eq. 5.217 invoking the macro DIREC in analogous way to that used to estimate ATN and TAA. Inputs to macro DIREC are the aircraft heading (SAI), direction of return steering vector (STVDA), and the coordinates of the positions of the aircraft and carrier battle group (CBG). A similar treatment is used for the aggressor fleet except that the variables names are changed to STVDG, STAAG, and STVMG for the angular difference between the heading angle and return vector, the desired direction of return vector , and its magnitude.

```
A       STVMA.K(I)=SQRT(MAX(X.K(I)-XN(I),-X.K(I)+XN(I))**2
X        +MAX(Y.K(I)-YN(I),-Y.K(I)+YN(I))**2)                          5.215
A       STVDA.K(I)=ARCSIN(X.K(I),XN(I),Y.K(I),YN(I),STVMA.K(I))       5.216
A       STCBF.K(I)=DIREC(SAI.K(I),STVDA.K(I),Y.K(I),YN(I))            5.217

NOTE    STVMA   - CBF STEERING VECTOR MAGNITUDE (M.)
NOTE    STVDA   - CBF STEERING VECTOR DIRECTION (DEG)
NOTE    STCBF   - ANGULAR DIFFERENCE BETWEEN SAI VECTOR AND RETURN STEERING
NOTE              VECTOR (DEGREES)
```

The sign convention adopted fro STCBF is the same as that used for ATN and TAA, that is, STCBF is positive when the CBG is at starboard side of the aircraft in question. Returning to the guidance algorithm, Eq. 5.217 computes the direction of the turn to establish each aircraft in their return leg. Note that if STCBF is positive or zero then a maximum turn rate maneuver is executed to the right to intercept the desired return course, otherwise a left turn is commanded. Finally, Eq. 5.218 checks whether or not STCBF is within the maximum sustained turn rate envelope defined as the product of SAI1M and DT and shown by the shaded area in Fig.5.28. This guidance scheme is similar to that used in Section 5.5.4.2 to follow a single target the only difference being the fact that in the former case a fixed "target"

(the carrier battle group) is used as the aiming point instead of a highly maneuverable target used in the latter.

The throttle setting control is varied only to establish an economic "cruise out" condition. Eq. 5.218 is a check for T3 active. Positive values of T3 imply that disengagement is in effect. Eq.219 restricts the value of the throttle setting (TS) to 0.85. Finally, a constant throttle setting rate of change (TSR4B) is used to accomplish the transition.

```
R       TSR4.KL(I)=CLIP(0,TSR4A.K(I),0,T3.K(I))                          5.218
A         TSR4A.K(I)=CLIP(-TSR4B(I),TSR4B(I),TS.K(I),.85)                5.219
T         TSR4B(*)=.005/.005/.005/.005                                   5.220

NOTE    TSR4      - THROTTLE SETTING RATE OF CHANGE IN DISENGAGEMENT PHASE
NOTE    TSR4A, TSR4B, INTERMEDIATE TSR4 VARIABLES
NOTE    TS        - CBF AIRCRAFT THROTTLE SETTING (DIM)
NOTE    T3        - TIMER TO START DISENGAGEMENT COMBAT PHASE
```

5.2.5 Aircraft System Effectiveness

This section covers the functions necessary to be accomplished by an aircraft in order to inflict damage on its opponents. Major portions covered include the detection-identification of the enemy aircraft, weapons launch, guidance, and detonation. Also, some important subsections on estimating radar and infrared probabilities of detection are included.

5.2.5.1 System Effectiveness Mirror Images

The confrontation between two air fleets implies, to a certain extent, similar goals for both sides. That is, to gain air superiority of a given airspace in order to deny its use to the enemy. In the remote escort scenario modeled one might think that the aggressor forces act defensively and the CBF fighters offensively, however, regardless of the terminology used the goal remains the same in both cases. A simple issue in this confrontation is the fact that the

tools used to achieve air superiority might differ from force to force depending upon the technologies (i.e., hardware) and tactics available to either side. It is possible to identify certain common elements or actions necessary to be undertaken if a force is to obtain air superiority. These are the ability to detect, identify, track the enemy, the capability to launch a determined number of weapons, guide them to their targets, and for them to detonate within a prescribed "miss envelope". These activities reflect the effectiveness of an aircraft system and they are manifested on both sides creating a mirror image principle as shown in Fig. 5.29. The diagram depicts the basic modeling principle in which the actions of one side, say the lethality of the CBF fleet, intrinsically affects the the status of the opponent (i.e., increase in the kill rate of aggressors) and viceversa. Events form what in systems dynamics is termed as a second order positive feedback loop structure where the two states are represented by the number of aircraft per side at any point in time and their respective kill rates (AGGKR, CBFKR) are influenced not only by the number of opponents but also by the lethalities of their weapons.

For the purpose of modeling and following standard practice [MIL-336-1, 1982] the aircraft systems effectiveness is evaluated as the product of five conditional probabilities corresponding to each one of the the five basic functions previously described. These probabilities are shown in Fig. 5.30 with some specific activities considered in the modeling process.

Mathematically, the probability of aircraft system effectiveness (P_{ASE}) is given by,

$$P_{ASEijk} = P_{LOSij} P_{Dij} P_{WLijk} P_{Gijk} P_{DEijk} \qquad 5.221$$

where, P_{LOSij} is the probability of line of sight (LOS), P_{Dij} the probability of detection-identification given line of sight detection, P_{WLijk} the probability of weapons launch given detection, P_{Gijk} the probability of successful guidance given weapons launch, and P_{DEijk} the probability of detonation given that successful guidance has taken place. Note that the subscripts i, j, and k refer to the launching vehicle, the target, and the weapons employed,

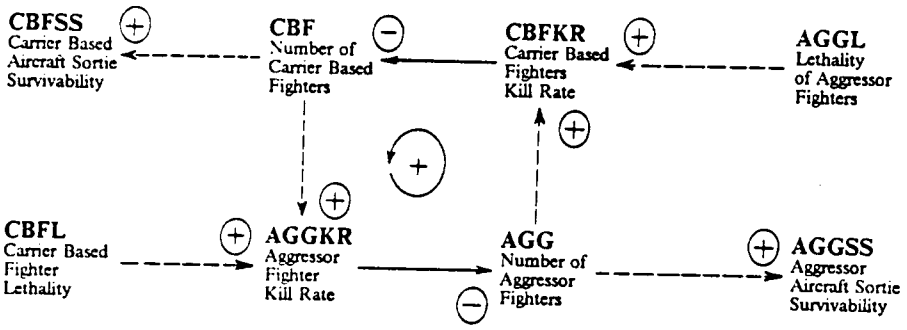


Figure 5.29 Second Order Feedback Loop Modeling Concept.

respectively. These elements of aircraft systems effectiveness are valid for both, friendly and aggressor forces. Eq. 5.222 depicts the previous expression in DYNAMO for the CBF aircraft.

```
A     PCBFE.K(I,J,K)=PALOS.K(I,J)*PAGGD.K(I,J)*PATWL.K(I,J,K)*
X     PATWSG.K(I,J,K)*PAWDET.K(K)                                    5.222

NOTE  PCBFE  - PROBABILITY OF CBF AIRCRAFT SYSTEMS EFFECTIVENESS (DIM)
```

where, PALOS is the probability of LOS, PATAE is the CBF fighter probability of aircraft systems effectiveness, PAGGD represents the probability of aggressor detection and identification, PATWL is the probability of weapons launch, PATWSG is the probability of weapons successful guidance, and PAWDET is the probability of weapons detonation. Notice the peculiar array representation of these terms. A three dimensional array format is used for PATAE since the capability of an aircraft i engaging several targets (j) needs to be accounted independently for each weapon k. This type of modeling can be represented graphically as shown in Fig. 5.31.

In this figure a 2 versus 4 engagement is depicted and the i aircraft has 4 different air-to-air classes of weapons. A similar approach is used to evaluate the aggressor aircraft system effectiveness (PAGGE) although particular variables are assigned for this purpose as shown in Eq. 5.223.

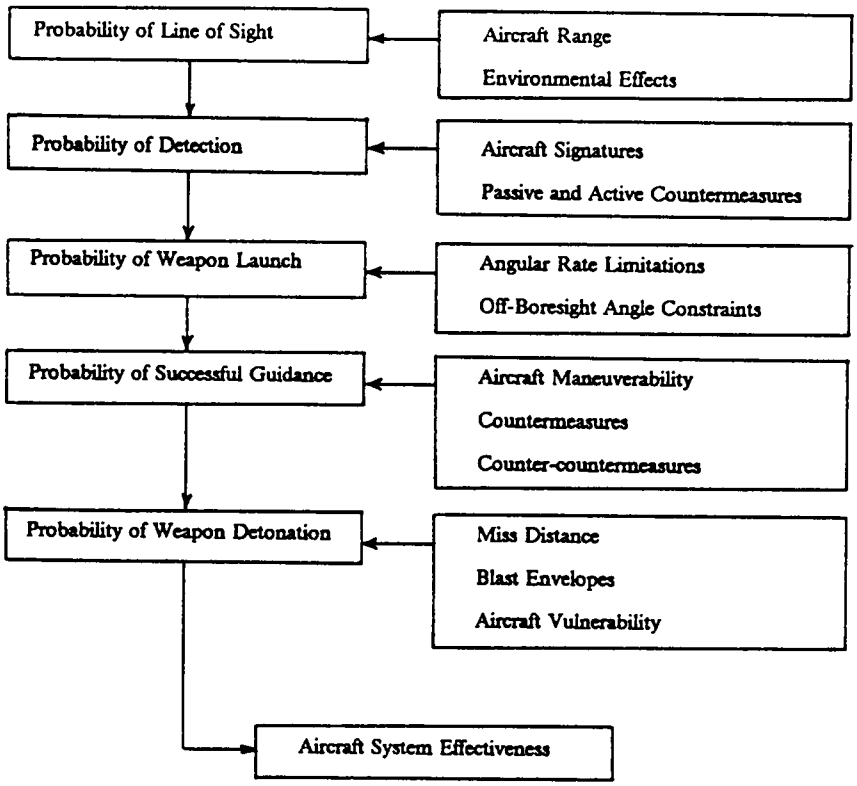
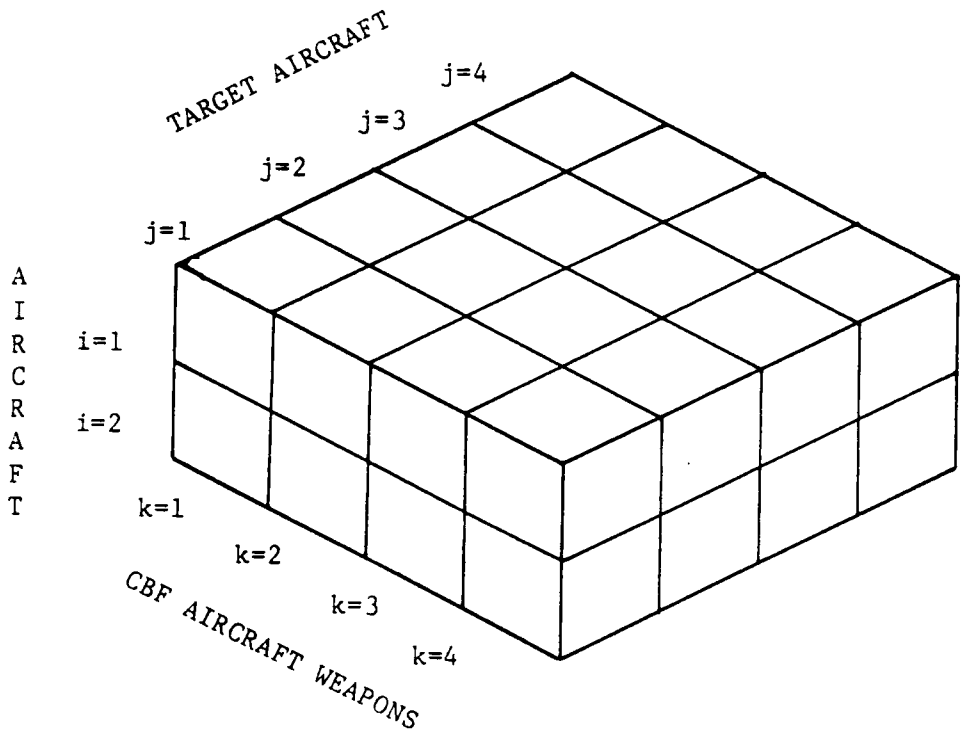


Figure 5.30 Aircraft Systems Effectiveness Modeling Concept.



NOTE: k=1 Long range AA missile
k=2 Medium range AA missile
k=3 Short range AA missile
k=4 Gun or Cannon

Figure 5.31 3-Dimensional System Effectiveness Array Representation.

```
A       PAGGE.K(I,J,L)=PALOS.K(I,J)*PCBFD.K(I,J)*PAGWL.K(I,J,K)*
X       PAGWSG.K(I,J,K)*PGWDET.K(K)                                    5.223
```

where, PCBFD is the probability of CBF aircraft detection and identification, PAGWL, PAGWSG, and PGWDET represent the probabilities of aggressor weapons launch, weapons successful guidance, and weapons detonation, respectively. Notice that PALOS is also present in this expression to represent the intervisibility requirement between target and attacker.

Probability of Line of Sight: The term PALOS is implemented as a table function containing the values of minimum altitudes for line of sight detection. The assumptions are that of a perfect spherical earth and the elimination of small altitude differential between combatants. Eq. 5.224 invokes the macro LOS and transfers the values of altitude (ALT) and line-of-sight distance (RLOS) in the process. The value of altitude is compared with those contained in the macro table for various ranges and PALOS is assigned either a zero or a unit value.

```
A       PALOS.K(I,J)=LOS(ALT.K(I),RLOS.K(I,J))                         5.224
```

Note that PALOS forms a two dimensional array ($M \times N$ matrix) containing the probabilities of LOS from each i to j aircraft and viceversa.

Aircraft Detection: The probability of aircraft detection terms, PAGGD and PCBFD, are computed as the maximum value between the radar and infrared detection probabilities. Eq. 5.225 shows this simple implementation for the CBF aircraft.

```
A       PAGGD.K(I,J)=MAX(PDIRG.K(I,J),PGRD.K(I,J))                     5.225
```

where, PDIRG is the probability of infrared detection of an aggressor and PGRD the probability of radar detection. Eq. 5.225A in Appendix A corresponds to the probability of detection of a carrier based fighter. Notice that no attempt has been made to model visual and aural

detection mechanisms since modern air combat technology seems to be directed towards full integration of weapons, navigation, and detection capabilities to the point of providing a "synthetic" visual and aural field of view generated inside the crew helmets [AGARD, 1986 and Lerner, 1986]. It is then very unlikely that future pilots will rely on their visual and aural senses to establish a long range engagement. Infrared and radar mechanisms (or other even more advanced yet to be developed) seem to cover the long, medium, and short detection ranges thus making unnecessary the inclusion of visual and aural submodels.

Radar Detection: The radar detection scheme used in this model is based upon computation of the cumulative probability of detection [Brookner, 1978]. The target model used in conjunction with the universal detection curves [13] is a Swerling I model which considers the aircraft as a large number of individual scattering elements with spectral variations only between two consecutive radar scans [Stimpson, 1985].

As it was mentioned before in Section 5.2.3.22 where the macro DTECT was explained, the use of the universal radar detection curves requires the knowledge of two important parameters. The first one is the ratio of the nominal radar range (R0) and the distance traveled by the target in one radar antenna scan of the opponent aircraft (DR) and defined as DR0DR. The second term is the ratio between the aircraft range from the target (RLOS) and the radar nominal range (R0) denoted by RCDR0. The nominal radar range (R0) used in this context is that obtained from any of the three radar range equations available in the model (see Appendix E). Eq. 5.226 shows the relationship to estimate the probability of radar detection of an aggressor aircraft (PGRD). The dummy variables PD5T, PD75T, PD9T, etc. contain the numerical values of the universal radar detection curves shown in Fig. 5.18. For a more detailed understanding of the mechanics of macro DTECT (see Section 5.2.3.22 and in particular Example 5.1).

```
A     PGRD.K(I,J)=DTECT(DRC.K(I,J),R0CBF.K(I,J),RLOS.K(I,J),PD5T,PD75T
X     ,PD9T,PD10T,PD13T,PD15T,PD175T,PD20T,PD22T,PD24T)*CLIP(0,1,
X     MAX(ATN.K(I,J),-ATN.K(I,J)),THETAA(I)/2)                          5.226
A     DRC.K(I,J)=MAX(V.K(I)*COS(ATN.K(I,J)/57.29)+VAG.K(J)*COS(TAA.K(I,J)
X     /57.29),-V.K(I)*COS(ATN.K(I,J)/57.29)-VAG.K(J)*COS(TAA.K(I,J)
```

```
X       /57.29))*TSA(I)                                                    5.227

NOTE    PGRD    - CUMULATIVE PROBABILITY OF AGGRESSOR AIRCRAFT RADAR
NOTE              DETECTION (DIM)
NOTE    DR      - DELTA RANGE COVERED BY THE TARGET WITH RESPECT TO THE
NOTE              ENEMY AIRCRAFT IN A RADAR FRAME SCAN INTERVAL.
```

Variable DRC stands for the distance traveled within radar antenna scans, R0CBF is the nominal radar detection range, RLOS is the range in LOS, ATN is the target aspect angle, and THETAA is the azimuth antenna train limits. Note that the right hand side of Eq. 5.226 is multiplied by a factor which zeroes the probability of detection if the target is outside the antenna training limits. Since the antenna moves with the flying platform the change in RLOS per simulation scan interval (TSA) denoted DRC for the CBF aircraft is computed according to Eq. 5.227. A similar treatment is used for the aggressor aircraft were ATN is replaced by TAA and TSA by TSGG which stands for the aggressor radar antenna scan time. The change in RLOS computed using TSGG is denoted as DRG as depicted in Eq. 5.227A in Appendix A.

The use of passive and active electronic countermeasures (ECM) has a profound effect on the outcome of the probability of detection of a target. Eq. 5.228 computes the nominal radar detection range (R0CBF) for the CBF aircraft). At this point the decision has to be made on whether or not to introduce jamming techniques into the simulation. There are three jamming switches that are used to implement the effect of noise jamming or not. The first one, SWG1 shown in Eq. 5.228.1, selects whether or not noise jamming is to be used. Eq. 5.228 branches control to R0ANJ, radar detection range in a "clear" environment if SWG1 is set to zero, otherwise SJAMON is selected and further decision has to be done about the type of jammer employed. The second switch, SWG2, selects between jamming activation time. If SWG2 is zero implies that noise jamming is employed throughout the entire mission otherwise jamming is activated at some specified time. In this case the initiation of the BVR combat phase is selected as jamming activation point via the parameter JAMTMM (Eq. 5.229). Finally, the third switch, SWG3, allows the user to select between stand-off and self screening jamming doctrines. Note from Eq. 5.228.4 that if SWG3 is set to zero then stand-off jamming is used.

```
A       R0CBF.K(I,J)=SWITCH(R0ANJ.K(I,J),SJAMON.K(I,J),SWG1)                    5.228
C         SWG1=0                                                                5.228.1
A         SJAMON.K(I,J)=SWITCH(SJAM1.K(I,J),SJAM2.K(I,J),SWG2)                  5.228.2
C           SWG2=0                                                              5.228.3
A           SJAM1.K(I,J)=SWITCH(R0ASOJ.K(I,J),R0ASSJ.K(I,J),SWG3)               5.228.4
C             SWG3=0                                                            5.228.5
A           SJAM2.K(I,J)=CLIP(R0ANJ.K(I,J),SJAM1.K(I,J),JAMTMM.K(I),1)          5.228.6
A            JAMTMM.K(I)=CLIP(1,0,T1.K(I),1)                                    5.229
```

The parameter JAMTMM defined in Eq. 5.229 is assumed in the nominal model to be a function of time. Particularly, the transitional point between the BVR ans ACM phases of the engagement. Off course the user can manipulate freely this parameter according to other tactics without having to deal with any other expression besides 5.229. The rationale in the nominal model for making JAMTMM dependent upon T1 is that at this point in the simulation either the presence of the enemy is known or one is being observed or fired upon by the enemy. This seems to suggest the employment of jamming techniques to delay the adversary's options.

No Jamming Radar Equations: The no jamming radar detection range (R0ANJ) depends upon several key parameters of the radar used as well as the radar signature of the target aircraft. Among the important factors considered in this model are the average radiating power (PAVA), the radar antenna diameter (ADA), the effective aperture factor (NUA), the angular scan time (TSA), radar system losses (LN), angular scan coverage (OMEGAA), and the effective radar signature of the target (ERCSG). Eqs. 5.230 through 5.241 show the DYNAMO equations to estimate the no jamming radar range for the CBF aircraft.

```
A       R0ANJ.K(I,J)=(RLPA(I)*ERCSG.K(I,J))**.25                                5.230
N         RLPA(I)=2*PAVA(I)*ADA(I)**2*TSA(I)*NUA**2/(PI**3*BK*TNO(I)
X         *LA(I)*OMEGAA(I))
T           PAVA(*)=200/200/200/200                                             5.231
T           ADA(*)=.91/.91/.91/.91                                              5.232
T           TSA(*)=3/3/3/3                                                      5.233
T           TNO(*)=400/400/400/400                                              5.234
T           LA(*)=16/16/16/16                                                   5.235
N           OMEGAA(I)=(THETAE(I)/57.29)*(THETAA(I)/57.29)                       5.236
T            THETAA(*)=120/120/120/120                                          5.237
T            THETAE(*)=30/30/30/30                                              5.238
C           BK=1.38E-23                                                         5.239
C           NUA=.8                                                              5.240
                                                                                5.241
NOTE    PAVA    - RADAR AVERAGE POWER (WATTS)
NOTE    ADA     - CBF RADAR ANTENNA DIAMETER (M)
NOTE    RCSG    - AGGRESSOR RADAR CROSS SECTIONAL AREA (SQ. METERS)
NOTE    RCSAAM  - RADAR CROSS SECTION ASPECT ANGLE MULTIPLIER (DIM)
```

```
NOTE     OMEGAA  - CBF VOLUME SEARCH AREA (DIM)
NOTE     THETAE  - SEARCH RADAR ELEVATION (RADIANS)
NOTE     THETAA  - AZIMUTH ANGLE COVERED BY RADAR IN VOLUME SCAN MODE (RAD)
NOTE     TNO     - RADAR NOISE TEMPERATURE (DEGREES KELVIN)
NOTE     LN      - SYSTEM LOSSES (DIM) CONVERTED FROM 12 DB TYPICAL
NOTE     BK      - BOLTZMANN CONSTANT (JOULES/DEG. KELVIN)
NOTE     NU      - EFFECTIVE APERTURE FACTOR FOR CBF RADAR ANTENNA (DIM)
```

For the sake of simplicity R0ANJ is expressed as the product of a radar lumped parameter (RLPA) and the fourth root of the effective radar signature of the target (ERCSG). Note that all radar parameters are expressed as constants values to allow quick changes to be performed in reruns to conduct sensitivity analyses. The values represented here are representative of existing technology and the nominal detection range for a 5 square meter target is about 180 km. Some simplifying assumptions have been made to arrive at Eq. 5.231 as explained in Appendix E of this dissertation. The effective cross sectional area of the target (ERCSG) as it will be shown later (Section 5.2.5) corrects the frontal RCS by aspect angle condition.

Noise Jamming Equations: Two active noise jamming techniques are modeled in ASALT I, these are: 1) self-screen (SSJ) and stand-off jamming (SOJ). In the former each individual aircraft carries electronic countermeasures (ECM) necessary to deny its presence to hostile forces. This equipment can be carried internally or externally in pods. In the latter, a dedicated airborne facility, assumed to be stationed in the vicinity of the carrier battle group in the nominal model, provides the jamming coverage for the escorting fleet.

```
A     R0AJ.K(I,J)=SWITCH(R0ASOJ.K(I,J),R0ASSJ.K(I,J),SWTCH)                    5.242
C      SWTCH=0                                                                 5.243
A      R0ASOJ.K(I,J)=((32*PAVA(I)*NUA*TSA(I)*ERCSG.K(I,J)*RJAM.K(I)**2)
X       /(PI*OMEGAA(I)*LA(I)*JDSOJ))**.25                                      5.244
A      RJAM.K(I)=SQRT(DIXJ.K(I)**2+DIYJ.K(I)**2+DIZJ.K(I)**2)                  5.245
A       DIXJ.K(I)=MAX(X.K(I)-XSJG,-X.K(I)+XSJG)                                5.246
A       DIYJ.K(I)=MAX(Y.K(I)-YSJG,-Y.K(I)+YSJG)                                5.247
A       DIZJ.K(I)=MAX(ALT.K(I)-ALTSJG,-ALT.K(I)+ALTSJG)                        5.248
C         XSJG=250000                                                          5.249
C         YSJG=0                                                               5.250
C         ALTSJG=6000                                                          5.251
N         JDGSOJ=PGSOJ*GGSOJ/BWGSOJ                                            5.252
C           PGSOJ=150                                                          5.253
C           GGSOJ=35                                                           5.254
C           BWGSOJ=2E8                                                         5.255

NOTE     SWTCH   - SWITCH FOR SPECIFYING SELF SCREENING OR STAND-OFF
NOTE               JAMMING. IF SWTCH=0 THEN STAND-OFF JAMMING IS USED
NOTE     R0AJ    - MAXIMUM RADAR DETECTION RANGE WITH JAMMER ON (METERS)
NOTE     R0ASOJ  - MAXIMUM DETECTION RANGE WITH STAND-OFF JAMMER ON (M)
NOTE     ROASSJ  - MAXIMUM DETECTION RANGE WITH SELF-SCREENING JAMMER ON (M)
```

```
NOTE      RJAM      - RANGE FROM JTH AIRCRAFT TO STANDOFF JAMMER (METERS)
NOTE      DIXJ      - DOWNRANGE DISTANCE FROM SOJ JAMMER TO JTH AIRCRAFT (M)
NOTE      DIYJ      - LATERAL DISTANCE FROM SOJ JAMMER TO JTH AIRCRAFT (M)
NOTE      DIZJ      - ALTITUDE DIFFERENTIAL FROM SOJ JAMMER TO JTH AIRCRAFT (M)
NOTE      XSJ,YSJ,ZSJ COORDINATES OF SOJ JAMMER (METERS)
NOTE      JDSOJ     - NOISE JAMMING POWER OF STAND-OFF JAMMER (W/HZ)
NOTE      PGSOJ     - AVERAGE POWER OF SOJ JAMMER(W)
NOTE      GGSOJ     - JAMMER GAIN (DIMENSIONLESS)
NOTE      BWGSOJ    - JAMMER BANDWIDTH (HZ)
```

Eq. 5.242 computes the nominal radar detection range with noise jamming in effect. SWTCH allows the user to select between stand-off and self-screen jamming. Note that if $SWTCH = 0$ (nominal case) stand-off jamming is in effect, otherwise self-screen jamming takes place. Eq. 5.244 depicts the modified radar range equation for SOJ jamming (R0ASOJ) which involves some simplifications as detailed in Appendix E. An important factor in the computation of R0ASOJ is the estimation of the distance from the aggressor jammer to the CBF fleet radars being jammed. This parameter, denoted RJAM, is computed in Eq. 5.245 and requires the knowledge of the aggressor jammer location with coordinates XSJG,YSJG,ALTSJG defined in Eqs. 5.249 through 5.251. The distances in the three spatial directions are computed in Eqs. 5.246 through 5.248. The jammer parameters; power, gain, and bandwidth are defined in Eqs. 5.253 through 5.255, respectively. Eq. 5.252 groups these parameters in what is termed the effective radiated power (JDGSOJ) of the aggressor fleet jammer.

Although this section has been dealing with the radar detection of aggressor fighters this last set of equations (3.242 through 5.245) involves a mixture of parameters associated with both forces. This fact dictates the use of a two dimensional array for R0AJ which should be interpreted as the radar range of aircraft i to each j under SOJ jamming conditions. A similar approach is used in determining the radar detection range of each aggressor under SOJ jamming operated by the friendly force. Eqs. 5.242A through 5.255A in Appendix A reflect these mirror image computations.

The selection (by the user) of self-screen jamming bring us to another form of the radar range equation similar to that for SOJ except that the distance from the jammer to the target is just the detection range itself, thus simplifying the radar range equation (3.251). This simplification is observed in Eq. 5.263 where it is seen that the range in this case is a function only of the square root of the radar parameters and the target signature instead of the fourth

root as when the jammer is not active. Eqs. 5.258 through 5.259 define the jammer characteristics (power, gain, and bandwidth) mounted either internally or externally on the aggressor aircraft. Note that in the nominal model assumes the power of the SSJ jammer to be one third of that of SOJ.

```
A       ROASSJ.K(I,J)=(32*PAVA(I)*NUA*TSA(I)*ERCSG.K(I,J)/(PI*OMEGAA(I)
X       *LA(I)*JDSSJ))**.5                                              5.256
N       JDSSJ=PSSJ*GSSJ/BWSSJ                                           5.257
C       PSSJ=50                                                         5.258
C       GSSJ=35                                                         5.259
C       BWSSJ=2E8                                                       5.260

NOTE    JDSSJ   - NOISE JAMMING POWER OF SELF-SCREENING JAMMER (W/HZ)
NOTE    PSSJ    - AVERAGE POWER OF SSJ JAMMER(W)
NOTE    GSSJ    - JAMMER GAIN (DIMENSIONLESS)
NOTE    BWSSJ   - JAMMER BANDWIDTH (HZ)
```

Radar Warning Receiver: Among the most common electronic system measures (ESM) incorporated in modern aircraft is a radar warning receiver (RWR). This device although passive in nature, is closely related to some of the radar parameters described in this section and hence deserves some explanation here. The basic RWR detection range equation [Hovanessian, 1984] for the CBF aircraft (RWRA) is shown in Eq. 5.261. Notice that the principal elements of RWRA pertain to those characteristics of the aggressor's aircraft radar that define the radiated energy by the radar which ultimately is what the RWR measures. Other parameters included in this equation are those related to the particular performance of the RWR. These factors, defined in Eqs. 5.262 through 5.265 are the bandwidth (BN), gain (RGAIN), system losses (LARWR), and the noise figure of the receiver (FR).

```
N       RWRA(I,J)=SQRT(9*PAVG(J)*ADG(J)**2*NUG*RGAIN(I)/((4*PI)**2*LARWR(I)
X       *BK*TNO(I)*BN(I)*FR(I)))                                        5.261
T         BN(*)=2E8/2E8/2E8/2E8                                         5.262
T         RGAIN(*)=10/10/10/10                                          5.263
T         LARWR(*)=20/20/20/20                                          5.264
T         FR(*)=20/20/20/20                                             5.265

NOTE    RWRA    - RADAR WARNING RECEIVER RANGE FOR CBF AIRCRAFT (METERS)
NOTE    RGAIN   - RADAR WARNING RECEIVER ANTENNA GAIN
NOTE    BN      - RWR RECEIVER BANDWIDTH (HERTZ)
NOTE    LARWR   - RECEIVER LOSSES (DIM)
NOTE    PAVG    - AGGRESSOR AVERAGE POWER (WATTS)
NOTE    BK      - BOLTZMANN CONSTANT (JOU/DEG KELVIN)
NOTE    FR      - NOISE FIGURE OF RWR RECEIVER
```

Radar Signature: The radar cross section area (RCS) is modeled as a level equation since variations of it due to weapons launched and azimuth are permitted. This is shown in Eq. 5.266. The initial value of RCS is computed in Eq. 5.267 as the sum of the clean aircraft radar cross section area (RCSGN) and the contribution of any external stores and/or jamming pods carried for a particular mission. The former is defined as a table function with numerical values corresponding to the frontal radar cross section (Eq. 5.268) while the latter one is the scalar product of the initial number of weapons (AGAWN) and the increment in RCS due to weapons (DRCSWG) defined in Eq. 5.270.

```
L       RCSG.K(J)=RCSG.J(J)*MULT2-(DT)(RCSRWG.JK(J))                          5.266
C         MULT2=1.0
N       RCSG(J)=RCSGN(J)+SCLPRD(AGAWN(J,*),1,4,DRCSWG(*),1)                   5.267
T         RCSGN(*)=5/5/5/5                                                    5.268
R       RCSRWG.KL(J)=SCLPRD(AGAWR.JK(J,*),1,4,DRCSWG(*),1)                    5.269
T         DRCSWG(*)=.4/.3/.2/0                                                5.270
A       ERCSG.K(I,J)=RCSG.K(J)*RCSAGM(ATN.K(I,J))                             5.271

NOTE    RCSG    - AGGRESSOR AIRCRAFT RADAR CROSS SECTION (SQ.M.)
NOTE    MULT2   - RCS MULTIPLICATIVE FACTOR (DIM)
NOTE    RCSRWG  - AGGRESSOR RCS RATE OF CHANGE (SQ.M/SEC)
NOTE    RCSGN   - CLEAN AGGRESSOR AIRCRAFT RCS (SQ.M.)
NOTE    AGAWR   - AGGRESSOR AIRCRAFT WEAPONS (UNITS)
NOTE    DRSCWG  - DELTA RCS DUE TO AGGRESSOR AIRCRAFT WEAPONS CARRIAGE (SQ.M.)
NOTE    ERCSG   - EFFECTIVE AGGRESSOR AIRCRAFT RCS (SQ.M.)
NOTE    RCSAGM  - AGGRESSOR RCS ASPECT ANGLE MULTIPLIER (DIM.)
```

Note that each weapon contributes differently to the total value of RCS as one might expect from the different sizes of missiles carried and their location under the fuselage and wings. The rate of change in RCS is defined in Eq. 5.269 as the product of the weapons rate of change and the delta RCS per weapon. Finally, the azimuth variation of RCS is a function of aspect angle and is implemented in Eq. 5.271. ERCSG stands for each aggressor aircraft as "seen" by each CBF fighter forming an $M \times N$ matrix. The macro RCSAGM is used in this case to estimate a multiplicative factor representing the azimuth changes in RCS.

Infrared Detection: The computation of the probability of infrared detection is broken down into three main aircraft contributions. These are: 1) The engine parts, 2) the engine exhaust products (i.e., exhaust gases), and 3) the infrared (IR) contribution due to aerodynamic heating of the aircraft skin surfaces. These contributions are assumed to be additive in nature in order

to determine the total IR signature at any point in time. Also, the value of the IR signature is affected by azimuth angle variations and this is accounted for in the model. The following discussion is applicable to the probability of infrared detection of an aggressor aircraft although equally applicable for the CBF aircraft with the parameter names changed accordingly.

```
A       PDIRG.K(I,J)=IRDET(SNOISG.K(I,J))                                  5.272
A       SNOISG.K(I,J)=HTG.K(I,J)/NEI.K(I)                                  5.273
A         NEI.K(I)=NEIB(I)*NEINAM.K(I)                                     5.274
T         NEIB(*)=2E-10/2E-10/2E-10/2E-10                                  5.275
A         NEINAM.K(I)=TABHL(NEIMT(*),SUM(AGG.K),1,6,1)                     5.276
T           NEIMT(*)=1/.98/.95/.91/.88/.84                                 5.277
A         HTG.K(I,J)=JAG.K(I,J)*TAUG.K(I,J)/(RLOS.K(I,J)*100)**2           5.278
A           TAUG.K(I,J)=EXP(-ALPH(ALTG.K(J))*RLOS.K(I,J)/1000)             5.279
A           JAG.K(I,J)=JTOTEG.K(J)*AF(TAA.K(I,J))                          5.280

NOTE    AF      - MACRO CORRECTING TARGET RADIANCE FOR ASPECT ANGLE
NOTE    JAG     - INFRARED RADIANCE CORRECTED BY ASPECT ANGLE
NOTE    HTG     - IRRADIANCE (W/SQ. CM.)
NOTE    TAUG    - RATIO OF TRANSMITTED RADIANT FLUX
NOTE    NEI     - NOISE EQUIVALENT IRRADIANCE OF SENSOR (W/SQ.CM.)
NOTE    NEIB    - BASELINE NEI (W/SQ. CM.)
NOTE    NEINAM  - NEI VS. NUMBER OF AGGRESSORS MULTIPLIER (DIM)
```

The probability of infrared aggressor detection (PDIRG) is computed according to Eq. 5.272 which invokes macro IRDET containing the curve for single look probability of detection for a false alarm rate of 10^{-6} This curve considers a detector-noise limited sensor, a single target in the field of view, and a single pulse signal received within each observation interval [Young, 1986]. The only input required in macro IRDET is the signal-to-noise ratio (SNOISG) defined in Eq. 5.273 as the ratio of the target IR radiance at the sensor (HTG) and the noise equivalent IR radiance of the sensor (NEI). Note that HTG is defined as an $M \times N$ matrix since the IR radiance of each target will vary depending upon the target aspect, field of view, distance, throttle control, speed, etc. while NEI is a unique value for each particular sensor. HTG is evaluated as the product of the effective radiant intensity (JAG) and the atmospheric transmittance (TAUG) all divided by the square of the distance (RLOS) between the sensor and the target (Eq. 2.278). For the purpose of simplicity, the atmospheric transmittance coefficient (ALPH), is modeled as a linear function of altitude. Eq. 5.279 shows the atmospheric transmittance (TAUG) to decay exponentially with the product of the line of sight distance and ALPH. Finally, in this set of expressions the aggressor aircraft effective radiant intensity (JAG)

is computed in 5.280 as the product of the total aircraft radiant intensity (JTOTEG) and a correction factor, AF, that accounts for the variations in total radiant intensity with aspect angle. Here, it is assumed that it is possible to find a single multiplier that describes azimuth variations in the radiant intensity of engines, exhaust plume, and aerodynamic heating effects collectively. These three contributions are added to estimate the total effective radiance (JTOTEG) and designated JEFFG, JPEFFG, and JSEFFG, respectively (see Eq. 5.281).

```
A     JTOTEG.K(J)=JEFFG.K(J)+JPEFFG.K(J)+JSEFFG.K(J)                    5.281
A     JEFFG.K(J)=SPECTR(EGTG.K(J),MUHIG1,MULOW1)*JEG.K(J)               5.282
A     JEG.K(J)=EMM*SIG*EGTG.K(J)**4*AEG.K(J)/(4*PI)                     5.283
A       EGTG.K(J)=EGTGB(J)*TSEGTG.K(J)                                  5.284
T         EGTGB(*)=980/980/980/980                                      5.285
A       TSEGTG.K(J)=TABHL(TSEGGT(*),TSG.K(J),.5,1,.1)                   5.286
T         TSEGGT(*)=.6/.78/.86/.94/1/2                                  5.287
A       AEG.K(J)=AEGB(J)*TSAEMG.K(J)*NEG(J)                             5.288
T         AEGB(*)=6030/6030/6030/6030                                   5.289
A         TSAEMG.K(J)=TABHL(TSAEGT(*),TSG.K(J),.5,1,.1)                 5.290
T         TSAEGT(*)=.9/.94/.97/.99/1/.96                                5.291
T         NEG(*)=2/2/2/2                                                5.292

NOTE  JTOTEG  - TOTAL EFFECTIVE RADIANCE (W/SR)
NOTE  JEFFG   - EFFECTIVE ENGINE RADIANCE (W/SR)
NOTE  JEG     - ENGINE RADIANCE (W/SR)
NOTE  EMM     - EMISSITIVITY FACTOR (I.E. GRAY BODY=.9)
NOTE  EGTG    - ENGINE EXHAUST TEMPERATURE (DEGREES ABSOLUTE)
NOTE  EGTGB   - BASELINE EGT (DEGREES ABSOLUTE)
NOTE  TSEGTG  - THROTTLE SETTING EGT MULTIPLIER (DIM)
NOTE  AEG     - ENGINE EXHAUST AREA (SQ. CM.)
NOTE  AEGB    - BASELINE ENGINE EXHAUST AREA (SQ. CM)
NOTE  TSAEMG  - THROTTLE SETTING EXHAUST AREA MULTIPLIER (DIM)
NOTE  NEG     - NUMBER OF ENGINES (UNITS)
```

The computation of the IR signature of the engine "hot" parts is performed in Eqs. 5.282 through 5.292. JEFFG is evaluated with the use of macro SPECTR which in fact determines the relative IR radiance of a blackbody given the extreme points in the IR emission spectrum. Inputs to this macro are the aggressor aircraft engine exhaust temperature (EGT) and the upper and lower limits of the IR emissions spectrum (MUHIGH and MULOW). The radiant intensity (JEG) is a lumped parameter containing the radiant emissitivity (0.9 used for engine parts), EGT, the engine exhaust area (AEG), and the Stefan-Boltzmann constant (SIG). EGT is , in reality, a function of many parameters that cannot be explicitly modeled in this context. For the sake of simplicity it is assumed that EGT is only a function of throttle setting since this parameter controls fuel-air ratio and afterburning use which are two important factors dictating EGT. The assumed nonlinear dependence of EGT with throttle position is modeled

with the introduction of a multiplier denoted TSEGTG which corrects a baseline exhaust gas temperature (EGTBG) accordingly. A pictorial representation of this multiplier is shown in Fig. 5.32.

The baseline value for EGT has been assumed to be 980 degrees absolute which represent a typical exhaust temperature for modern combat aircraft engines (Eq. 5.285). Note that this baseline value corresponds to a throttle setting of 0.9 equivalent to maximum military power (MMP) as it will be shown later.

The engine exhaust area (AEG) is also a function of throttle setting to simulate changes occuring in the exhaust nozzle area at various flight regimes. Eq. 5.289 shows the DYNAMO expression for AEG where TSAEMG is the multiplier that corrects the engine exhaust area due to throttle setting changes and NEG is the number of engines per aggressor aircraft. A baseline area of 6030 square centimeters has been assumed in the nominal model and its variation with throttle setting can be seen pictorially in Fig. 5.33. Eq. 5.292 states the number of engines per aircraft.

The second contribution to the infrared signature is that of the engine exhaust plume (JPEFFG). The exhaust plume can be , in general, neglected for non-afterburning operation [Hudson, 1969]. However, it becomes increasingly important as afterburning conditions are present an thus it is necessary to incorporate some computational procedure to estimate the exhaust plume contribution in this model.

```
A       JPEFFG.K(J)=SPECTR(EGTG.K(J),MUHIG2,MULOW2)
X       *JPG.K(J)                                                    5.293
A       JPG.K(J)=.5*SIG*(0.85*EGTG.K(J))**4*APG.K(J)/(4*PI)          5.294
A         APG.K(J)=APGB(J)*TSAPMG.K(J)                               5.295
T           APGB(*)=2.54E4/2.54E4/2.54E4/2.54E4                      5.296
A           TSAPMG.K(J)=TABHL(TSAPGM(*),TSG.K(J),.5,1,.1)            5.297
T             TSAPGM(*)=.9/.94/.96/.98/1/25                          5.298
C         MUHIG2=4.55                                                5.299
C         MULOW2=4.30                                                5.300

NOTE    JPG      - PLUME RADIANCE (W/SR)
NOTE    JPEFFG   - EFFECTIVE PLUME RADIANCE (W/SR)
NOTE    APG      - EQUIVALENT EXHAUST TEMPERATURE SURFACE (SQ. CM)
NOTE    APGB     - BASELINE EXHAUST TEMP. SURFACE (SQ. CM)
NOTE    TSAPMG   - THROTTLE SETTING EXHAUST TEMP. SURFACE MULTIPLIER (DIM)
NOTE    MUHIG2   - UPPER LIMIT OF IR EMISSION BOUNDARY (MICRONS)
NOTE    MULOW2   - LOWER LIMIT OF IR EMISSION BOUNDARY (MICRONS)
```

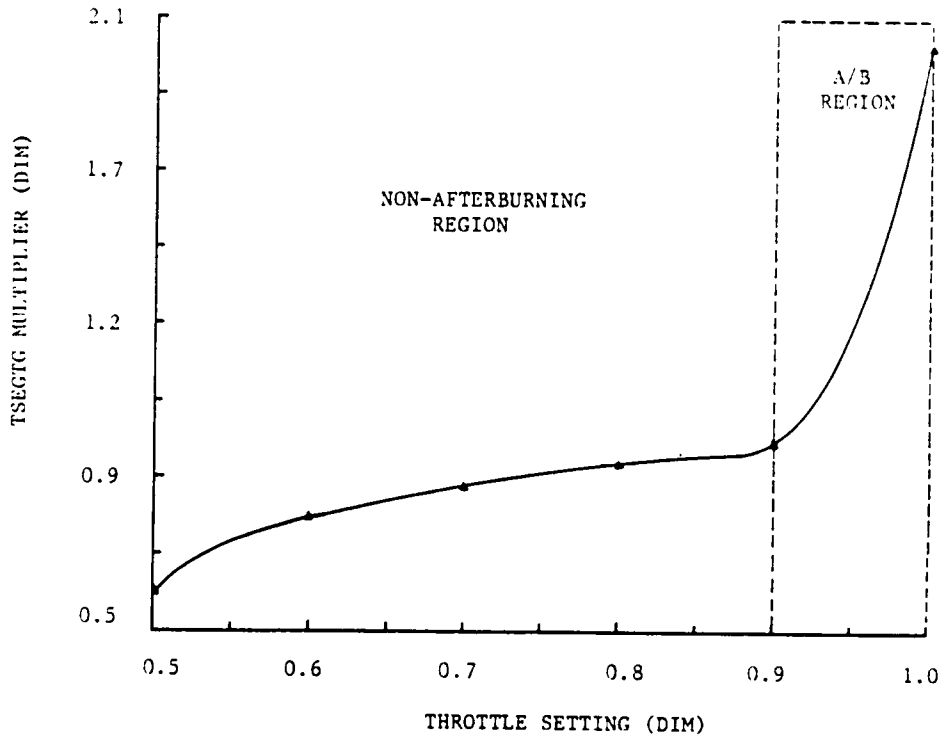


Figure 5.32 Throttle Setting versus EGT Multiplier.

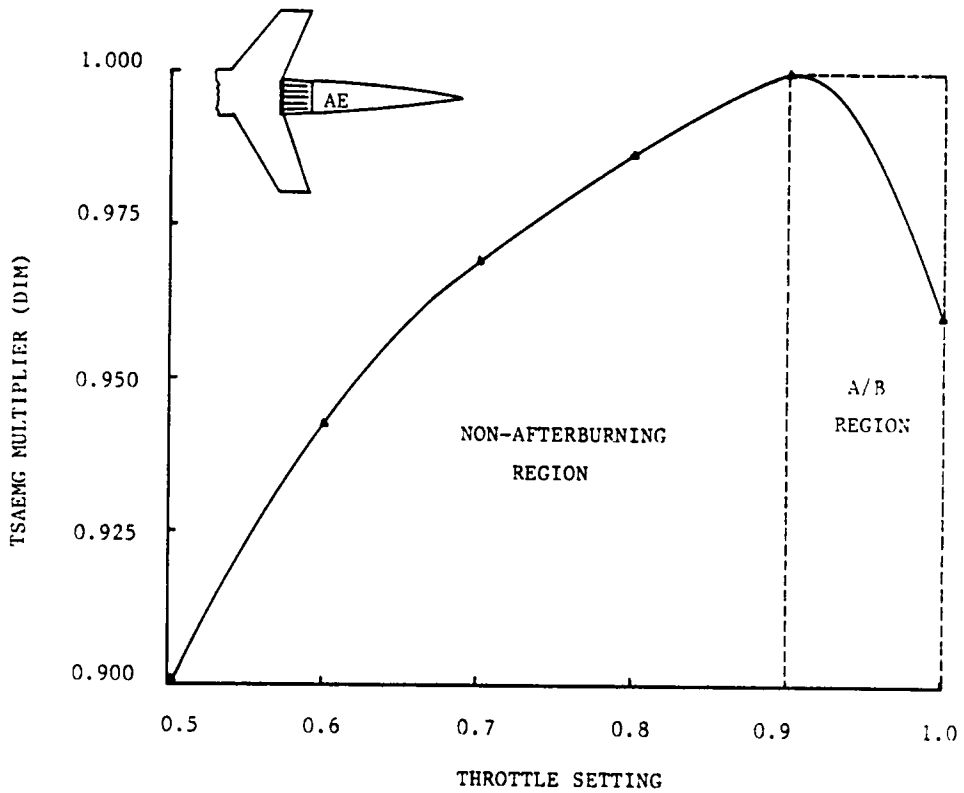


Figure 5.33 Engine Exhaust Nozzle Area Variation with Throttle Setting.

Macro SPECTR (see Section 5.2.3.5) is also used in the computation of the plume radiant intensity (JPEFFG). The input parameters are EGT and the two limiting values of the IR emission spectrum (MUHIG2 and MULOW2) as shown in Eq. 5.293. There are several simplifying assumptions made in this submodel to arrive at the expression for JPEFFG. First, since the principal products of incomplete combustion are carbon dioxide and water vapor it is assumed that the principal IR radiance band occurs between 4.3 μ and 4.55 μ corresponding to the values of MULOW2 and MUHIG2, respectively (Eqs. 5.299 and 5.300). The second simplification is necessary to estimate the exhaust plume temperature from the engine exhaust temperature (EGT). Assuming a perfectly adiabatic expansion taking place at the exhaust nozzle the temperature after the expansion (T_∞) can be found from the following simple expression,

$$T_\infty = T_{EG}\left(\frac{P_{EG}}{P_\infty}\right)^{\frac{\gamma-1}{\gamma}} \qquad 5.301$$

where, T_{EG} is the temperature of the exhaust gases before the expansion, P_{EG} is the pressure before the expansion, P_∞ the pressure after the expansion (ideally the atmospheric pressure), and γ the ratio of specific heats. A further assumption suggested by Hudson [1969] is that the pressure ratio of Eq. 5.301 is typically 0.5 for high subsonic speeds thus 3.301 reduces to,

$$T_\infty = 0.85\ EGT \qquad 5.302$$

which is the simplifying form used in this model.

Another exogenous input in this section constitutes the area of the plume (APG). The estimation of this parameter is not easy since it depends on many factors such flight speed, by-pass ratio, throttle setting, nozzle geometry, afterburning setting, etc. Since most of these parameters are not modeled explicitly, it is assumed that throttle setting (TSG) can be considered a good candidate for independent variable in the causal relationship between APG and TSG. Eqs. 5.295 through 5.298 depict the implementation of this assumptions in the model.

The last contribution to the infrared signature of an aircraft assumed in ASALT I is that due to the aerothermodynamic heating effects occurring on the aircraft's skin. Macro SPECTR is also used in this section to estimate the effective skin friction IR radiance as seen in Eq. 5.303. Input parameters are the stagnation skin temperature (TSTGG) and the upper and lower limits of the IR radiant spectrum (MUHIG1 and MULOW1). The skin friction IR radiance (JSG) is then computed in a similar fashion as that for the exhaust plume. The skin radiant emissitivity constant (EMM), the Stefan-Boltzmann constant (SIG), the equivalent reflective wetted area (ASG), and the skin stagnation temperature (TSTGG) are among the parameters needed to estimate JSG as seen in Eq. 5.304. A conservative estimate has been introduced in this equation by assuming that 25 percent of the total aircraft wetted area (ASG) approaches the stagnation temperature. Note the multiplicative factor to account for this in Eq. 5.304. The estimation of aircraft wetted area can be made for preliminary analysis in terms of aircraft takeoff weight according to Roskam [1985]. For low aspect ratio, slender fighter aircraft Roskam found this correlation to be of the form shown in Eq. 5.306. Notice the introduction of two constants in this equation, C and D, which stand for the regression coefficients obtained analytically from a data base comprised of 20 modern fighter aircraft. Although new technology manufacturing methods could change the actual values of this regression coefficients due to the extensive use of composite materials in future combat aircraft the user can easily modify these coefficients according to potential expectations without compromising the validity of the method.

```
A       JSEFFG.K(J)=SPECTR(TSTGG.K(J),MUHIG1,MULOW1)
X       *JSG.K(J)                                                          5.303
A         JSG.K(J)=EMM*SIG*(TSTGG.K(J)+273)**4*0.25*ASG.K(J)/(4*PI)        5.304
A           TSTGG.K(J)=TEMPG.K(J)*(1+R*(GAMA-1)*MACHG.K(J)**2/2)           5.305
N             ASG(J)=10**(C+LOGN(MAGN(J)**D)*(10000/10.7584)               5.306
C               C=-0.1289                                                  5.307
C               D=0.7506                                                   5.308

NOTE    JSEFF   - EFFECTIVE SKIN FRICTION RADIANCE (W/SR)
NOTE    JS      - SKIN FRICTION RADIANCE (W/SR)
NOTE    TSTAG   - STAGNATION TEMPERATURE (DEG ABSOLUTE)
NOTE    R       - FLOW RECOVERY FACTOR (.85 ASSUMED FOR MIXED FLOW)
NOTE    ASG     - AGGRESSOR AIRCRAFT SKIN WETTED AREA (SQ. CM.)
```

Eqs. 5.307 and 5.308 define the regression coefficients obtained in reference 31 and used in the nominal model. Notice the use of a multiplicative factor in Eq. 5.306 to convert aircraft wetted area from square feet to square centimeters used in all previous computations. Finally, the computation of the stagnation temperature is performed using the isentropic relationship between temperature and mach number shown in Eq. 5.305. Further details of all the equations used in this infrared submodel can be found in Appendix F of this document.

The previous discussion has been applied to the probability of infrared detection of an aggressor aircraft. Exactly the same scheme is used for the IR detection of CBF aircraft although different variable names have been adopted, accordingly. Appendix A contains the complete set of equations used for this purpose numbered with an "A" at the end to differentiate them from those related to the aggressor fleet.

Aircraft Weapons Launch: The probability of aircraft weapons launch (PATWL and PAGWL) is modeled as a function of four important factors shown in Eqs. 5.309 and 5.309A. For the CBF aircraft (Eq. 5.309) these factors are: 1) the probability that the target is within the firing envelope (PAGGFE), 2) the probability that the target aircraft is tracked (PAGTR), 3) the probability of pilot's confidence factor to launch (AMICF), and 4) the probability that the attacking aircraft is in the proper launching attitude (PCBFLA). Notice that Eq. 5.309A corresponds to the probability of weapons launch for the aggressor aircraft (PAGGWL) with similar parameters than those used for the CBF aircraft.

```
A     PATWL.K(I,J,K)=PAGGFE.K(I,J,K)*PAGTR.K(I,J)*AMICF.K(I,J,K)
X     PCBFLA.K(I)                                                    5.309
A     PAGWL.K(I,J,L)=PCBFFE.K(I,J,L)*PATTR.K(I,J)*GMICF.K(I,J,L)
X     PAGGLA.K(J)                                                    5.309A
A       PAGGFE.K(I,J,K)=BINARY(RLOS.K(I,J),MAAMLE.K(I,J,K))          5.310
A       PCBFFE.K(I,J,L)=BINARY(RLOS.K(I,J),MIGMLE.K(I,J,L))          5.310A

NOTE  PATWL  - PROB. CBF WEAPONS LAUNCH (DIM)
NOTE  PAGFE  - PROB. OF AGGRESSOR IN FIRING ENVELOPE OF WEAPON K
NOTE  PAGGFE - PROB. OF AGGRESOR (JTH ACFT) IN FIRING ENVELOPE OF ITH.
NOTE  PCBFFE - PROB. OF CBF (ITH ACFT) IN FIRING ENVELOPE OF JTH.
NOTE  PCBFT  - PROB. OF CBF IN LAUNCH ATTITUDE (DIM)
NOTE  PASTF  - PROB. OF CBF HAVING SUFFICIENT TIME TO FIRE (DIM)
NOTE  PAGWL  - PROB. OF AGGRESSOR WEAPONS LAUNCH (DIM)
NOTE  PATFE  - PROB. OF CBF IN FIRING ENVELOPE OF WEAPON L
NOTE  PAGAT  - PROB. OF AGGRESSOR IN LAUNCH ATTITUDE (DIM)
NOTE  PGSTF  - PROB. OF AGGRESSOR HAVING SUFFICIENT TIME TO FIRE (DIM)
```

The probability the target aircraft is within the weapons firing envelope is evaluated in Eqs. 5.310 and 5.310A for both the aggressor and the CBF aircraft, respectively. Macro BINARY is used to assign a unit value to the condition of the target inside the weapons kinematic envelope, zero otherwise. Inputs to this macro are range in line of sight from the attacker to the target aircraft (RLOS) and the maximum weapon kinematic flight envelope of the attacking aircraft designated CBFMLE and AGGMLE, respectively.

The probability of tracking (PAGTR for probability of aggressor tracking) is just a simple extension of the probability of detection, and in particular, radar detection. In order to simulate a loss in radar range capability associated with a track-while-scan radar mode (TWS) two assumptions are made: 1) TWS do not takes place until the cumulative probability of detection is above 0.9 and 2) TWS is constrained to azimuth limitations below pulse doppler search mode (nominal radar mode simulated in ASALT I). Eq. 5.311 illustrates the implementation of the probability of the *j* aggressor aircraft being tracked by the *ith* CBF aircraft. A similar implementation is done for the tracking of a CBF aircraft as seen in Eq. 5.311A in Appendix A.

```
A       PAGTR.K(I,J)=CLIP(PGRD.K(I,J),0,PGRD.K(I,J),.9)*
X       CLIP(1,0,TWSCBF(I)/2,ABS(ATN.K(I,J)))                    5.311
T       TWSCBF=60/60/60/60                                       5.112

NOTE    PAGTR   - PROBABILITY OF AGGRESSOR AIRCRAFT BEING TRACKED (DIM)
NOTE    PGRD    - PROBABILITY OF AGG DETECTION (DIM)
NOTE    TWSCBF  - CBF AIRCRAFT RADAR AZIMUTH COVERAGE IN TRACK-WHILE-SCAN
NOTE              MODE (DEGREES)
NOTE    ATN     - ASPECT ANGLE MEASURED FROM CBF TO AGG AIRCRAFT (DEGREES)
```

PAGTR is set for simplicity equal to the probability of aggressor aircraft detection (PGRD) for values of PGRD above the 0.9 threshold imposed in the first assumption of the previous paragraph. The second multiplicative term in 5.311 restricts the TWS radar mode azimuth coverage to 60 degrees (i.e., 30 on either side of the aircraft) as defined by TWSCBF in Eq. 5.312.

The third factor considered in the computation of PATWL is the subjective consideration denoted the probability of pilot's confidence factor to launch, AMICF. This parameter has been adopted from the missile intercept confidence factor (MICF) concept developed as part of the

MISVAL program [Scott, 1979 and Lutter, 1981] to provide aircrews with air-to-air weapons launch awareness capability against maneuvering targets. The purpose of MICF is to evaluate a single parameter presented to the pilot in an easy to interpret display format, that gives an indication of the goodness of his launch condition with respect to the target's position [Scott, 1979]. There are four information parameters needed to estimate the single valued AMICF as shown in Eq. 5.313. These are: 1) the LOS range between the attacker and the target (RLOS), 2) the weapon's maximum kinematic envelope (MAAMLE), 3) the weapon never escape envelope for a maneuvering target (ANEMLE), and 4) the minimum weapon launch envelope (MINMLE). These four parameters constitute inputs to macro MICF explained in Section 5.2.3.12 and used to estimate AMICF. It should be realized that in practice it might be difficult to estimate some of these parameters with great accuracy when "perfect" information about the target is not known. Thus some assumptions need to be made in order to estimate ANEMLE, MAAMLE, and MINMLE due to their dependance upon the particular states of the attacker and the target confronted.

```
A       AMICF.K(I,J,K)=MICF(RLOS.K(I,J),MAAMLE.K(I,J,K),ANEMLE.K(I,J,K)
X       ,MINMLE.K(I,J,K))                                                    5.313
A         MAAMLE.K(I,J,K)=MRBASE(K)*MRBSM(ATN.K(I,J))*MRASM.K(I)*MRALM.K(I)  5.314
T           MRBASE(*)=130000/47000/7500/2500                                 5.315
A           MRASM.K(I)=TABHL(MRASMT(*),MACH.K(I),0.6,1.6,.2)                 5.316
T           MRASMT(*)=.75/.84/1/1.16/1.25/1.3                                5.317
A           MRALM.K(I)=TABHL(MRALMT(*),ALT.K(I),0,18000,3000)                5.318
T           MRALMT(*)=.6/.72/.87/1/1.13/1.28/1.4                             5.319
A         MINMLE.K(I,J,K)=PMLEC(K)*MAAMLE.K(I,J,K)                           5.320
T           PMLEC(*)=.04/.05/.10/.20                                         5.321
A         ANEMLE.K(I,J,K)=NEMLEC.K(I)*MAAMLE.K(I,J,K)                        5.322
A           NEMLEC.K(I)=TABHL(NEMLCT(*),NCOM.K(I),0,8.0,1.0)                 5.323
T             NEMLCT(*)=0.5/.47/.44/.39/.37/.33/.28/.24/.20                  5.324

NOTE    MAAMLE  -  MAXIMUM AIR-TO-AIR KTH WEAPON RANGE FROM ITH TO JTH
NOTE               AIRCRAFT (METERS)
NOTE    MRBASE  -  BASELINE MAXIMUM MISSILE/GUN RANGE IN METERS (FRONTAL
NOTE               ATTACK)
NOTE    MRBSM   -  MISSILE/GUN RANGE VS. BORESIGHT ANGLE MULTIPLIER (DIM)
NOTE    MRALM   -  MISSILE/GUN RANGE VS. ALTITUDE MULTIPLIER (DIM)
NOTE    MRASM   -  MISSILE/GUN RANGE VS. AIRCRAFT SPEED MULTIPLIER (DIM)
NOTE    MINMLE  -  MINIMUM MISSILE/GUN LAUNCH ENVELOPE (M)
NOTE    ANEMLE  -  CBF WEAPONS NEVER SCAPE LAUNCH ENVELOPE (M)
NOTE    AMICF   -  CBF MISSILE INTERCEPT CONFIDENCE FACTOR (DIM)
NOTE    PMLEC   -  PERCENT MAAMLE ALLOCATED AS MINMLE (DIM)
NOTE    NEMLEM  -  NEVER EXCEED MLE MULTIPLIER (DIM)
```

The computation of MAAMLE is performed in Eq. 5.314. It can be seen that MAAMLE is the product of four parameters: MRBASE, MRSBSM, MRASM, and MRALM. MRBASE is defined

as the maximum weapon kinematic range provided that a nominal set of conditions is met. These conditions are a zero aspect angle from the target (frontal hemisphere launch) at a flight mach number of one and altitude of 9 km. above mean sea level. The three remaining parameters are used to correct this nominal maximum kinematic weapons range due to off-boresight launch (MRBSM), flight speed (MRASM, and flight altitude (MRALM) of the launching platform. The weapon's nominal maximum launch envelopes are defined in Eq. 5.315 for the long range, medium range, and short range air-to-air missiles as well as those for the cannon or gun. MRBSM standing for the missile range off-boresight multiplier makes use of the macro of the same name with a single input being the target aspect angle (ATN) as detailed in Section 5.2.3.11. The resulting planview of the air-to-air kinematic envelopes of the CBF aircraft are shown in Fig. 5.7 in Section 5.2.2.5 of this dissertation.

The second multiplier MRASM, missile range vs. aircraft speed multiplier, is used to simulate the typical weapon range degradation associated with low speed launches. The trend modeled in Eq. 5.317 is depicted graphically in Fig. 5.34. The third multiplier affecting MRBASE is the weapon range vs. altitude multiplier, MRALM. This multiplier tries to capture the degradation in weapon range typically observed in the lower troposphere. Eqs. 5.318 and 5.319 implement MRALM in the DYNAMO language and their result is seen graphically in Fig. 5.34. The net effect of these three multipliers can be better appreciated in in a three dimensional plot showing the general trends postulated in Eqs. 5.315 through 5.319. A series of weapon "stream tubes" are generated showing the most disadvantageous regions for missile launch occurring in the low speed, low altitude environment. Fig. 5.35 shows the influence of these three multipliers in the nominal weapon launch envelope.

Next in the sequence of input parameters for macro MICF is the definition of the never escape weapon envelopes (ANEMLE). This parameter represents one of the most difficult variables to quantify. Each engagement offers a unique geometry and aircraft energy characteristics that added to the particular air-to-air weapon aerodynamic performance and control limitations dictate the shape of the ANEMLE envelope. The introduction of higher speed on board computers seems to make it feasible to compare current engagement

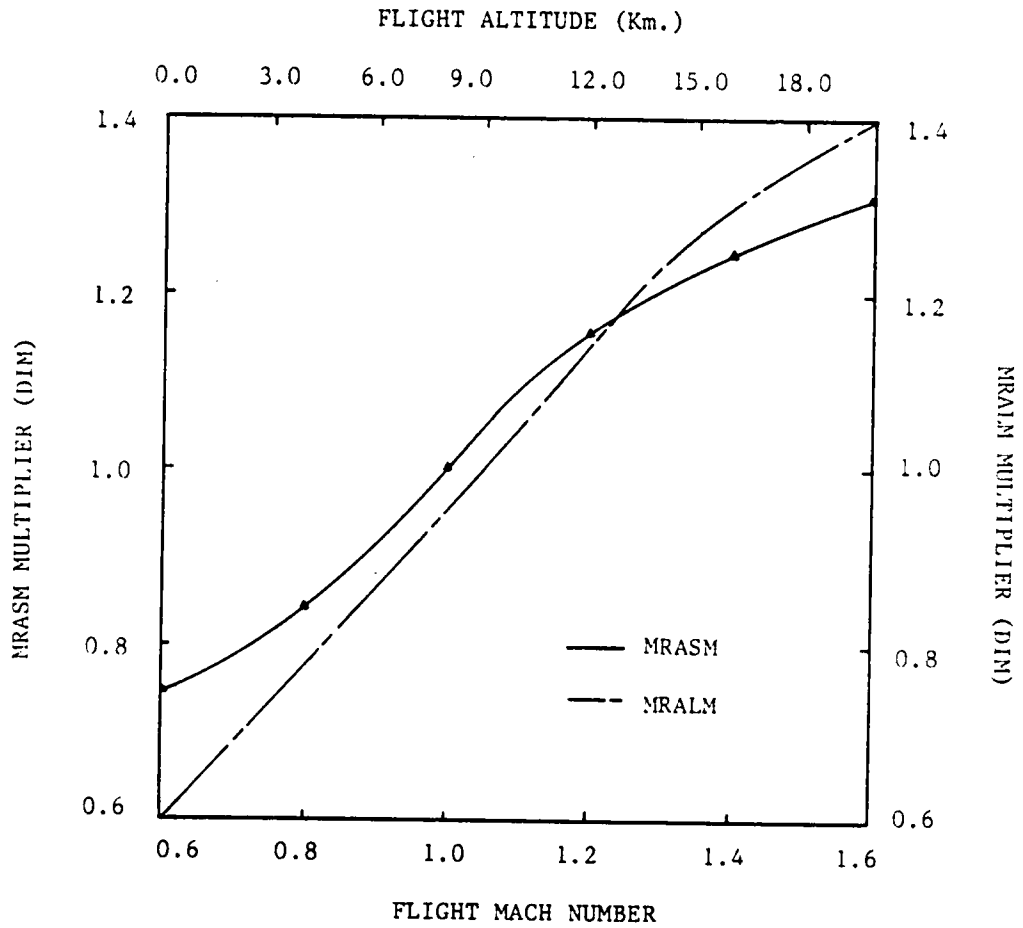


Figure 5.34 Weapon Range vs. Launch Speed and Altitude Multipliers

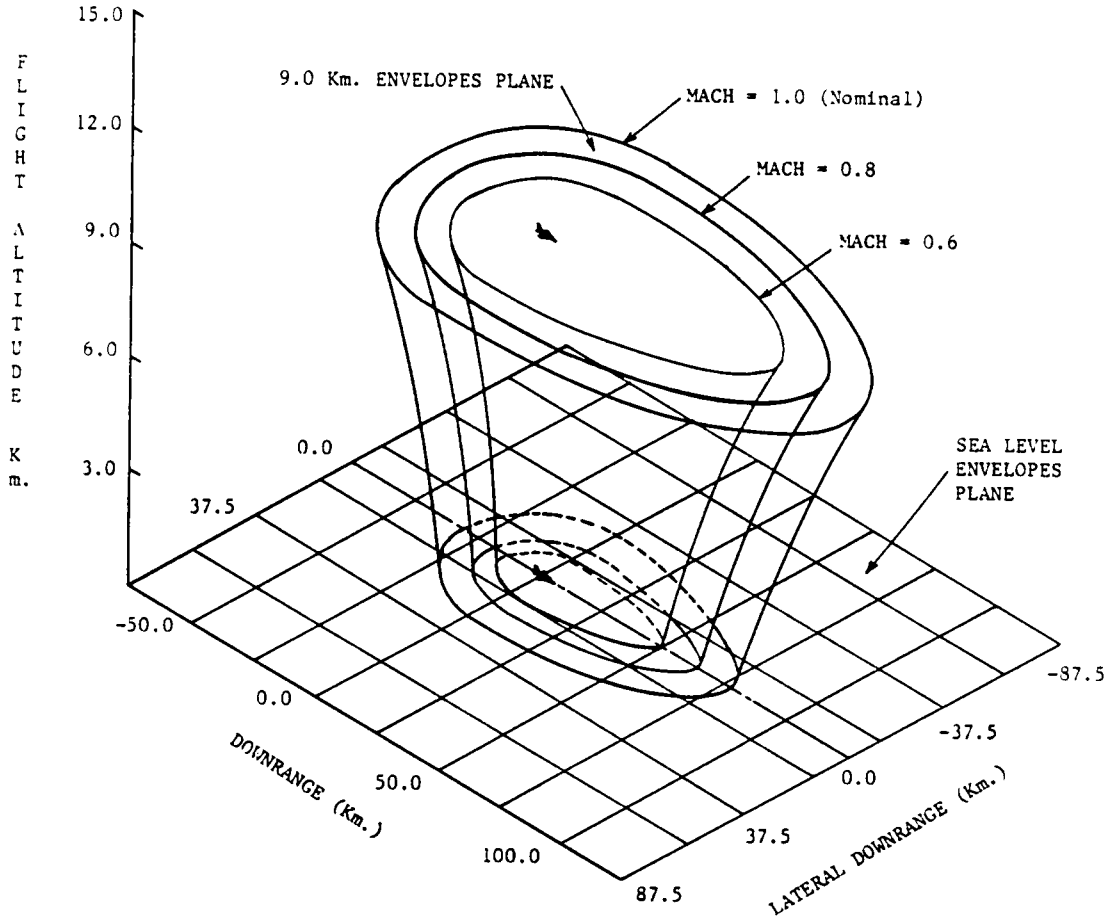


Figure 5.35 Three Dimensional Missile Range Representation.

geometries with pre-stored weapon launch envelopes function of the attacker load factor and the virtual target flight path as could be extracted from an advanced radar [Spick and Gunston, 1983]. For modeling purposes suppose that a series of pre-stored weapon never escape envelopes can be defined only in terms of the state of affairs of the attacker, particularly the commanded turn rate (NCOM) and the maximum weapon launch envelope (MAAMLE). This implies an imperfect information state of the game that can probably be realistically justifiable. Eq. 5.317 defines then ANEMLE as the product of MAAMLE and a multiplier denoted NEMLEM which is a function of NCOM as previously assumed. The trend of this multiplier is shown in Fig. 5.36

Another important parameter used in the computation of MICF is the minimum range weapon launch envelope, MINMLE. This variable is a function of the traditional aerodynamic and control parameters as well as the particular warhead fuzing capabilities [Shaw, 1986]. For simplicity in the modeling, MINMLE is assumed to be some fraction of the maximum weapon kinematic envelope (MAAMLE) as shown in Eq. 5.320. The factor PMLEC represents the percent of MAAMLE that defines the minimum weapon boundary (MINMLE) and as can be seen from Eq. 5.321 the assumed values range from 4% for the long range air-to-air weapons to 15% for the cannon. This later restriction on the cannon use at very short range ($<$ 300 mts.) is to simulate a dangerous region usually associated with potential ingestion of target debris.

Once the four factors necessary to estimate AMICF have been determined these are used as inputs in the macro MICF. MICF is used in this context as a measure of the pilot willingness to launch a weapon to a target if the four range information parameters previously described are estimated by an on-board computer and available to the crew as a single parameter. The information presented to the pilot as a single value is usually displayed as a circular trend indicator in a head-up display (HUD). As explained in Section 5.2.3.12 MICF takes values ranging from zero, when the target range in LOS (RLOS) coincides with the maximum weapon kinematic envelope (MAAMLE), to unity when RLOS is equal to the never escape weapons envelope (ANEMLE). This then is interpreted in ASALT I as the probability that a fighter pilot

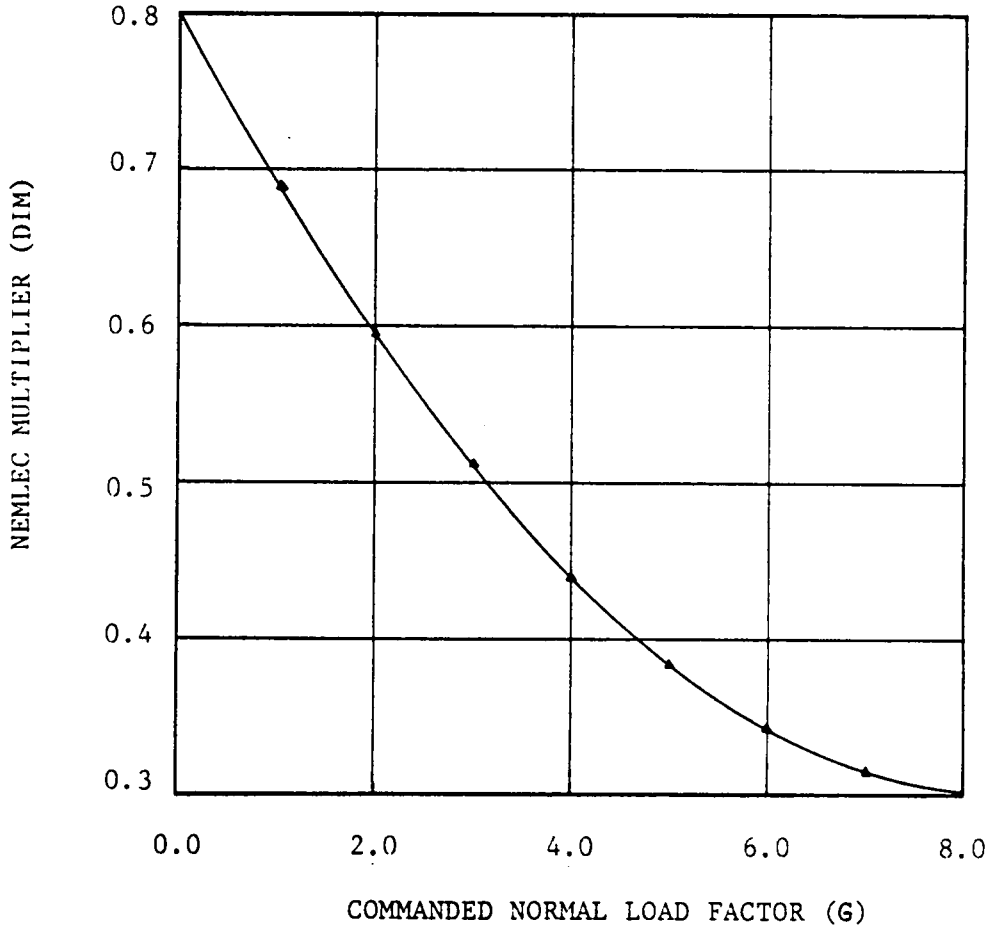


Figure 5.36 Never Escape Weapon Envelope vs. Commanded Load Factor Multiplier.

takes action to fire an air-to-air weapon. Eqs. 5.313A through 5.324A in Appendix A show the DYNAMO equations used in determining MICF for each aggressor aircraft (GMICF).

Returning to the expression to estimate the probability of weapons launch (PATWL) shown in Eq. 5.309, the last parameter needed in this sequence is the assessment of whether or not the aircraft is in a proper attitude to launch its air-to-air weapons. PCBFLA is the propability of the *ith* aircraft being in a proper launch attitude. This parameter is only necessary if there are some launch restrictions in the aircraft flight envelope which in practice limits the lethality of the aircraft. To exemplify this in the model it has been assumed that both aircraft are restricted to launch below load factors below six G's. Eqs. 3.325 and 5.325A define PCBFLA and PAGGLA in terms of the respective aircraft commanded load factors (NCOM and NCOMG) aircraft, respectively. The actual aircraft maneuvering launch limits are defined as MELAC and MELAG for the CBF and AGG aircraft, respectively and shown in Eqs. 5.326 and 5.326A.

```
A       PCBFLA.K(I)=CLIP(0,1,NCOM.K(I),MELAC(I))                    5.325
A       PAGGLA.K(J)=CLIP(0,1,NCOMG.K(I),MELAG(I))                   5.325A
T       MELAC(*)=6/6/6/6                                            5.326
T       MELAG(*)=6/6/6/6                                            5.327

NOTE    PCBFLA  - PROBABILITY OF CBF IN LAUNCH ATTITUDE (DIM)
NOTE    PAGGLA  - PROBABILITY OF AGG IN LAUNCH ATTITUDE (DIM)
NOTE    NCOM    - CBF AIRCRAFT COMMANDED LOAD FACTOR (G)
NOTE    NCOMG   - AGG AIRCRAFT COMMANDED LOAD FACTOR (G)
NOTE    MELAC   - CBF MAXIMUM LAUNCH ATTITUDE LOAD FACTOR (G)
NOTE    MELAG   - AGG MAXIMUM LAUNCH ATTITUDE LOAD FACTOR (G)
```

Air-to-Air Weapons:

The number of weapons on each aircraft constitutes an important state variable in this model and as such is represented as a level variable with a single rate variable. Using the CBF aircraft equations as example to describe this section computations define CBFW as the number of aircraft weapons at any point in time (Eq. 5.328) and CBFWR the rate of change of weapons with time. Eqs. 5.329 through 5.333 initializes the number of weapons carried by each CBF aircraft in terms of four table functions corresponding to each one of the different weapons carried. It is noted that the original weapons load comprises 4 long range air-to-air

missiles (LRAAM), two medium range air-to-air missiles (MRAAM), two short range air-to-air missiles (SRAAM) and a cannon with 1000 rounds of ammunition (Eq. 5.333). All missiles have "all-aspect" capability (i.e., they can be launched at high angles off the target) and are of the true "fire-and-forget" type (i.e., no assistance from the launching platform is needed once the weapon is released). The LRAAM and MRAAM are doppler radar guided while the SRAAM is assumed to be infrared guided.

```
L     CBFW.K(I,K)=CBFW.J(I,K)-(DT)(CBFWR.JK(I,K))                          5.328
N       CBFW(I,K)=CBFWN(*,K)                                               5.329
T       CBFWN(*,1)=4/4/4/4                                                 5.330
T       CBFWN(*,2)=2/2/2/2                                                 5.331
T       CBFWN(*,3)=2/2/2/2                                                 5.332
T       CBFWN(*,4)=1000/1000/1000/1000                                     5.333
T       CBFAWW(*)=450/160/90/.25                                           5.334

R     CBFWR.KL(I,K)=MIN(CBFWRA.K(I,K),AAWLR(I,K)*SUMV(PATWL.K(I,*,K),1,JJ
X       )/60)                                                            5.335
A       CBFWRA.K(I,K)=CLIP(0,CBFW.K(I,K)/DT,0,CBFW.K(I,K))               5.336
A       FCBFWR.K(I,K)=CBFW.K(I,K)/(CBFWN(I,K)+1E-6)                      5.337
T       AAWLR(*,1)=2/2/2/2                                               5.338
T       AAWLR(*,2)=2/2/2/2                                               5.339
T       AAWLR(*,3)=2/2/2/2                                               5.340
T       AAWLR(*,4)=4000/4000/4000/4000                                   5.341
A       AAAWL.K(I,J,K)=CBFWR.JK(I,K)*CBF.K(I)                            5.342

NOTE  CBFAWW  - CBF AIR WEAPONS WEIGHT (LBS/MISSILE)
NOTE  CBFW    - CBF AIR WEAPONS (MISSILE UNITS)
NOTE  CBFWR   - CBF AIR WEAPONS LAUNCHING RATE
NOTE  CBFWN   - INITIAL NUMBER OF CBF AIR WEAPONS (MISSILE UNITS)
NOTE  AAAWL   - CBF AIR-TO-AIR WARHEADS LAUNCHED
NOTE  FCBFWR  - CBF AIR-TO-AIR WEAPONS REMAINING
```

Table 5.2 summarizes the number of weapons carried by both, the CBF and aggressor aircraft. Eq. 5.334 defines the corresponding masses for each weapon carried and these values are also shown in table 5.2.

The computation of CBFWR is based on a conversion from a maximum weapons launch rate capability (AAWLR) to an actual number of weapons launched as firing opportunities arise through the combat. CBFWR is taken to be the minimum between the number of CBF weapons remaining and the product of of the maximum weapon launch rate (AAWLR) and the probability of weapons launch (PATWL) previously explained. Notice that the MIN function (see Section 3.2.3) is used only to avoid the driving of CBFW to negative values. Also note that a factor has been used to properly convert from the maximum weapons launch rate capability (in weapons/minute) to the actual weapons launched (weapons/second) once the probability

Table 5.2 Nominal Air-to-Air Weapons and Their Capabilities.

Aircraft	Weapon Type	Subscript Notation	Number of Weapons	Weapon Mass (kg.)	Maximum Range (km.)
CBF	LRAAM	K=1	4	450	130
	MRAAM	K=2	2	160	47
	SRAAM	K=3	2	90	7.5
	Cannon	K=4	1000	.25	2.5
AGG	LRAAM	L=1	4	500	67
	MRAAM	L=2	2	170	35
	SRAAM	L=3	2	110	6.5
	Cannon	L=4	1000	.25	2.5

of weapons launch has been estimated. Eq. 5.336 contains the expression to estimate the last burst of weapons to be delivered before their depletion. Eq. 5.337 computes the fraction of weapons remaining (FCBFWR) as the quotient of the number of weapons at any time (CBFW) and the initial number of weapons carried (CBFWN) defined in Eqs. 5.330 through 5.333. The maximum weapon launch rates are defined in Eqs. 5.338 through 5.341. Each table function is associated with a particular k weapon (i.e., for all i aircraft denoted by the asterisk in the array notation). Finally in this sequence, the number of weapons launched per side (AAAWL) is computed as the product of the weapons launch rate (CBFWR) and the number of CBF aircraft as shown in Eq. 5.342.

Weapons Successful Guidance: The probability of weapon successful guidance is a function of several factors: 1) the weapon and fire control system aiming errors, 2) the target avoidance capability, 3) the weapons lock-on and homing guidance capability, and 4) the target aircraft guidance countermeasures used. For the CBF aircraft these factors are designated CAIME, PGAC, PCLOH, and AGCM, respectively. The equations to be used in this section are replicated for the aggressor aircraft in Appendix A. Eq. 5.343 shows the expression to evaluate the probability of CBF aircraft weapon successful guidance (PCBWSG) as the product of the four variables previously mentioned.

```
A       PCBWSG.K(I,J,K)=(1-CAIME.K(I,J))*AGAC.K(I,J,K)*(1-AGCM.K(J,K))
```

```
X       *PCLOH.K(I,J,K)                                                    5.343
A        CAIME.K(J,K)=AIMEK(K)*(1-NCOMG.K(J)**Z)                           5.344
T          AIMEK(*)=-.08/-.08/-.08/-.085                                   5.345
C          Z=1.5                                                           5.346

NOTE    CAIME    - CBF AIRCRAFT WEAPON AIMING ERROR (DIM)
NOTE    AIMEK    - AIMING ERROR CONSTANT
NOTE    NCOMG    - AGGRESSOR COMMANDED LOAD FACTOR (G)
NOTE    Z        - AIMING ERROR GROWTH FACTOR CONSTANT
```

Aiming Error: The aiming error is assumed to be a function of the aircraft radar tracking capabilities and the maneuvering state of the aggressor. Information about this last contribution can be extracted from the aggressor aircraft commanded load factor (NCOMG). The point made here is that a highly maneuvering target aircraft will represent more challenge for the radar tracking and firing control systems that a non-maneuvering one. Eq. 5.344 depicts the expression used to evaluate CAIME as the product of a constant AIMEK and the aggressor aircraft commanded load factor raised to some power Z. In this case the following generalized expression is used,

$$CAIME = K\,(1 - NCOMG^{Z}) \qquad 5.347$$

where, Z and K are two constants associated with each particular weapon and NCOMG the load factor being pulled by the target. The idea to include constant Z (i.e., greater than unity) is to model greater discrepancies at high load factors as are normally expected. Eq. 5.345 defines the constant AIMEK for each one of the weapons carried by the CBF aircraft. It is noted that the aiming error for the cannon is greater than that of the air-to-air missiles as one might expect in the more unsteady environment where the cannon is used, typified by "jinking" maneuvers and turn reversals which seem to incorporate higher errors in the gun sights. Fig. 5.37 depicts graphically the trend of the aiming errors described.

Aircraft Avoidance Capability: The second multiplicative term in Eq. 5.343 involves the capability of the target (i.e., the aggressor aircraft in this particular case) to avoid an air-to-air weapon shot (AGAC). This avoidance capability in general will be a function of the target

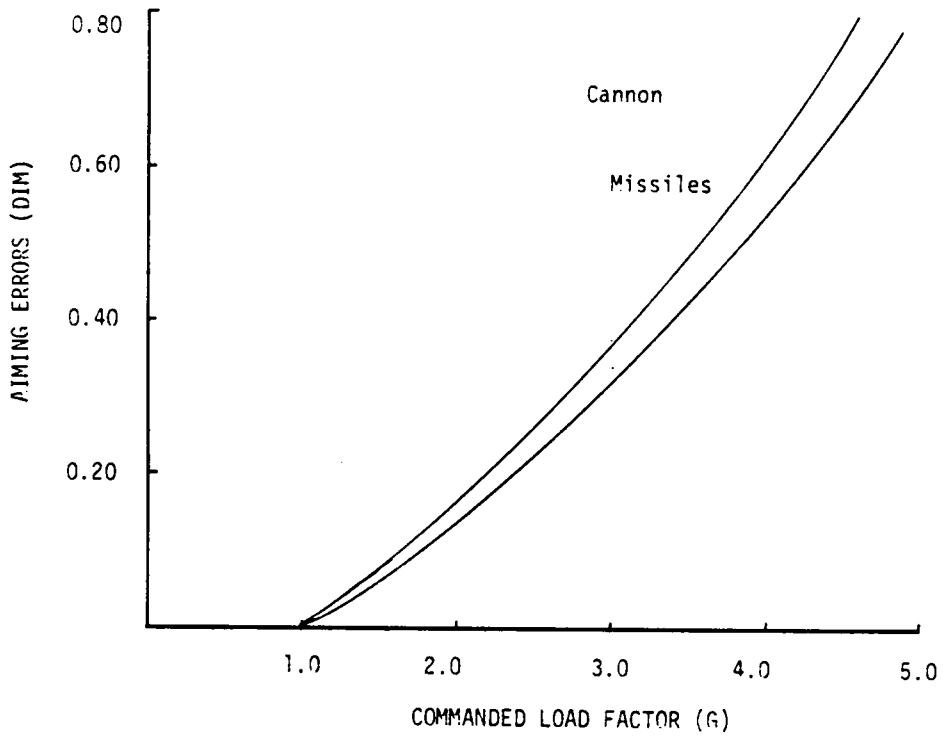


Figure 5.37 Aiming Errors for Air-to-Air Weapons

warning capability (AGWC) and the target maneuverability (AGMC) as shown in Eq. 5.348. The target aircraft maneuvering capability (AGMC) is modeled as a function of the sustained turning capabilities of the target aircraft and those of the weapon fired at it. Eq. 5.349 shows AGCM as a table function where the independent variable is the ratio of the maximum available turn rate of the aggressor (SAIG1M) and that of the oncoming missile (SAIWEA).

```
A       AGAC.K(I,J,K)=AGMC.K(J,K)*AGWC.K(I,J,K)                                    5.348
A         AGMC.K(J,K)=TABHL(AGMCT(*,K),SAIG1M.K(J)/SAIWEA(K),0,2,.2)               5.349
T           AGMCT(*,1)=1/.99/.97/.93/.86/.5/.22/.11/.06/.03/0                      5.350
T           AGMCT(*,2)=1/.99/.97/.93/.86/.5/.22/.11/.06/.03/0                      5.351
T           AGMCT(*,3)=1/.99/.97/.93/.86/.5/.22/.11/.06/.03/0                      5.352
T           AGMCT(*,4)=1/1/1/1/1/1/1/1/1/1/1                                       5.353
N           SAIWEA(K)=YAWRTE(ANMIS(K),AMAS(K))*57.29                               5.354
T             ANMIS(*)=30/25/25/100                                                5.355
T             AMAS(*)=1400/1300/1200/600                                           5.356

NOTE    AGAC    - AGGRESSOR AIRCRAFT AVOIDANCE CAPABILITY (DIM)
NOTE    AGMC    - AGGRESSOR AIRCRAFT MANEUVERING CAPABILITY (DIM)
NOTE    AGWC    - AGGRESSOR AIRCRAFT WARNING CAPABILITY (DIM)
NOTE    SAIG1M  - AGGRESSOR AIRCRAFT MAXIMUM SUSTAINED LOAD FACTOR (G)
NOTE    SAIWEA  - WEAPON MAXIMUM LOAD FACTOR (G)
NOTE    ANMIS   - MAXIMUM CBF WEAPON NORMAL LOAD FACTOR (G)
NOTE    AMAS    - AVERAGE CBF WEAPON SPEED (M/SEC.)
```

Eqs. 5.350 through 5.353 define an expected trend for this variable which ina more detailed analysis would incorporate factors arising from the end game scenario between the aircraft and the propagator. Candidates for this exogenous analysis could be the missile control time constant, gimbal limitations in the tracking and guidance systems, aerodynamic constraints, etc. The idea of AGCM is to estimate the probability that a missile outmaneuvers the target and thus estimates the probability of successful guidance. Fig. 5.38 depicts graphically the tabular values contained in Eqs. 5.349 through 5.353. Notice that a starting to point to infer the values chosen is to realize that when the sustained turn rates of the missile and target are equal (i.e., $\psi_s/\psi_m = 1$ the outcome of target intercept and missile miss are the same everything else being equal. A peculiar point observed from Fig. 5.38 is that AGMC for the cannon projectiles is deliberately defined as unity since this computational sequence only applies to guided weapons. Also notice that although the computation of SAIWEA is executed for the cannon (i.e., k=4) the statement in Eq. 5.354 has no physical meaning due to the unguided characteristics of the cannon projectiles. The computation of the missile maximum sustained turn rate (SAIWEA) is performed in Eq. 5.354. Macro YAWRTE is used for this

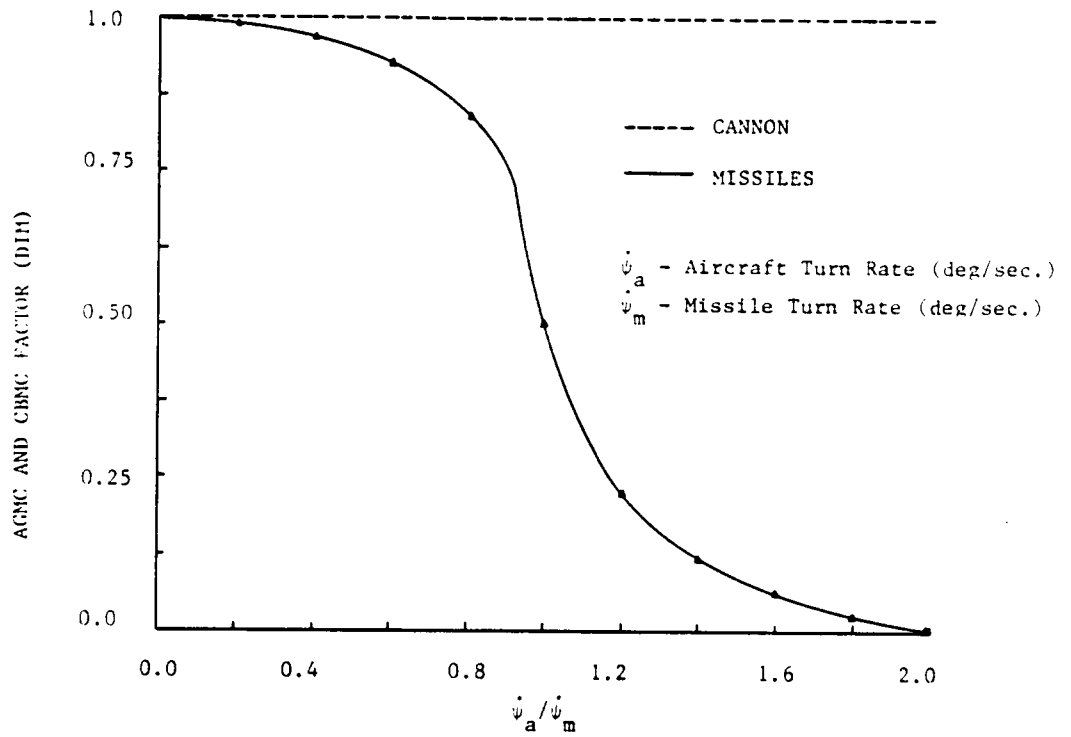


Figure 5.38 Aircraft Maneuvering Capability (AGMC and CBMC).

purpose and input requirements are the missile average speed (AMAS) and the maximum permissible missile normal load factor (ANMIS) defined in Eqs. 5.355 and 5.356, respectively.

The second factor to evaluate AGAC is the target aircraft warning capability (AGWC). This factor tries to estimate the degree of crew situational awareness of the target aircraft when a missile has been launched. The candidate factors to assess AGWC are the crew perception-identification-judgement-reaction time (AGIJRT), and the missile time of flight (MTOFA) to reach the target.

```
A       AGWC.K(I,J,K)=SAWE(MTOFA.K(I,J,K),AGIJRT(K))                    5.357
T         AGIJRT(*)=5/5/3/1.5                                           5.358

NOTE    AGWC    - AGGRESSOR AIRCRAFT WARNING CAPABILITY (DIM.)
NOTE    AGWCT   - TABLE CONTAINING NUMERICAL VALUES OF AGWC
NOTE    AGIJRT  - AGGRESSOR AIRCRAFT CREW PERCEPTION-IDENTIFICATION-
NOTE              REACTION TIME (SEC.)
```

AGWC is modeled in terms of the ratio of the missile time of flight and the perception reaction time (MTOFA/AGIJRT) which gives an indication of the physiological constraints of the target aircraft crew to perceive, the danger of a propagator fired to them and then react with an evasive maneuver. Eq. 5.357 shows the expression to estimate AGWC where macro SAWE is used. The inputs to this macro are the weapon time of flight (MTOFA) and the perception-reaction time (AGIJRT) which is defined in Eq. 5.358. Fig. 5.39 represents graphically the general trend of AGWC as a function of MTOFA and AGIJRT as computed by macro SAWE. Note that the reaction times assumed for the crew are not the same for all the weapons since the mechanisms to detect each weapon vary significantly. For example, the detection of an active missile in the beyond visual range (BVR) engagement phase should take longer to perceive an approaching missile than a passive launch where the aircraft are in close combat and within visual range of each other.

Aircraft Countermeasure Capability: The third factor arising in Eq. 5.343 to estimate PCBWSG is the aggressor countermeasure capability (AGCM). This variable is introduced to assess the effect of passive countermeasures in the successful guidance of an air-to-air missile. The

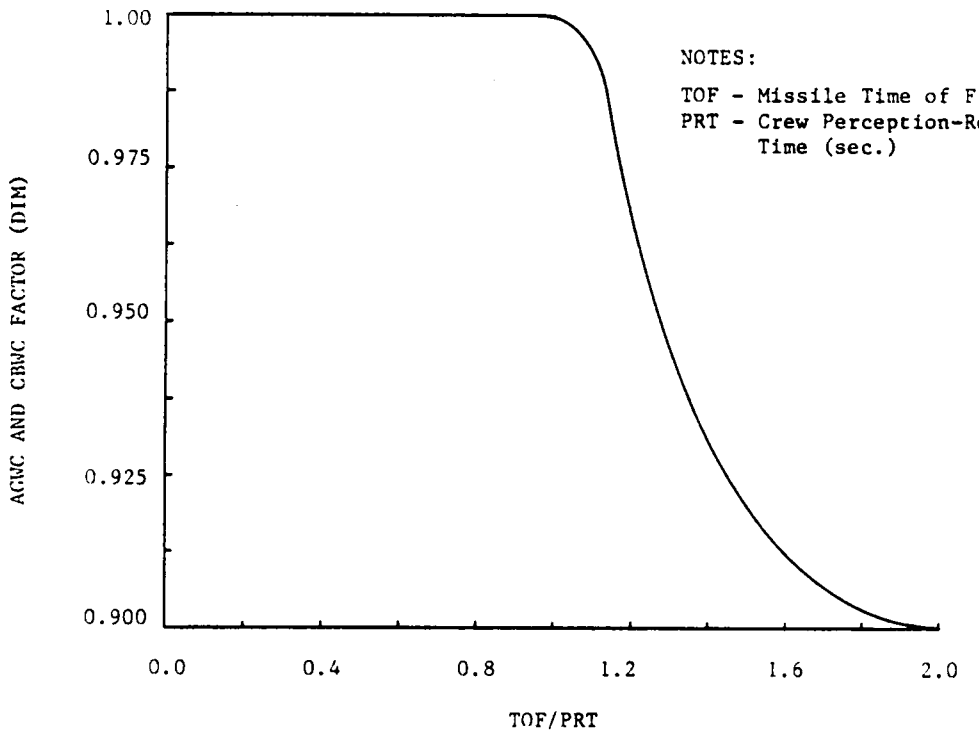


Figure 5.39 Target Aircraft Warning Capability (AGWC and CBWC).

effect of AGCM is to reduce the probability of successful guidance and the candidate variable to be considered here is the number of expendables launched, NEXLG. It is known that careful and timely employment of expendable cartridges such as infrared decoys and rapid bloom chaff (RBC) can have a significant leverage in the end game outcome between a missile and its target as has been demonstrated in recent air-to-air confrontations in Beirut (1982) and the Falklands Islands (1982) [Walter, 1983; Spick and Gunston, 1983; and Johnson, 1986]. Thus although the end game scenario between the missile and its target is not explicitly modeled it is necessary to incorporate a degradation factor in our model to account for the employment of passive countermeasures.

```
A       AGCM.K(J,K)=TABHL(AGCMT(*,K),NEXLG.K(J,K),0.0,4.0,0.5)                    5.359
T         AGCMT(*,1)=0/.02/.05/.07/.1/.13/.15/.16/.17                             5.360
T         AGCMT(*,2)=0/.02/.05/.07/.1/.13/.15/.16/.17                             5.361
T         AGCMT(*,3)=0/.018/.035/.045/.06/.075/.088/.095/.10                      5.362
T         AGCMT(*,4)=0/0/0/0/0/0/0/0/0                                            5.363

NOTE    AGCM    - AGGRESSOR AIRCRAFT COUNTERMEASURE CAPABILITY (DIM)
NOTE    AGCMT   - TABLE CONTAINING VALUES OF AGCM
NOTE    NEXLG   - AGGRESSOR AIRCRAFT EXPENDABLES LAUNCHED (CARTRIDGES/SEC.)
```

Eq. 5.359 defines AGCM in terms of the number of countermeasure cartridges launched (NEXLG). NEXLG as well as AGCM constitute two dimensional matrices containing array elements from the *j th* aircraft (i.e., aggressor) for each *k th* weapon (i.e., CBF air-to-air weapons) so that each aggressor aircraft reduces the probability of CBF weapon successful guidance by a certain amount AGCM when a number of passive expendable cartridges are employed (NEXLG). Eqs. 5.360 through 5.363 show the typical trend associated with this weapon guidance reduction capability (AGCM) for the various types of weapons employed in this model. Fig. 5.40 illustrates these trends graphically.

It is noted that rapid bloom chaff (RBC) cartridges achieve the highest reduction in the countermeasure capability variable (AGCM) of the two passive CM sources. The infrared curve shows a medium performance with up to 10% in AGCM reduction gains possible for up to four IR decoys launched simultaneously. Lastly the cannon is unaffected by passive countermeasures as modeled with a horizontal dotted line. Similar equations are developed for the estimation of the probability of successful guidance of aggressor weapons (Eqs. 5.343A

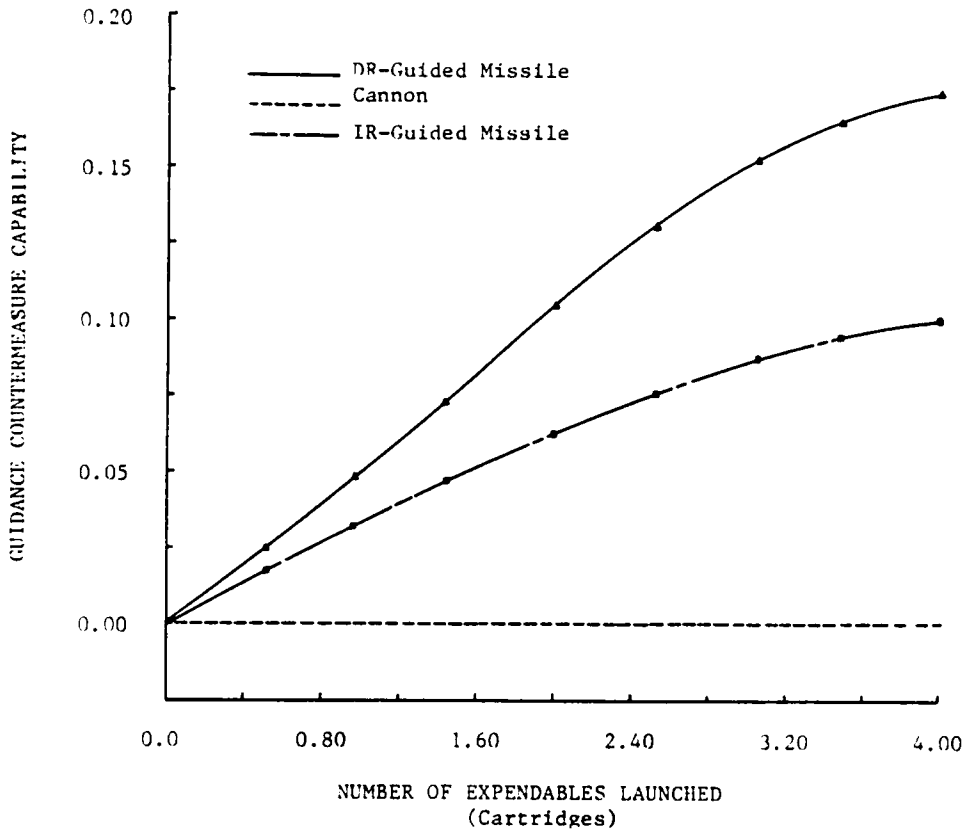


Figure 5.40 Aircraft Guidance Countermeasure Capability (AGCM and CBCM).

through 5.363A). Now we turn our attention to the number of expendables carried on each aircraft.

Aircraft Passive Countermeasures: Two types of passive countermeasures are modeled in ASALT I: infrared decoys and rapid bloom chaff (RBC) which are assumed to be carried internally and thus do not represent additional drag penalties to the "mother" aircraft. Eq. 5.364 expresses the number of expendable cartridges (NESPG) for the aggressor aircraft as a level variable with DEXPG as the only rate. DEXPG stands for the rate of change of expendables per second. Eqs. 5.365 through 5.369 define the number of expendables carried initially in terms of four table functions. A mixture of 100 RBC cartridges (50 allocated to long range missiles and 50 more to medium range missiles) and 100 IR decoys is assumed for the nominal model. Note that again, no allocation is done for the cannon since this item is not affected by passive countermeasures. Eq. 5.370 estimates the rate of change of expendables with time (DEXPG). This estimation is based on the assumption that an aircrew will make use of these expendable only under situations of imminent danger, for example, when the probability of launch of the opponent is very high. Due to the fact that ASALT I distributes activities throughout the simulation it is necessary to limit the use of expendables to very small simulation bands constrained by the high probability of launch by the attacker. In order to model this fact a second multiplicative term is added to the expression for DEXPG which activates the launch of expendables after a particular probability of weapons launch, PATWL, is exceeded (CBFET). The baseline value for CBFET in the model is assumed to be 0.9 as defined in Eq. 5.371. The first term in Eq. 5.370 computes the value of DEXPG based on a desired expendable launch rate (MNEXPG) and the probability of CBF weapons launch (PATWL). A MIN function is embedded in this expression to avoid driving NEXPG to negative values. Note that the last burst of expendables launched, before exhaustion, corresponds to the first term inside the MIN function.

L	NEXPG.K(J,K)=NEXPG.J(J,K)-(DT)(DEXPG.JK(J,K))	5.364
N	NEXPG(J,K)=NEXPGN(J,*)	5.365

```
T       NEXPGN(*,1)=50/50/50/50                                                    5.366
T       NEXPGN(*,2)=50/50/50/50                                                    5.367
T       NEXPGN(*,3)=100/100/100/100                                                5.368
T       NEXPGN(*,4)=0/0/0/0                                                        5.369
R      DEXPG.KL(J,K)=MIN(NEXPG.K(J,K)/DT,MNEXRG(J,K)*SUMV(PATWL.K(*,J,K)
X       ,1,II))*CLIP(0,1,CBFET,SUMV(PATWL.K(*,J,K),1,II)/II)                       5.370
C       CBFET=.9                                                                   5.371
T       MNEXRG(*,1)=.5/.5/.5/.5                                                    5.372
T       MNEXRG(*,2)=.5/.5/.5/.5                                                    5.373
T       MNEXRG(*,3)=.5/.5/.5/.5                                                    5.374
T       MNEXRG(*,4)=0/0/0/0                                                        5.375
L     GWEXP.K(J)=GWEXP.J(J)-(DT)(GWEXPR.JK(J))                                     5.376
N      GWEXP(J)=SCLPRD(NEXPGN(J,*),1,KK,UWEXPG(*),1)                               5.377
T        UWEXPG(*)=1/1/1/0                                                        5.378
R      GWEXPR.KL(J)=SCLPRD(DEXPG.JK(J,*),1,KK,UWEXPG(*),1)                         5.379
A     NEXLG.K(J,K)=DEXPG.JK(J,K)                                                   5.380

NOTE    NEXPC    - NUMBER OF CBF EXPENDABLES (CARTRIDGES)
NOTE    NEXPCN   - INITIAL NUMBER OF EXPENDABLES (CARTRIDGES)
NOTE    DEXPC    - RATE OF CHANGE OF EXPENDABLES (CARTRIDGES/SEC.)
NOTE    CWEXP    - CBF TOTAL EXPENDABLE MASS (KG.)
NOTE    UWEXPC   - CBF EXPENDABLE CARTRIDGE MASS (KG/CARTRIDGE)
NOTE    CWEXPR   - CBF EXPENDABLE MASS RATE OF CHANGE (KG./SEC)
NOTE    MNEXRC   - DESIRED EXPENDABLE LAUNCH RATE (CARTRIDGES PER SECOND)
NOTE    NEXLC    - NUMBER OF EXPENDABLES LAUNCHED PER SIMULATION INTERVAL
NOTE               (CARTRIDGES/DT)
```

The next set of table functions, Eqs. 5.372 through 5.375 define the desired expendable launch rate, MNEXRG, in cartridges per second. Note that Eq. 5.375 zeroes all values of MNEXRG for the cannon which as discussed before is not subjected to countermeasures. Eq. 5.376 computes the total mass due to expendables at any point in time for each aggressor aircraft (GWEXP). This parameter is also used accordingly in the computation of the aircraft mass. The initialization of GWEXP takes place in Eq. 5.377 with the computation of the scalar product (SCLPRD) of the initial number of expendables (NEXPGN) and the mass per expendable cartridge (UWEXPG). The total expendable mass rate of change, GWEXPR, is evaluated in 5.379 as the scalar product of NEXPG and UWEXPG. Finally, the number of countermeasure cartridges launched (NEXLG) for each aggressor against each CBF weapon during a simulation time interval is just the product of DEXPG and the simulation step size (DT). Changes in the expendable launch doctrine can be performed by varying the minimum launch threshold (CBFET) to any desired level.

Missile Lock-on and Homing Capability: The capability of an air-to-air missile to lock-on and home on its target (PCLOH) is dependent upon the the type of homing guidance used, as well as the relative geometry of the target with respect to the attacker. It has been said in Section

5.2.1 of this dissertation that the three types of air-to-air missiles modeled employ two types of homing guidance, that is active and passive. Since the missile trajectories are not explicitly modeled it is not possible to assess the control limitations associated with the navigation system of each weapon. It is however, possible to infer some trends for PCLOH in terms of the geometry of the engagement, namely the target aspect angle (ATN), which could well be derived from known seeker and aerodynamic limitations.

The approach taken to model PCLOH is the following. It is known that each weapon has a different probability of lock-on and home on a target. Thus a factor particular to each weapon (K) is introduced in the equation for PCLOH. Secondly, although the air-to-air missiles carried by both aggressors and CBF aircraft have all-aspect capability it can be argued that a reduction in the lock-on and homing capability is present for large off-boresight launches (e.g., beam quarter launches) due to kinematic considerations as well as the characteristic "look-up" requirements under this conditions [Shaw, 1986]. To account for this reduction in PCLOH a general expression is devised containing the weapon type and the target aspect angle at launch (ATN) as candidate independent variables.

```
A       PCLOH.K(I,J,K)=1-LOCK(K)*ABS(ATN.K(I,J)/57.29)                    5.381
T         LOCK(*)=6.87E-2/6.87E-2/1.43E-1/0                               5.382
NOTE
NOTE    PCLOH   - CBF WEAPON LOCK-ON AND HOMING CAPABILITY (DIM)
NOTE    LOCK    - CBF WEAPON LOCK-ON AND HOMING CONSTANT (DIM)
NOTE    ATN     - TARGET ASPECT ANGLE (DEG.)
```

The expression shown in in 5.381 contains a lock-on and homing constant (LOCK) particular to each weapon times the target aspect angle (ATN). This linear relationship can be easily adapted with some power affecting the ATN term if more penalization (i.e., lower values of PCLOH) are wanted at high angle-off launch conditions. The absolute value macro is used since ATN is bounded to negative values as well. The resulting trend of these equations can be seen in Fig. 5.41. Nominal values for the weapon lock-on constants are defined in Eq. 5.382. Note that it has been assumed that the IR-guided SRAAM missile have a more modest lock-on capability than of its doppler-radar guided counterparts due to a more constrained missile

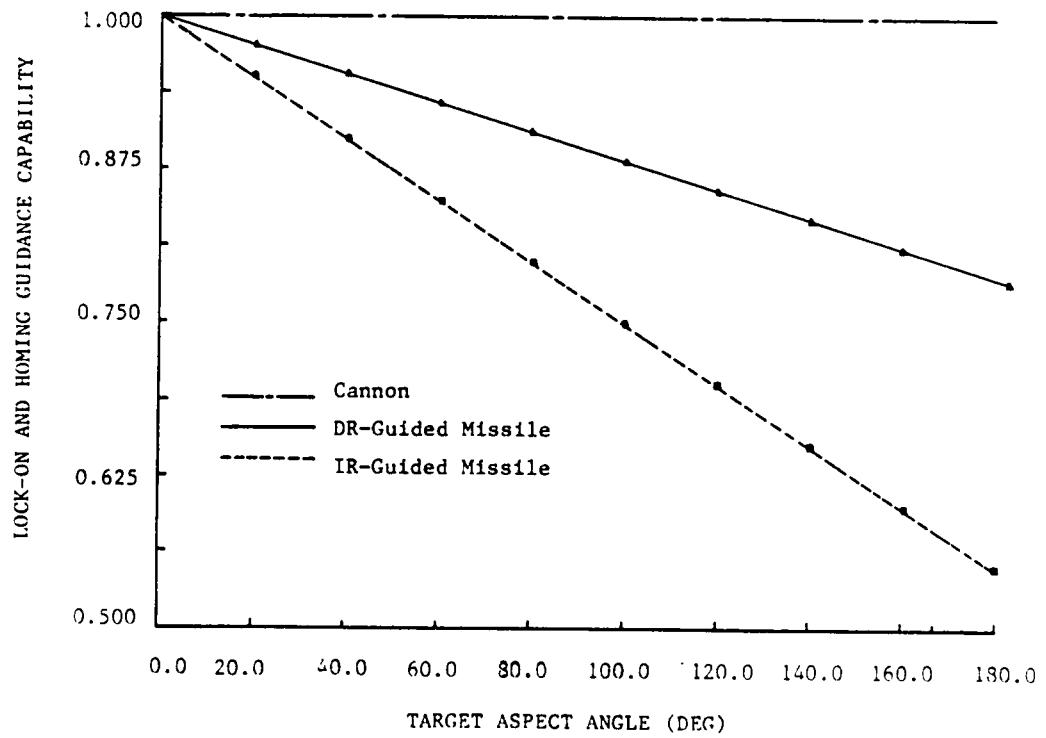


Figure 5.41 Weapon Lock-on and Homing Capability vs. Target Aspect Angle.

volume to mount sophisticated sensors. Also, the cannon projectiles are not subjected to this analysis and mathematically are assigned a value of unity for their respective PCLOH.

Weapons Detonation: Returning to the basic equation to estimate the probability of aircraft system effectiveness (3.221) in Section 5.2.5 of this dissertation it is seen that the last factor considered is the probability of weapons detonation, denoted PCBWDE and PAGWDE for the carrier-based and aggressor aircraft, respectively. The determination of the probability of weapons detonation is assumed to be a function of the particular weapon fuzing characteristics. Furthermore, the fuzing characteristics depend, to some degree, upon the geometry of the engagement particularly the end-game portion of it. The simplification made here is that PCBWDE (as well as PAGWDE) is a function of target aspect angle at launch (ATN) and some constant depending upon the weapon used and denoted KDET. The idea is very similar to that used for PCLOH in the previous section and the purpose is to model a degradation in the probability of weapons detonation due to fuzing problems associated with beam quarter intercept geometries where the warhead fragment spray cone generally travels away from a turning target thus reducing the lethality of the weapon [Shaw, 1986]. The general expression used here takes the following form,

$$P_{\text{det } ijk} = 1 - K_{\text{det } k}\ ATN_{ij}^{Z_{\text{det}}} \qquad 5.383$$

where, $P_{\text{det } ijk}$ is the probability of the *kth* weapon launched by the *ith* aircraft (CBF) detonating on a *j* aircraft (aggressor), $K_{\text{det } k}$ is the detonation constant associated with each *kth* weapon, ATN_{ij} is the target aspect angle from the *ith* to a *jth* aircraft, and Z_{det} is another constant that penalizes P_{det} for large values of ATN (for $Z_{\text{det}} > 0$) as it might occur in the real system.

```
A       PCBWDE.K(I,J,K)=1-KDETC(K)*(ATN.K(I,J)/57.29)*(ATN.K(I,J)/57.29)      5.384
T         KDETC(*)=1.52E-2/1.52E-2/2.53E-2/0                                  5.385

NOTE    PCBWDE  - PROBABILITY OF CBF WEAPON DETONATION (DIM)
NOTE    KDETC   - CBF WEAPON DETONATION CONSTANT (DIM)
NOTE    ATN     - TARGET ASPECT ANGLE MEASURED FROM CBF AIRCRAFT (DEG.)
NOTE    ZDET    - CBF WEAPON GROWTH FACTOR (DIM)
```

Eq. 5.384 replaces 5.383 in the DYNAMO language and the net effect of this function is seen in Fig. 5.42 for the constants defined in 5.385. Notice that Eq. 5.385 has been written assuming $Z_{det} = 2$ in an explicit way to avoid problems with the DYNAMO compiler when raising a number to a power (it uses a logarithmic conversion resulting in an error for ATN values of zero). As can be seen from Fig. 5.42 a lower probability of weapon detonation constant has been assumed for the IR-guided missile when compared with that of the radar-guided ones on the ground that the former one has less internal volume to accommodate the more sophisticated fuzing mechanisms that can be carried by the latter ones.

5.2.6 Application of Attrition Equations to ASALT I

This section deals in detail with the application of the attrition equations described in Section 5.2.4.1 to the ASALT I model. This discussion was purposely delayed to give the reader some familiarity not only with the language but also with the multitude of variables considered in the model and which now are "funneled" towards the ultimate goal to estimate parameters such as the probability of aircraft survival per sortie $P_{S/S}$ for both forces and the exchange ratio per sortie *ER* as described in Section 5.2.2.6. Also, the concept of single shot kill probability is described and its use in the computation of aircraft sortie survivability.

5.2.6.1 *Weapon Single Shot Kill Probability*

Each weapon carried by the combatants in this model has associated peculiar performance characteristics that up to now have been defined in terms of the probabilities to successful guidance and detonation with no regard at the intrinsic lethality characteristics of it. The lethality of a weapon, also referred as the weapon killing capability, is typically defined terms of the single shot kill probability P_{SSK} . This term assumes that guidance and detonation

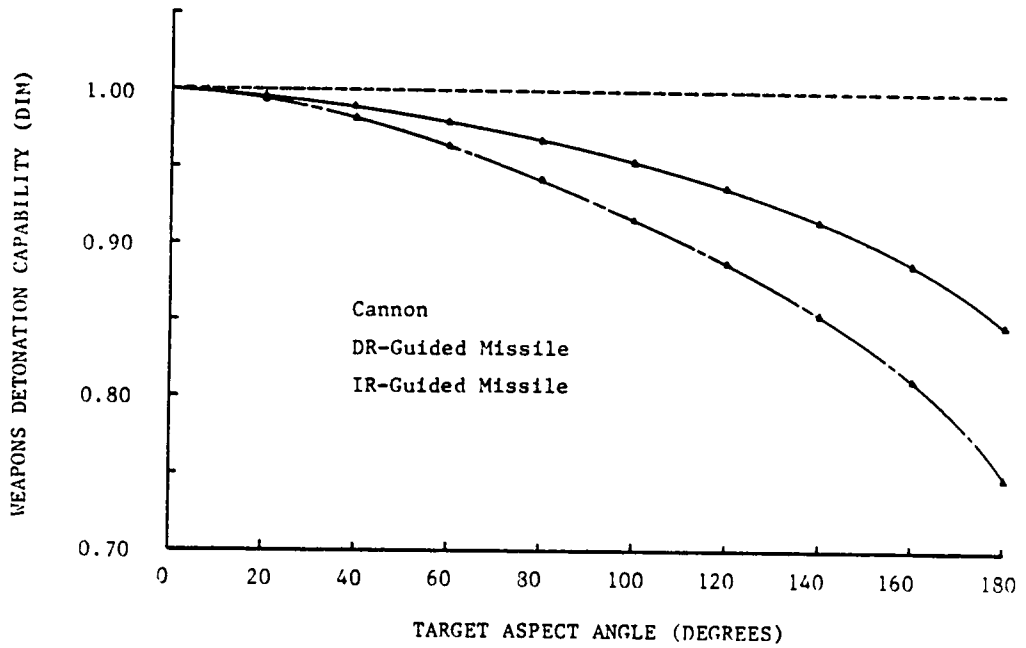


Figure 5.42 Weapons Detonation Capability vs. Target Angle.

of the weapon do occur and only estimates the terminal effects of the weapon upon the target. It is also generally aknowledged the fact that P_{SSK} is a function of the warhead size and the target vulnerability (i.e., ability to withstand a particular level of damage). The vulnerability assessment incorporates very detailed analysis of the aircraft systems (i.e., kill trees) as well as geometric considerations of the terminal effects of the weapon where many "aspects" or intercept geometries are analyzed to determine the target level of damage for a particular situation. A great deal of effort among the survivability community has been done in characterizing P_{SSK} for most of the known threats and hence it is not our intent to replicate efforts but rather to address the aircraft susceptibility issue in more detail. Also, ASALT I models the participant aircraft as point masses and it is possible to develop a very complex analysis to determine P_{SSK} .

```
A       PASSK.K(L)=PASSKB(L)                                          5.386
T         PASSKB(*)=0.2/.2/.1/.001                                    5.387
A       PGSSK.K(K)=PGSSKB(K)                                          5.386A
T         PGSSKB(*)=.2/.2/.1/.001                                     5.387A

NOTE    PALOS   - PROBABILITY OF LINE OF SIGHT (DIM)
NOTE    PASSK   - PROBABILITY OF SINGLE SHOT KILL OF CBF (DIM)
NOTE    PGSSK   - PROBABILITY OF SINGLE SHOT KILL OF AGGRESSOR (DIM)
```

The probabilities of single shot kill are defined in Eqs. 5.386 and 3.386A for the CBF and aggressor aircraft, respectively. Their numerical values are shown in 5.387 and 5.397A in table function form where the first value is associated with the long range weapon (LRAAM), the second one with the medium range missile (MRAAM), the third with the short range missile (SRAAM), and the fourth with the cannon projectiles.

5.2.6.2 *Computation of Attrition Coefficients*

In Section 5.2.4.1 the attrition equations were first introduced in their differential form and mention was made about the aircraft effectiveness parameters terms which sometimes are

also referred as attrition coefficients. The same set of equations are shown below for their careful analysis.

$$\frac{dCBF(t)}{dt} = -AGG(t)_{se}\,AGG(t) \qquad 5.120$$

$$\frac{dAGG(t)}{dt} = -CBF(t)_{se}\,CBF(t) \qquad 5.121$$

where, CBF(t) and AGG(t) represent the number of friendly and aggressor aircraft at time t, CBF_{se} and AGG_{se} are aircraft system effectiveness parameters (attrition coefficients) for friendly and aggressor forces, respectively. These time dependent coefficients are in part the purpose of why we have to rely in simulation since it is not possible to estimate them in a simple analytical form. A very naive way of interpreting these coefficients is to associate them with the probabilities of kill of the aircraft in the two forces at any time t. Taking the particular case of the M force (i.e., carrier-based aircraft) this reduces to say that the attrition rate of M aircraft at time *t* is just the product of the probability of M aircraft being killed and the number of surviving aircraft at time *t*. The probability of an aircraft kill in an encounter is one minus the probability of the same aircraft surviving the encounter expressed mathematically as follows,

$$P_{K/E} = P_{ASE} - P_{ASE}(1 - P_{SSK})^n \qquad 5.388$$

where, $P_{K/E}$ is the probability of kill per encounter, P_{ASE} the probability of aircraft system effectiveness, P_{SSK} the probability of weapon single shot kill, and *n* is the number of shots fired at the target. From Section 4.0 the probability of aircraft systems effectiveness was found to be,

$$P_{ASE} = P_{LOS}\,P_D\,P_{WL}\,P_G\,P_{DE} \qquad 5.221$$

where, P_{LOS} is the probability of line of sight (LOS), P_D the probability of detection-identification given LOS, P_{WL} the probability of weapons launch given detection, P_G the probability of

successful guidance given weapons launch, and the probability of successful guidance, and P_{DE} the probability of detonation given that successful guidance has taken place. Substituting Eq. 5.221 into 5.388 yields,

$$P_{K/E} = P_{LOS}\, P_D\, P_{WL}\, P_G\, P_{DE}\, \{1-(1-P_{SSK})^n\} \qquad 5.389$$

which is in turn the form wanted to replace the attrition coefficients shown in Eqs. 5.118 and 5.119. Let PKCBF and PKAGG be the probabilities of kill for CBF and aggressor aircraft, respectively. Using 5.389 and the previous model nomenclature for the probabilities of aircraft system effectiveness described in Section 5.2.5 it is possible to write the expressions for the attrition coefficients for the friendly and aggressor aircraft in DYNAMO as shown in Eqs. 5.390 and 5.390A.

```
A       PKAGG.K(I,J,K)=PCBFE.K(I,J,K)-PCBFE.K(I,J,K)*(1-PGSSK.K(K))**
X        AAAWL.K(I,J,K)                                                  5.390
A       PKCBF.K(I,J,L)=PAGGE.K(I,J,L)-PAGGE.K(I,J,L)*(1-PASSK.K(L))**
X        GAAWL.K(I,J,L)                                                  5.390A

NOTE    PSCBF   - PROBABILITY OF CBF SURVIVAL PER ENCOUNTER (DIM)
NOTE    PSAGG   - AGGRESSOR PROBABILITY OF SURVIVAL PER ENCOUNTER (DIM)
NOTE    PCBFE   - PROBABILITY OF CBF EFFECTIVENESS (DIM)
NOTE    PAGGE   - PROBABILITY OF AGGRESSOR EFFECTIVENESS (DIM)
NOTE    PASSK   - CBF WEAPON SINGLE SHOT KILL PROBABILITY (DIM)
NOTE    PGSSK   - AGGRESSOR WEAPON SINGLE SHOT KILL PROBABILITY (DIM)
NOTE    AAAWL   - CBF AIR-TO-AIR WEAPONS LAUNCHED (UNITS)
NOTE    GAAWL   - AGGRESSOR AIRCRAFT AIR-TO-AIR WEAPONS LAUNCHED (UNITS)
```

The fact that PKAGG and PKCBF are three dimensional arrays is to account for kills of opportunity that might occur at certain phases of the air engagement where an *i th* aircraft (CBF) engages *j* targets (aggressor aircraft) with *k* number of weapons each one representing an array dimension as explained in Section 5.2.4.2. Once the probabilities of aircraft kill have been found on both forces it is possible to substitute results of 5.390 and 5.390A into Eqs. 3.118 and 5.119 in order to find the attrition rates for the two opposing forces as shown in Eqs. 5.391 and 5.391A.

```
A       CBFKR.K(I,L)=CLIP(CBF.K(I)/DT,SUM(CBFKR3.KL(I,*,L))
X        ,SUM(CBFKR3.KL(I,*,L))*DT,CBF.K(I))*CLIP(1,0,SUM(CBFKR3.KL(I,*,L))
X        ,0)                                                            5.391
R       CBFKR3.KL(I,J,L)=DELAY3(PKCBF.K(I,J,L)*CBF.K(I),CBFDEL.K(I,J,L)) 5.392
A        CBFDEL.K(I,J,L)=MAX(MTOFG.K(I,J,L),5*DT)                       5.393
```

```
A       MTOFG.K(I,J,L)=TFLY(RLOS.K(I,J),GMAS(L),V.K(I),ATN.K(I,J))                    5.394
A     AGGKR.K(J,K)=CLIP(AGG.K(J)/DT,SUM(AGGKR3.KL(*,J,K))
X      ,SUM(AGGKR3.KL(*,J,K))*DT,AGG.K(J))*CLIP(1,0,SUM(AGGKR3.KL(*,J,K))
X      ,0)                                                                          5.391A
R     AGGKR3.KL(I,J,K)=DELAY3(PKAGG.K(I,J,K)*AGG.K(J),AGGDEL.K(I,J,K))             5.392A
A      AGGDEL.K(I,J,K)=MAX(MTOFA.K(I,J,K),5*DT)                                     5.393A
A       MTOFA.K(I,J,K)=TFLY(RLOS.K(I,J),AMAS(K),VAG.K(J),TAA.K(I,J))                5.394A

NOTE    AGGKR   - AGGRESSOR AIRCRAFT KILL RATE (AIRCRAFT/UNIT TIME)
NOTE    CBFKR   - CBF KILL RATE (AIRCRAFT/UNIT TIME)
NOTE    AGGKR3  - DELAYED AGGRESSOR AIRCRAFT KILL RATE (AIRCRAFT/UNIT TIME)
NOTE    CBFKR3  - DELAYED CBF KILL RATE (AIRCRAFT/UNIT TIME)
```

CBFKR and AGGKR represent the CBF and aggressor aircraft kill rates where the lethality of all the opposing aircraft has been aggregated so that a two dimensional structure is achieved for AGGKR and CBFKR from the initial three dimensional array structure used to define the lethality functions of the enemy aircraft (i.e., P_{ASE}). Eqs. 5.392 and 5.392A represent also the CBF and aggressor kill rates with a three dimensional structure (i.e., three dimensional arrays) which are subjected to some time delays, CBFDEL and AGGDEL, to account for the weapon time of flight to reach its target. CBFDEL and AGGDEL are defined in Eqs. 5.393 and 5.393A as the maximum value between the approximated weapon time of flight (MTOFA and MTOFG) and five times the simulation interval (DT) to avoid some language inaccuracies for small values of the time delay constants (see reference 35 for more information). Note that CBFKR3 and AGGKR3 have been defined as rate variables while CBFKR and AGGKR are auxiliary variables to be computed in the same simulation interval as the former ones. The weapons time of flight are computed in Eqs. 5.394 and 3.394A where MTOFA is the time of flight associated with the CBF aircraft weapons and MTOFG is that of the aggressor weapons. The reader must keep in mind that the array dimensional reduction performed in the previous set of equations is necessary because the lethality functions of an attacker aircraft (i.e., defined in three dimensional arrays) need to be "funneled" towards each target represented by a one dimensional array. In DYNAMO there are two possible ways to accomplish this array reduction using SCLPRD function or SUM/SUMV functions (Section 3.2.3.6). In this case the latter case is the alternative since we are trying to aggregate the results contained in larger arrays into dimensionaly simpler expressions.

Once the aircraft kill rates have been reduced to a two dimensional structure as shown in Eqs. 5.391 and 5.391A it is now possible to reduce and incorporate them into one dimensional level equations that estimate the number of surviving aircraft. Using nomenclature of Eqs. 5.118 and 5.119 define CBF and AGG as the surviving aircraft for the carrier battle group and the aggressor force, respectively, as shown in Eqs. 5.395 and 5.395.

```
L    CBF.K(I)=CBF.J(I)-(DT)(SUM(CBFKR.JK(I,*)))                    5.395
N     CBF(I)=CBFI(I)                                               5.396
T     CBFI(*)=1/1/1/1                                              5.397
L    AGG.K(J)=AGG.J(J)-(DT)(SUM(AGGKR.JK(J,*)))                    5.395A
N     AGG(J)=AGGI(J)                                               5.396A
T     AGGI(*)=1/1/1/1                                              5.397A

NOTE CBF    - NUMBER OF ADVANCED TACTICAL FIGHTERS (AIRCRAFT)
NOTE CBFI   - INITIAL NUMBER OF CBF (AIRCRAFT)
NOTE AGG    - NUMBER OF AGGRESSOR AIRCRAFT (AIRCRAFT)
NOTE AGGI   - INITIAL NUMBER OF AGGRESSOR AIRCRAFT (AIRCRAFT)
NOTE PSCBF  - PROBABILITY OF SURVIVAL OF CBF (DIM) AGAINST L WEAPONS
```

Note that in Eqs. 5.395 and 5.395A the two dimensional aircraft attrition rates are further reduced dimensionally by aggregating the attritions of all weapons employed against each target. This way the net effect of all weapons aimed to a target from many "shooters" is estimated. Eqs. 5.396 and 5.397 initialize the number of CBF aircraft as unit entities which are degraded accordingly to the attrition rates experienced during the simulation using the "co-kill" scheme explained in Section 4.2. Eqs. 5.396A through 5.397A accomplish the same objective for the aggressor aircraft force. Note that for the case shown a four versus four engagement is assumed.

Also in this section, it might be interesting to obtain statistics about the air engagement that could be used as indicators of the combined performance of the combatants. The exchange ratio (ERATIO) can be defined as the quotient of the fraction of the CBF force lost and and that of the aggressor force lost as shown in Eq. 5.398. The fractions of the force lost per side are computed using the average number of aircraft remaining in each one of the two forces computed in Eqs. 5.399 and 5.400.

```
S    ERATIO.K=(1-AVCBF.K)/(1-AVAGG.K+1E-6)                         5.398
S    AVCBF.K=SUM(CBF.K)/SUM(CBFI)                                  5.399
S    AVAGG.K=SUM(AGG.K)/SUM(AGGI)                                  5.400
```

```
NOTE    ERATIO  - EXCHANGE RATIO (DIM)
NOTE    AVCBF   - AVERAGE NUMBER OF AIRCRAFT IN CBF FORCE (AIRCRAFT)
NOTE    AVAGG   - AVERAGE NUMBER OF AIRCRAFT IN AGG FORCE (AIRCRAFT)
NOTE    CBF     - NUMBER OF CBF AIRCRAFT AT ANY TIME (AIRCRAFT)
NOTE    AGG     - NUMBER OF AIRCRAFT IN AGG AT ANY TIME (AIRCRAFT)
NOTE    CBFI    - INITIAL NUMBER OF CBF AIRCRAFT (AIRCRAFT)
NOTE    AGGI    - INITIAL NUMBER OF AGG AIRCRAFT (AIRCRAFT)
```

5.2.7 Aircraft Characteristics and Performance

This section deals with the modeling of the relevant aircraft characteristics considered in order to accurately represent the dynamic behavior of the air vehicles engaged in this simulation. The section starts with the description of the atmosphere used in the model. It then goes into the details of engine modeling, aircraft geometry, weight, and performance. The approach used throughout these sub-sections is exactly the same for both aircraft fleets with the usual exception that the variable names for the aggressor aircraft are differentiated from those associated with the carrier-based fighter in order to keep consistency in the array notation adopted in Section 5.2.4.2. The differences in variable names have been kept to a minimum, notably a simple "G" or "AGG" differentiates the aggressor variables from those of the CBF aircraft which carry a "CB" or "A" string on them.

5.2.7.1 Atmospheric Characteristics

Before the performance of an air vehicle can be assessed it is necessary to know with some degree of accuracy the characteristics of the fluid surrounding the vehicle. The basic laws of fluid statics predict accurately the behavior of important parameters such as temperature, density, and pressure at any altitude conforming to an ideal atmosphere termed as the international standard atmosphere. Numerical values of these atmospheric parameters can be found in any aerodynamics or fluid mechanics text [Roskam, 1981]. A typical approximation to describe the standard atmosphere (ICAO 1962) is to consider a linearly

varying temperature in the troposphere ($h \leq 11000\,m$.) with a constant temperature lapse rate of -6.5 °C for every one thousand meters. In the tropopause as well as the stratosphere the temperature is considered invariant at -56.3 °C (216.7 deg. absolute).

```
A       TEMP.K(I)=TEM(ALT.K(I))                                          5.401
A         THE.K(I)=TEMP.K(I)/T0                                          5.402
A         DELTA.K(I)=PRATIO(ALT.K(I))                                    5.403
A         SGMA.K(I)=SIGM(DELTA.K(I),THE.K(I))                            5.404
C       P0=1.013E5                                                       5.405
C       RHO=1.125                                                        5.406
C       GAMA=1.4                                                         5.407
C       T0=288.2                                                         5.408

NOTE    TEMP    - ATMOSPHERIC TEMPERATURE ASSOCIATED WITH CBF AIRCRAFT (DEG.
                  ABSOLUTE
NOTE    ALT     - CBF AIRCRAFT ALTITUDE (METERS)
NOTE    THE     - TEMPERATURE RATIO (DIM)
NOTE    SGMA    - DENSITY RATIO (DIM)
NOTE    P0      - SEA LEVEL STANDARD PRESSURE (PA)
NOTE    GAMMA   - RATIO OF SPECIFIC HEATS (DIM)
NOTE    DELTA   - ATMOSPHERIC PRESSURE RATIO (DIM)
NOTE    T0      - SEA LEVEL STANDARD TEMPERATURE (DEG KELVIN)
NOTE    DELTA   - PRESSURE RATIO (DIM)
```

Eq. 5.401 finds the atmospheric temperature (TEMP) to be used in the computation of the CBF aircraft performance using macro TEM described in Section 5.2.3.2. The only input to this macro is the aircraft altitude ALT. Also of interest is the atmospheric temperature ratio at altitude, THE, found using Eq. 5.402 which divides the previously computed temperature by the sea level temperature (T0) defined in Eq. 5.408. The pressure ratio is computed by macro PRATIO also defined Section 5.2.3.2 and the resulting value denoted DELTA (Eq. 5.403) is used to finally arrive to the density ratio SGMA according to Eq. 5.404. A summary of the temperature, density, and pressure ratio variations is given as follows,

$$T_h = \begin{cases} 216.7 \quad if \quad h \geq 11000\,m \\ \\ T_0 - \lambda h \quad if \quad h < 11000\,m \end{cases} \qquad 5.409$$

where, λ is the temperature lapse rate, h is the altitude and T_h is the temperature at altitude (deg. absolute).

$$P_h = \begin{cases} P_{TR}\ k_1\ e^{-(\frac{h-h_{TR}}{k_2})} & \text{if} \quad h \geq 11000\,m \\ \\ P_{SL}\,(T_h)^{k_3} & \text{if} \quad h < 11000\,m \end{cases} \qquad 5.410$$

where, P_{TR} and h_{TR} are the pressure and altitude at the tropopause level, P_{SL} the sea level international standard atmosphere (ISA) pressure value defined in 3.405, T_h is the temperature at altitude, and k_1, k_2, and k_3 are three constants with numerical values as indicated in Eq. 5.20 (Section 5.2.3.2).

$$\rho_h = \rho_0\ \sigma \qquad 5.411$$

$$\sigma = \frac{\delta}{\theta} = (\frac{T_0}{T_h})(\frac{P_h}{P_0}) \qquad 5.412$$

where, ρ_h ∧ ρ_0 are the density values

at altitude and at sea level, respectively, σ the density ratio defined in Eq. 5.405 as the ratio of the pressure ratio δ and the temperature ratio θ.

Another important characteristic of the standard atmosphere is the computation of the speed of sound (*a*) which bears direct relationship with the performance measures to be described later. Eqs. 5.16 and 5.17 (Section 5.2.3.2) estimated the speed of sound as a table function containing the values of a from the standard atmosphere tables [Roskam and Lan, 1982]. A typical application of macro SSOUND, the macro implemented to estimate the speed of sound at altitude, is used to convert speed values into mach number (Eq. 5.413) which is used in repeated occasions independent variable of several table functions.

```
A       MACH.K(I)=V.K(I)/SSOUND(ALT.K(I))                    5.413

NOTE    MACH    - CBF AIRCRAFT MACH NUMBER (DIM)
NOTE    V       - CBF AIRCRAFT SPEED (M/SEC.)
NOTE    SSOUND  - SPEED OF SOUND MACRO
NOTE    ALT     - AIRCRAFT ALTITUDE (M.)
```

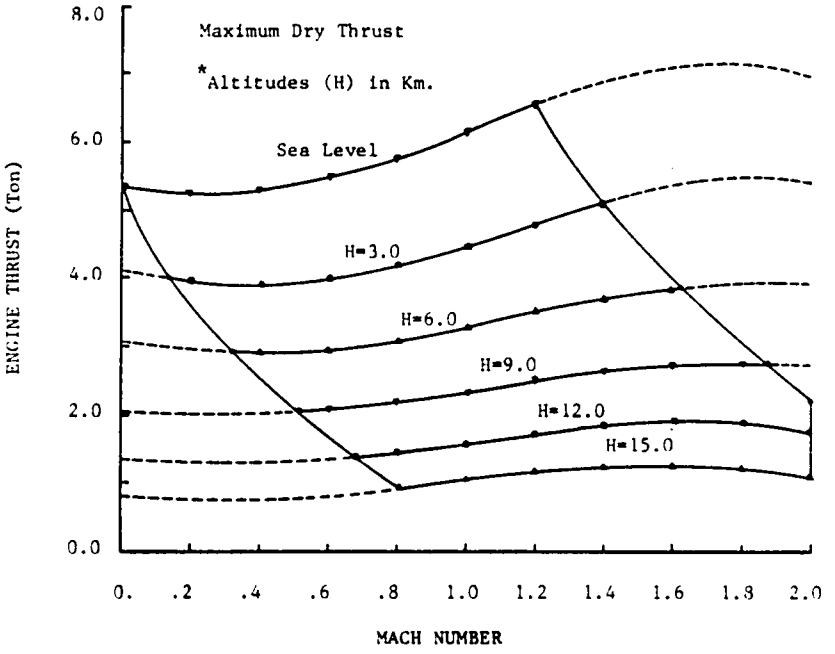
5.2.7.2 *Engine Parameters*

Two sets of curves are necessary to specify the minimum engine performance required to predict aircraft performance: thrust and specific fuel consumption (SFC) curves. The engine thrust (THRUST) is a function of flight speed (MACH), altitude (ALT), and throttle setting (TS).

```
A       T.K(I)=Tabcbf.k(I)*THRUST.K(I)*G*NE(I)                                          5.414
C         TMULT=1.0                                                                     5.414.1
A       THRUST.K(I)=CLIP(THAB.K(I),THNAB.K(I),TS.K(I),TCUT)*TMULT                       5.415
A       THNAB.K(I)=TABHL(THNABT(*),MACH.K(I),0,2,.2)*SGMA.K(I)                          5.416
T       THNABT(*)=5320/5177/5242/5465/5795/6183/6578/6930/7190/7307/7231                5.417
A       THAB.K(I)=TABHL(THABT(*),MACH.K(I),0,2,.2)*SGMA.K(I)                            5.418
T       THABT(*)=8131/7793/7851/8248/8876/9625/10388/11056/11523/11678/11415            5.419
C       TCUT=0.9                                                                        5.419.1
A       TABCBF.K(I)=CLIP(TABC1.K(I),TS.K(I),TS.K(I),TCUT)                               5.419.2
A         TAB1C.K(I)=THCMIN/THCMAX+(1-(THCMIN/THCMAX))*TS.K(I)-TCUT)                    5.419.3
C       THCMIN=5320                                                                     5.419.4
C       THCMAX=8131                                                                     5.419.5
C       TSMAX=1.00                                                                      5.419.6

NOTE    T       - ENGINE THRUST (NEWTONS)
NOTE    TS      - THROTTLE SETTING (DIM)
NOTE    THRUST  - ENGINE THRUST (LB) CORRECTED BY DENSITY EFFECTS
NOTE    THNAB   - NON-AFTERBURNING ENGINE THRUST (LB) CORRECTED BY SPEED
NOTE    THAB    - FULL AFTERBURNING ENGINE THRUST (LB) CORRECTED BY SPEED
NOTE    TABCBF  - THROTTLE SETTING PARAMETER FOR CBF AIRCRAFT (DIM)
NOTE    THCMAX  - MAXIMUM VALUE OF THRUST WITH FULL AFTERBURNER (KG)
NOTE    THCMIN  - MINIMUM VALUE OF THRUST WITH FULL AFTERBURNER (KG)
NOTE    TSMAX   - MAXIMUM VALUE OF THROTTLE SETTING (DIM)
```

Eq. 5.414 defines the maximum available engine thrust (in kg.) at any given mach number and altitude. The parameter TABCBF is used to differentiate between values of thrust for two levels corresponding to a no afterburning operation mode (THNAB) and an afterburning mode (THAB). Afterburner level is commanded automatically when the throttle setting exceeds a threshold value of 0.9. Eqs. 5.416 and 5.417 define the thrust values for maximum "dry operation". Note that the thrust values are specified simply as a function of mach number in Eq. 5.417. The correction of thrust due altitude is assumed, for simplicity, to be a linear function of density ratio (σ). In real life this estimation tends to be somewhat pessimistic for most modern low by-pass ratio turbofan engines although the trend is, in general, valid for first order approximations. Eqs. 5.418 and 5.419 define in a similar way the values of the maximum available thrust with full afterburner operational. Note again that the same altitude correction has been assumed. The combined effect of altitude and flight speed is better depicted in Fig.



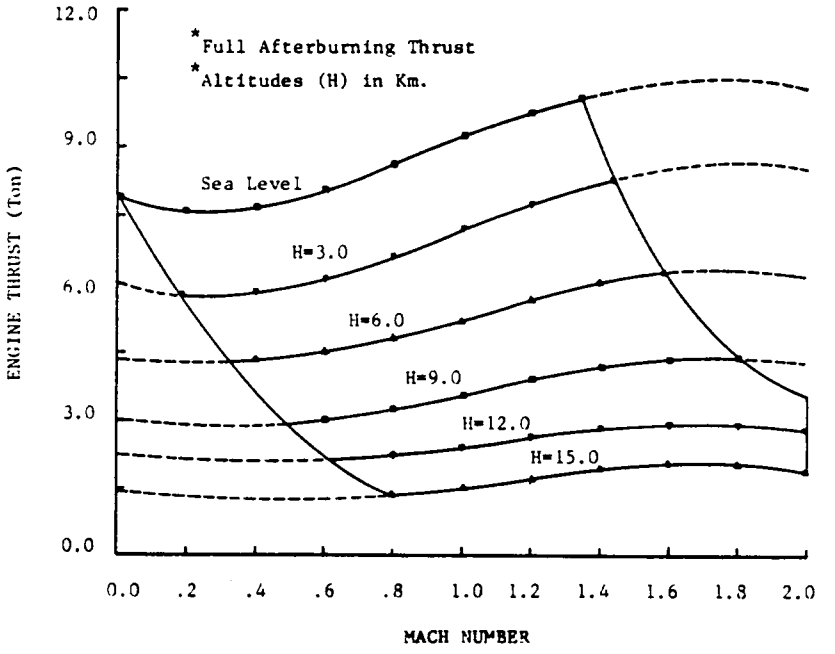


Figure 5.43 CBF Aircraft Engine Thrust Data.

5.43. The dotted lines in this figure indicate that the curves are defined for a full range of mach numbers ranging from zero to two. However, aerodynamic limitations of the aircraft bound the useful operational range as shown by the solid lines.

Another input to the model are the thrust specific fuel consumption (TSFC) vs. mach number curves typically obtained from the engine manufacturer. The implementation of these curves is done exactly the same way as the thrust curves with the exception that the variation of TSFC is not, in general, as marked than that for thrust. The sequence of DYNAMO equations in this subsection starts with the computation of the fuel flow rate (FFLOW) shown in Eq. 5.420. TSFC is defined in Eq. 5.421 with a CLIP statement to differentiate the fuel consumptions using military power (SNAB) and full afterburning (SAB) which are estimated in Eqs. 5.426 and 5.422, respectively. It is note from these equations that two multipliers denoted SABM and SNABM are introduced to account for the small variations in TSFC with altitude in both the dry and full afterburning operating modes. These multipliers are defined in Eqs. 5.245 and 5.428 as a function of altitude as one might expect. The TSFC trends are shown in Fig. 5.44 for the the CBF aircraft engine modeled in the nominal case.

```
R     FFLOW.KL(I)=T.K(I)*SFC.K(I)/G                                          5.420
A     SFC.K(I)=CLIP(SAB.K(I),SNAB.K(I),TS.K(I),.9)/3600                      5.421
A     SAB.K(I)=TABHL(SABT(*),MACH.K(I),0,2.0,.2)*SABM.K(I)                   5.422
T     SABT(*)=1.6/1.67/1.70/1.72/1.70/1.73/1.75/1.79/1.84/1.89/1.96          5.423
A     SABM.K(I)=TABHL(SABMT(*),ALT.K(I),0,18000,3000)                        5.424
T     SABMT(*)=1/.95/.94/.97/1.02/1.13/1.34                                  5.425
A     SNAB.K(I)=TABHL(SNABT(*),MACH.K(I),0,2.0,.2)*SNABM.K(I)                5.426
T     SNABT(*)=.90/.91/.92/.94/.96/.98/1.03/1.08/1.14/1.20/1.30              5.427
A     SNABM.K(I)=TABHL(SNABMT(*),ALT.K(I),0,18000,3000)                      5.428
T     SNABMT(*)=1/.94/.89/.87/.89/.99/1.09                                   5.429

NOTE  SFC    - ENGINE THRUST SPECIFIC FUEL CONSUMPTION (KG/KG/HR)
NOTE  SAB    - AFTERBURNING TSFC CORRECTED BY MACH NO. AND ALTITUDE
NOTE  SNAB   - NON-AFTERBURNING TSFC CORRECTED BY MACH NO. AND ALTITUDE
NOTE  SABM   - AFTERBURNING TSFC ALTITUDE CORRECTION MULTIPLIER (DIM)
NOTE  SNABM  - NON-AFTERBURNING TSFC ALTITUDE CORRECTION FACTOR MULT.(DIM)
```

A natural extension of the fuel flow (FFLOW) constitutes the computation of the fuel remaining at any point in time (FUEL). FUEL is modeled as a level variable with FFLOW as the only rate out as shown in Eq. 5.430. The initial amount of fuel mass allocated for the mission (FUELN) is defined in Eq. 5.431 with the actual numerical values shown in 5.432 in a table function. This

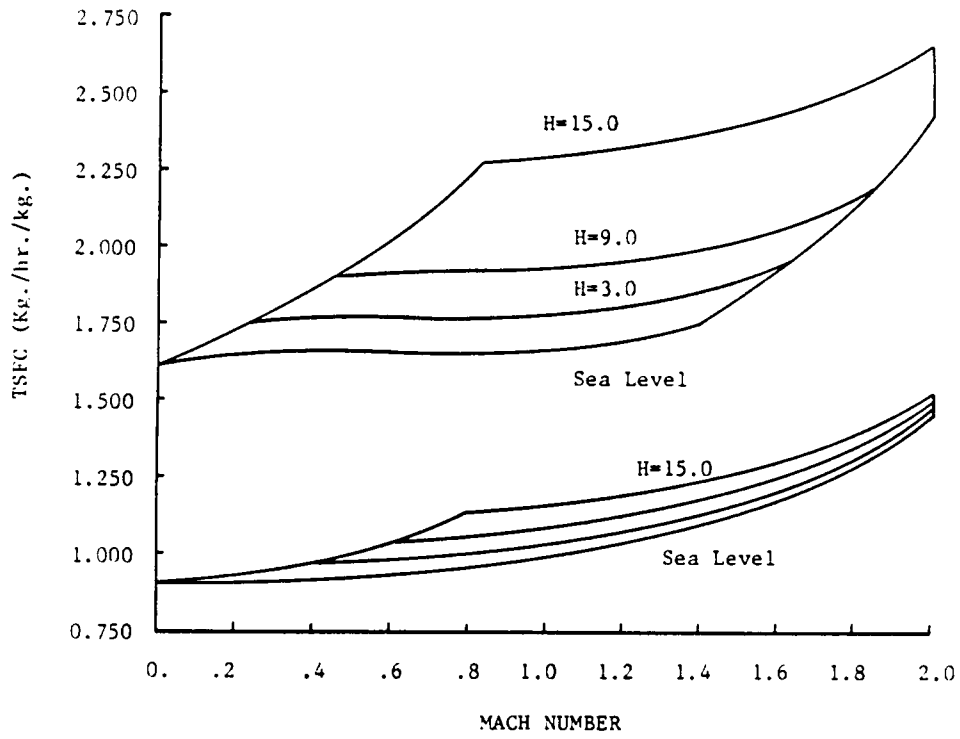


Figure 5.44 CBF Aircraft Engine TSFC Data.

simple modeling of the fuel mass allow quick changes to the nominal values to perform sensitivity analysis on combat persistance tactics.

```
L       FUEL.K(I)=FUEL.J(I)-(DT)(FFLOW.JK(I))                    5.430
N         FUEL(I)=FUELN(I)                                       5.431
T         FUELN(*)=7000/7000/7000/7000                           5.432
A         FUELR.K(I)=FUEL.K(I)/FUELN(I)                          5.433

NOTE    FUEL    - CBF FUEL STATE (KG.)
NOTE    FUELN   - INITIAL CBF FUEL STATE (KG.)
NOTE    FUELR   - CBF FUEL FRACTION REMAINING (KG.)
```

5.2.7.3 *Aircraft Aerodynamics*

This section contains the computation of the two basic aerodynamic coefficients considered in any aircraft performance analysis: lift and drag coefficients. Starting with the basic geometry of the aircraft inputs to the model are wing area (S), aspect ratio (AR), and wing efficiency factor (EFF) defined in Eqs. 4.434 through 4.436.

```
T       S(*)=40/40/40/40                                         5.434
T       AR(*)=3.5/3.5/3.5                                        5.435
T       EFF(*)=.79/.79/.79/.79                                   5.436

NOTE    S       - CBF AIRCRAFT WING AREA (SQ. M.)
NOTE    AR      - CBF AIRCRAFT WING ASPECT RATIO (DIM)
NOTE    EFF     - CBF AIRCRAFT OSWALD'S EFFICIENCY NUMBER (DIM)
```

The next important variable modeled is the drag coefficient (CD) which is broken down into its lift dependent and lift independent contributions denoted by CDLI and CDI, respectively. The lift independent contribution is assumed to be the linear combination of the wing-body zero lift drag (CDO) and the parasite drag associated with the weapon carriage. This last one is defined as the scalar product of the number of weapons (CBFW) and the drag increment due to weapons (CDWEAP) defined in Eq. 5.442. The total aircraft drag coefficient is shown in Eq. 5.437 while its two components are depicted in Eqs. 5.438 and 5.439, respectively. CDO is defined in 5.440 as a table function where the independent variable is the flight mach number (MACH). Numerical values for this table function are listed in Eq. 5.441 while Fig. 5.45 depicts

them graphically. This also shows the effect of weapons carriage on drag coefficient for the two aircraft modeled.

```
A       CD.K(I)=CDLI.K(I)+CDI.K(I)                                                  5.437
A       CDLI.K(I)=CDO.K(I)+SCLPRD(CBFW.K(I,*),1,4,CDWEAP,1)                         5.438
A       CDI.K(I)=CL.K(I)**2/(PI*AR(I)*EFF(I))                                       5.439
A       CDO.K(I)=TABHL(CDOT(*),MACH.K(1),0,2,.1)*MULT                               5.440
T       CDOT(*)=.011/.011/.011/.011/.011/.011/.011/.011/.011/.012/.02/.023
X        /.024/.023/.022/.021/.0205/.0203/.02/.0205/.022                            5.441
T       CDWEAP(*)=.002/.0015/.001/0                                                 5.442

NOTE    CD      - TOTAL DRAG COEFFICIENT (DIM)
NOTE    CD0     - ZERO LIFT DRAG COEFFICIENT (DIM)
NOTE    CDI     - INDUCED DRAG COEFFICIENT (DIM)
NOTE    CDWEAP  - CBF WEAPONS PARASITE DRAG COEFFICIENT INCREASE (DIM)
NOTE    CDLI    - LIFT INDEPENDENT DRAG COEFFICIENT (DIM)
NOTE    CDOT    - NUMERICAL CDO DRAG COEFFICIENT VALUES (DIM)
NOTE    MULT    - CDO MULTIPLIER PARAMETER TO IMPLEMENT SENSITIVITY ANALYSES
```

The total aircraft drag (D) is estimated in the traditional way in terms of the dynamic pressure (Q), aircraft wing area (S), and the complete aircraft drag coefficient (CD) as seen in Eq. 5.443. The dynamic pressure term is defined in 5.444 in terms of the atmospheric pressure (PO), ratio of specific heats (GAMA), and mach number (MACH). The lift coefficient (CL) is computed in terms of the commanded load factor (NCOM), the aircraft mass (WK), dynamic pressure (Q), and wing area (S) as shown in Eq. 5.445. This lift coefficient has been constrained by maximum lift capability ($C_{L_{max}}$) as well as sustained turning considerations as will become evident later.

```
A       D.K(I)=Q.K(I)*S(I)*CD.K(I)                                                  5.443
A       Q.K(I)=.5*PO*GAMMA*DELTA.K(I)*MACH.K(I)**2                                  5.444
A       CL.K(I)=2*NCOM.K(I)*WK.K(I)*G/(Q.K(I)*S(I))                                 5.445

NOTE    D       - CBF TOTAL DRAG (NEWTONS)
NOTE    Q       - DYNAMIC PRESSURE (PA) ASSOCIATED WITH CBF AIRCRAFT
NOTE    CL      - CBF AIRCRAFT LIFT COEFFICIENT (DIM)
```

5.2.7.4 *Aircraft Performance*

Basic aircraft point performance equations are used in this model to calculate the actual and potential performance capabilities of the aircraft at any point in time. Fig. 5.46 illustrates

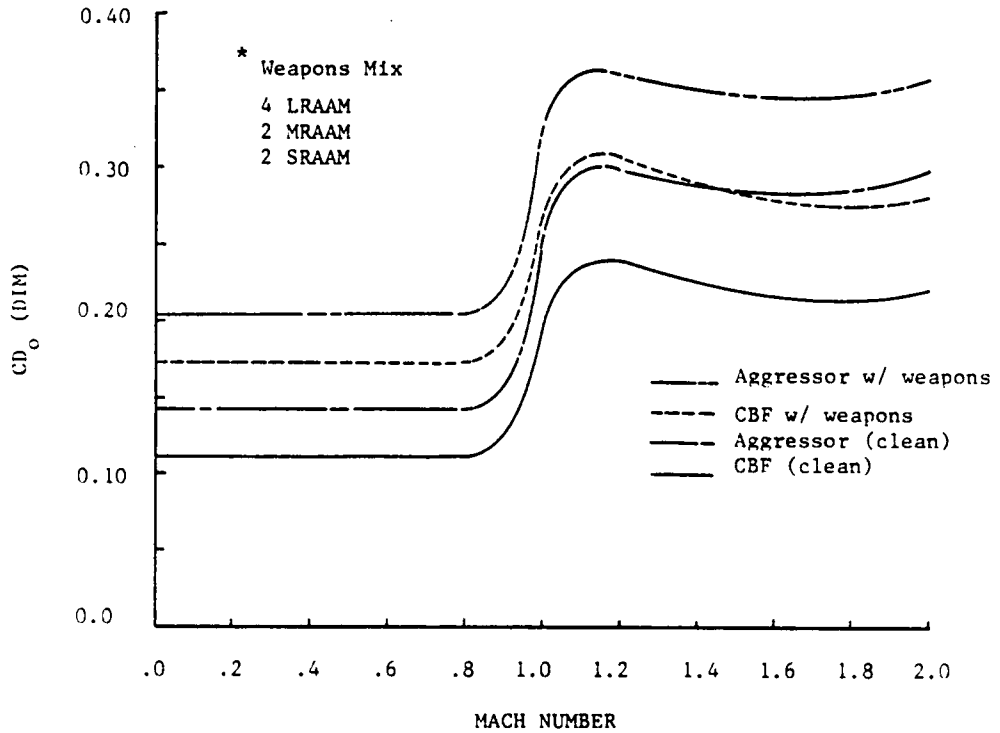


Figure 5.45 Lift-Independent Drag Coefficient Curves.

a functional flow diagram containing the principal elements to assess each aircraft performance capabilities.

The diagram starts with the knowledge of the level variables defining defining the aircraft states: position, velocity, mass, weapon status, etc. From these states the maximum useful load factor capability, NAMAX, is estimated in terms of the thrust available (THRUST), crew tolerance, and structural considerations as seen in blocks 1 through 5. Following, in block 5, the lift coefficient limited by this load factor (CLNAX) is computed according to Eq. 5.448. However, due to aerodynamic limitations the lift coefficient is restricted to a maximum value denoted CLMAX (Eq. 5.450). Thus the maximum useful lift coefficient (CL1) is computed as the minimum of CLNAX and CLMAX as shown in Eq. 5.449. and Eq. 5.452 shows the estimation of the "corrected" load factor (N1) from which the maximum useful turn rate (SAI1M) is derived. Notice the use of macro YAWRTE to execute this computation according to Eq. 5.166.

```
A       NAMAX.K(I)=LOADF(Q.K(I),WK.K(I),WINGK(I),THRUST.K(I),S(I),CDO.K(I)
X        ,NSTRUC(I))                                                    5.446
T          NSTRUC(*)=7/7/7/7                                            5.447
A       CLNAX.K(I)=2*NAMAX.K(I)*WK.K(I)*G/(Q.K(I)*S(I))                 5.448
A       CL1.K(I)=MIN(CLMAX.K(I),CLNAX.K(I))                             5.449
A         CLMAX.K(I)=CLMAXA(I)                                          5.450
T         CLMAXA(*)=1.5/1.5/1.5/1.5                                     5.451
A       N1.K(I)=Q.K(I)*S(I)*CL1.K(I)/(WK.K(I)*G)                        5.452
A       SAI1M.K(I)=YAWRTE(N1.K(I),V.K(I))*57.29                         5.453
A       SAICO.K(I)=MIN(SAI1M.K(I),ABS(RSAIA.JK(I)))                     5.454
A       NCOM.K(I)=SQRT(1+(SAICO.K(I)*V.K(I)/(G*57.29))**2)              5.455
A       VC.K(I)=SQRT(2*NSTRUC(*)*G*WK.K(I)/(RHO*SGMA.K(I)*S(*)
X         *CLMAX.K(*)))                                                 5.456

NOTE    NAMAX   - MAXIMUM POTENTIALLY AVAILABLE LOAD FACTOR IF MAX THRUST
NOTE              IS APPLIED INSTANTANEOUSLY
NOTE    CLNAX   - MAXIMUM LIFT COEFFICIENT AVAILABLE FOR TURNING AT NAMAX
NOTE    CL1     - MAXIMUM LIFT COEFFICIENT CONSTRAINED DUE TO TURN OR
NOTE              MAXIMUM FLOW SEPARATION CHARACTERISTICS
NOTE    N1      - LOAD FACTOR CONSTRAINED BY THIS LIFT COEFFICIENT
NOTE    SAI1M   - MAXIMUM USABLE TURN RATE CAPABILITY CONSTRAINED BY N1
NOTE    SAICO   - DESIRED TURN RATE (CONSTRAINED BY NAVIGATION SCHEME)
NOTE    NCOM    - LOAD FACTOR CORRESPONDING THE DESIRED TURN RATE
NOTE    CL      - CL AT DESIRED LOAD FACTOR
NOTE    VC      - CBF CORNER SPEED (M/S)
```

It was shown in Section 5.2.4.5 that the control variables were varied according to a pure pursuit guidance strategy. However, it was not fully evident how the aircraft performance limitations were interrelated with this algorithm. Once the maximum useful turn rate (SAI1M) is computed in Eq. 5.453 (Fig. 5.45) this information is used in conjunction with the geometric

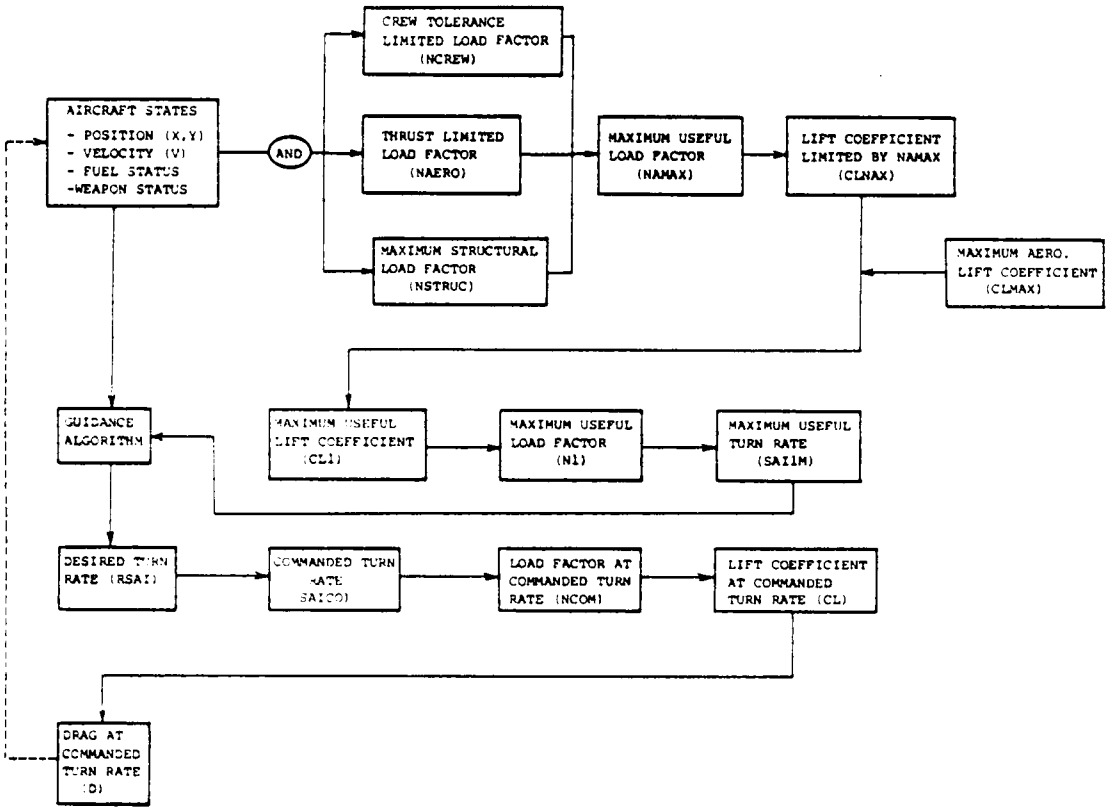


Figure 5.46 Flow Diagram to Assess Aircraft Performance.

considerations of the pursuit to estimate a desired turn rate (RSAI) and thus a commanded turn rate (SAICO) as depicted in Eq. 5.454. The load factor at the commanded turn turn rate (NCOM) is then evaluated in Eq. 5.455. Thrust and drag are used to compute aircraft acceleration along the flight path and ultimately the new states can be derived for the next simulation interval (block 15 in fig 5.45). Eq. 5.456 estimates the aircraft corner speed (VC) which is used in scheduling the throttle setting as explained in Section 5.2.4.5.

A last item to be estimated in this sub-section is the commanded angle of attack at any point in time (ALP). As it might be recalled from Section 5.2.7.3 (Eq. 5.144) the aircraft angle of attack (ALP) is used to estimate the aircraft acceleration along the flight path and it constitutes a major contribution to the induced drag term (implicitly). Eqs. 5.457 and 5.458 specify the three dimensional wing-body lift curve slope as a table function with mach number as the independent variable. Notice that CLALP for slender short aspect ratio wings usually associated with fighter aircraft experiences notorious changes in the transonic range (i.e., $0.8 < MACH < 1.2$) followed by a drastic drop in the supersonic range. ALPO in Eq. 5.459 represents the zero lift angle angle of attack (in radians) used to compute ALP. Note that a small number is assumed since, in general, fighter aircraft wing sections are nearly symmetrical and possess very little camber. Finally, Eq. 5.460 computes the desired angle of attack value.

```
A     CLALP.K(I)=TABHL(CLALT,MACH.K(I),0,2,.4)                    5.457
T     CLALT=4.2/3.5/4.8/3.7/3.1/2.4                               5.458
T     ALPO(*)=-.015/-.015/-.015/-.015                             5.459
A     ALP.K(I)=(CL.K(I)/CLALP.K(I))+ALPO(I)                       5.460

NOTE  CLALP  - THREE DIMENSIONAL AIRCRAFT WING LIFT CURVE SLOPE (1/RAD)
NOTE  CLALT  - NUMERICAL VALUES FOR LIFT CURVE SLOPE VS. MACH NUMBER
NOTE  CLALT  - NUMERICAL VALUES FOR LIFT CURVE SLOPE VS. MACH NUMBER
NOTE  ALPO   - ZERO LIFT COEFFICIENT ANGLE OF ATTACK (RAD)
NOTE  ALP    - ANGLE OF ATTACK (RAD)
```

5.3 *Surface Attack Mission Scenario Model*

5.3.1 Combat Scenario of ASALT II

The combat scenario of this simulation model represents a strike mission against an inland target heavily protected by anti-aircraft artillery (AAA) and surface-to-air missiles (SAM). The target area is located 400 km. from a naval carrier battle group (CBG) from which the strike is launched. The strike takes place immediately after a remote escort is launched against the major source of the enemy counter air capability stationed at a base near by (Fig. 5.1). This model isolates the strike mission of this integrated attack and tries to assess the impact of several technologies and tactics that can be incorporated into aircraft design and operations to upgrade survivability at the sortie level.

The carrier-based fleet comprises a number of high performance, mach 1.7 plus dash capability, fighters. In the nominal model each aircraft is loaded with six air-to-surface missiles and ten 220-kg bombs. Also, the aircraft can carry active and passive electronic countermeasure systems (ECM) in the form of chaff dispensers and external ECM pods.

The defensive ground sites are strategically located along the proposed aircraft flight path in a five defensive ring configuration as depicted in Fig. 5.47. These sites can have radar-guided or infrared-guided missiles as well as AAA or a combination of the three. A long range surveillance radar located 100 km. from the main target site (defensive weapon sites are also targets of the striking force) provides early warning coverage for the sites although each particular installation possesses its own tracking capability associated with the weapons deployed on it.

The CBF aircraft employ the air-to-surface missiles as threat suppression mechanism against the defensive weapon sites and the bombs are primarily used for the main target. The

mission calls for a nominal HI-LO-HI altitude schedule to be flown with a single pass for weapons delivery to the main target area.

Air-to-surface interactions take place as the defensive sites fire upon the striking aircraft and these retaliate with their threat suppression mechanisms. The levels of damage for both, defensive sites and aircraft are integrated through time in order to estimate the probabilities of survival per sortie for both sides. The simulation ends as the aircraft egresses from the hostile environment and clears the last defensive ring in its flight back to the carrier battle group.

5.3.2 Model Inputs and Outputs

The model inputs and outputs of ASALT II follow the same format of those use in a previous model (ASALT I) with some minor differences dictated by the particular nature of the mission. Aerodynamic data, propulsion characteristics, sensors data, aircraft signatures, and weapon kinematic envelopes are defined for both the aircraft attacking force and the defense weapons sites. An added element to the input list of this model is the specification of the aircraft paths to be flown to the main target area. This description, as will be seen later, is performed individually so that each aircraft can fly completely different flight paths to the target. This capability is complemented by the specification of aircraft altitudes and speeds for each one of the segments defining an individual trajectory. These previous characteristics add versatility to the model specially to explore the use of various attack tactics through the mission. The main outputs of this model are the aircraft survivability per sortie ($P_{CBFS/S}$) and the defense weapon sites probability of survival($P_{DWSS/S}$). Each aircraft and defense weapon unit are assumed to have a unity probability of survival at the beginning of the simulation. As before, the values of $P_{CBFS/S}$ and $P_{DWSS/S}$ are reduced according to the attrition equations developed in section (?) using the co-kill probability scheme. The average probability of

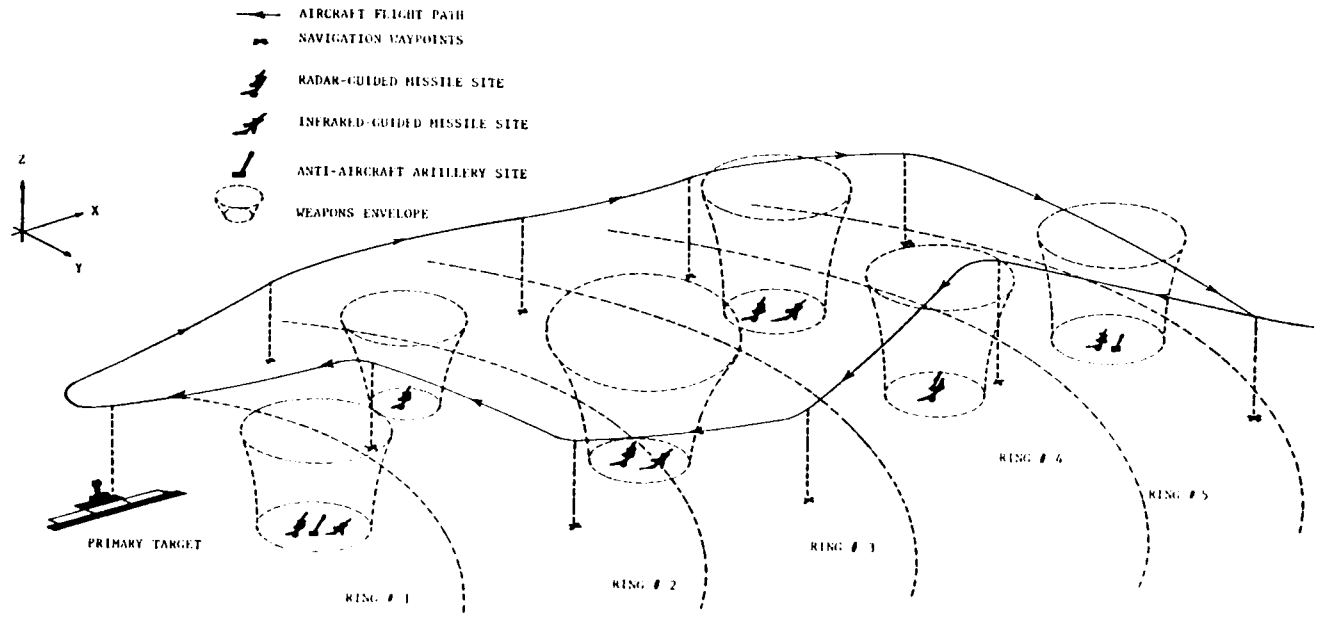


Figure 5.47 ASALT II Mission Scenario.

survival for each of the fleets is also calculated in the program as well as the exchange ratio at the end of the sortie (*ER*).

5.3.3 Model Structure

The main purpose of this section is to give the reader some familiarity with the differences existing between the ASALT I and ASALT II models. These differences stem from the use of two different programming languages. ASALT II was written in WATFIV which is a version of the traditional FORTRAN 77 upper level programming language incorporating many advanced structured programming features and good debugging capabilities. ASALT I on the other hand, was written in DYNAMO III, the particular continuous simulation language associated with the systems dynamics methodology explained in Chapter 3 of this dissertation. It should be realized that although DYNAMO III is FORTRAN-based the structuring of both models is somewhat different due to the automatic sorting capabilities of the DYNAMO III compiler. In other words, DYNAMO III automatically arranges the model equations in a logical order of execution, whereas the FORTRAN compiler expects the equations to be sequentially ordered as is true for most programming languages in use. This makes ASALT II a more structured model although not necessarily more readable than ASALT I. An important characteristic that should also be kept in mind is the fact that FORTRAN is particularly unfriendly to dynamic array implementations in the model subroutines. The use of the PARAMETER statement and the explicit description of the array size in the SUBROUTINE statement was compared and the latter approach was decided to be more meaningful and thus implemented. However, the reader may observe the fact that some of the subroutines in the code seem to accomplish similar tasks when in fact the array dimensions (not size) are different. The tradeoff taken in this approach is readability versus compactness since it is possible to address a one or two-dimensional array with a three-dimensional array with the proper fixtures to one or two of the dimensions in which case careful attention should be paid

when addressing the internal elements of the reduced arrays due to the sequential storage capabilities of the computer. This discussion will become clearer when the model subroutines are described in more detail.

Figure 5.48 depicts a general flowchart for ASALT II model. From this figure it is seen that a first block defining the mission scenario and initializing the state variables of the problem is used. The second block estimates some of logistic variables such as aircraft fuel requirements, payload and mission weights, aircraft operational suitability etc. This block is also used to zero some aircraft rate variables (e.g. acceleration) before the control variables takeover. The third block starts the dynamic portion of the simulation by computing many auxiliary variables necessary to compute the rate variables later on. This block takes approximately 90 percent of the computational burden in the entire simulation. All the geometrical aspects of the engaging forces are computed here as well as all the activities that lead to the detection, launch, guidance, and detonation of weapons from both, aircraft and defense weapon sites. The fourth block deals with the estimation of rate variables. Parameters such as fuel flow, attrition rates, speed and position changes, weapons launching rates, etc. are among the important variables computed. The fifth block updates the state variables according to a prescribed integration scheme. The last block in the dynamic loop is a printing submodule to display the time variations of any selected variable in the simulation. The dynamic loop shown in the diagram is executed until the time variable (TIME) reaches a desired final time (FTIME) or when the aircraft reach the specified initial positions.

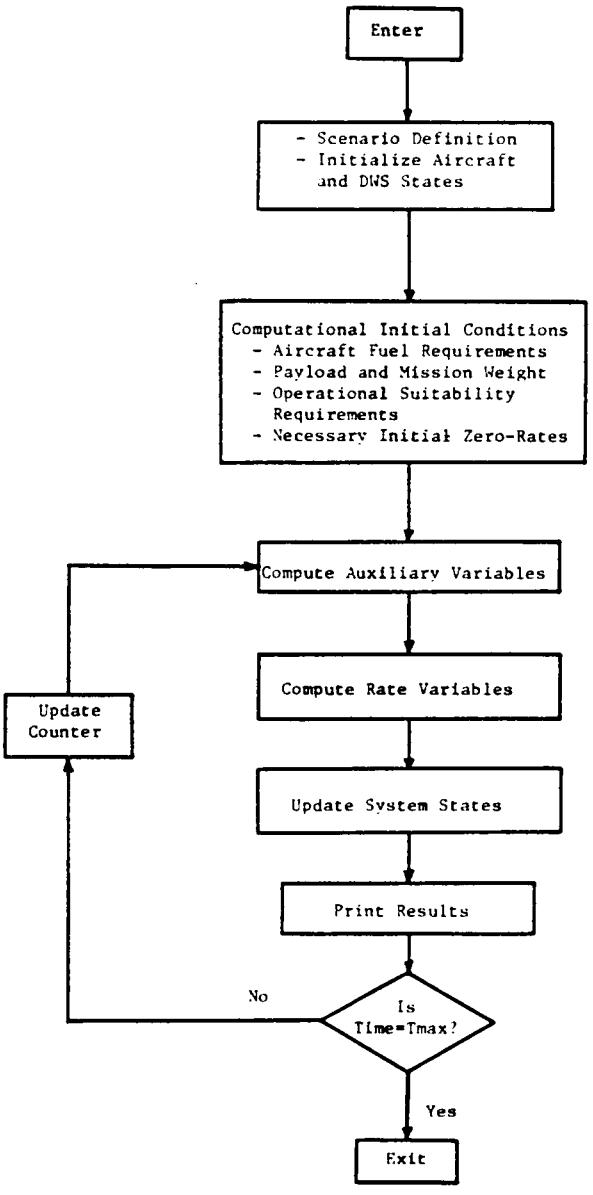


Figure 5.48 ASALT II Model Structure.

5.3.4 Model Subroutines

5.3.4.1 Subroutine DISTT

This subroutine computes the horizontal distance from the *i th* aircraft to each *j th* target site. Eqs. 5.461 through 5.463 compute the downrange (DX), lateral range (DY), and resultant range (DD). Also, the line-of-sight vector from the aircraft to each target (ALOS) is evaluated according to Eqs. 5.466 through 5.470. Note that four equations are used for ALOS corresponding to four different cartesian quadrants where the engagement could potentially take place. The inputs to this subroutine are the cartesian coordinates of the aircraft (AX,AY), those of the target (TX,TY), the number of aircraft (NA), the number of targets (NP), and π.

```
      SUBROUTINE DISTT (AX, AY, TX, TY, DX, DY, DD, NA, NP,ALOS, PI)
C
      INTEGER NA, NP, I, J
      REAL  AX(NA), AY(NA), TX(NP), TY(NP), DX(NA,NP)
      REAL  DY(NA,NP), DD(NA,NP), ALOS (NA,NP), PI
      DO 006 I=1,NA
        DO 006 J=1,NP
          DX(I,J) = AMAX1(AX(I)-TX(J),-AX(I)+TX(J))                    5.461
          DY(I,J) = AMAX1(AY(I)-TY(J),-AY(I)+TY(J))                    5.462
          DD(I,J)  = SQRT(DX(I,J)**2+DY(I,J)**2)                       5.463
          IF (AY(I).GE.TY(J)) THEN                                     5.464
            IF (AX(I).GE.TX(J)) THEN                                   5.465
              ALOS(I,J) = ARSIN (DY(I,J)/(DD(I,J)+1.0E-6)) + PI        5.466
            ELSE
              ALOS(I,J) = 2.*PI-ARSIN (DY(I,J)/(DD(I,J)+1.0E-6))       5.467
            ENDIF
          ELSE
            IF (AX(I).GE.TX(J)) THEN                                   5.468
              ALOS(I,J) = PI - ARSIN (DY(I,J)/(DD(I,J)+1.0E-6))        5.469
            ELSE
              ALOS(I,J) = ARSIN (DY(I,J)/(DD(I,J)+1.0E-6))             5.470
            ENDIF
          ENDIF
006   CONTINUE
      RETURN
      END
```

5.3.4.2 *Subroutine DISTW*

This subroutine computes the horizontal distance from an aircraft to each waypoint defining the aircraft path flown to the main target. It also evaluates the corresponding line-of-sight angle (ALOS) to each waypoint. The treatment is exactly the same as that used in previous subroutine (DISTT) with the notable exception that the array dimensions of the waypoint vector are of higher order than those used in DISTT. The reason behind this fact is that waypoints are specific for each aircraft and hence require explicit two-dimensional definition meanwhile the defense weapon sites are aircraft independent in their definition. WX(NA,NP) and WY(NA,NP) represent the cartesian coordinates of each waypoint (i.e. NP of them) for each NA aircraft. As before, (AX,AY) represent the coordinates of an aircraft at some point in time. Eqs. 5.471 through 5.473 compute the respective downrange, lateral range, and resultant range to the waypoint. Eqs. 5.476 through 5.480 assign the corresponding line-of-sight direction depending upon the geometry of the engagement.

```
      SUBROUTINE DISTW (AX, AY, WX, WY, DX, DY, DD, NA, NP,ALOS, PI)
C
      INTEGER NA, NP, I, J
      REAL  AX(NA), AY(NA), WX(NA,NP), WY(NA,NP), DX(NA,NP)
      REAL  DY(NA,NP), DD(NA,NP), ALOS (NA,NP), PI
      DO 006 I=1,NA
        DO 006 J=1,NP
          DX(I,J) = AMAX1(AX(I)-WX(I,J),-AX(I)+WX(I,J))                    5.471
          DY(I,J) = AMAX1(AY(I)-WY(I,J),-AY(I)+WY(I,J))                    5.472
          DD(I,J)  = SQRT(DX(I,J)**2+DY(I,J)**2)                           5.473
          IF (AY(I).GE.WY(I,J)) THEN                                       5.474
            IF (AX(I).GE.WX(I,J)) THEN                                     5.475
              ALOS(I,J) = ARSIN (DY(I,J)/(DD(I,J)+1.0E-6)) + PI            5.476
             ELSE
              ALOS(I,J) = 2.*PI-ARSIN (DY(I,J)/(DD(I,J)+1.0E-6))           5.477
            ENDIF
           ELSE
            IF (AX(I).GE.WX(I,J)) THEN                                     5.478
              ALOS(I,J) = PI - ARSIN (DY(I,J)/(DD(I,J)+1.0E-6))            5.479
             ELSE
              ALOS(I,J) = ARSIN (DY(I,J)/(DD(I,J)+1.0E-6))                 5.480
            ENDIF
          ENDIF
006     CONTINUE
      RETURN
      END
```

5.3.4.3 *Subroutine DIRECW*

The main purpose of this subroutine is to compute the bearing angle (ANGLE) subtent between the aircraft heading (AHEAD) and the waypoint line-of-sight vector (ALOS). The bearing angle convention is similar as that adopted for the target aspect angles, ATN and TAA, in ASALT I model (see Fig. 5.12) where positive bearing angles are assigned to waypoints located starboard to the aircraft velocity vector. Eqs. 5.483 through 5.487 assign the corresponding bearing angle for all possible engagement geometries (i.e. four quadrant configurations). Subroutine inputs are the lateral downrange positions of the aircraft (AY) and that of the waypoint (WY), the number of aircraft (NA), the number of waypoints (NP), the line-of-sight angle (ALOS), and the aircraft present heading (AHEAD).

```
      SUBROUTINE DIRECW (AHEAD, ALOS, AY, WY, NA, NP, PI, ANGLE)
C
      INTEGER NA, NP, I, J
      REAL  AY(NA), WY(NA,NP), AHEAD(NA), ALOS(NA,NP), ANGLE(NA,NP),
     +        PI
      DO 011 I=1,NA
        DO 011 J=1,NP
          IF (AY(I) .GE. WY(I,J)) THEN                                  5.481
            IF (-PI .GE. (AHEAD(I)-ALOS(I,J))) THEN                     5.482
              ANGLE(I,J) = 2.*PI + (AHEAD(I) - ALOS(I,J))               5.483
            ELSE
              ANGLE(I,J) = AHEAD(I) - ALOS(I,J)                         5.484
            ENDIF
          ELSE
            IF (PI .GE. (AHEAD(I)-ALOS(I,J))) THEN                      5.485
              ANGLE(I,J) = AHEAD(I) - ALOS(I,J)                         5.486
            ELSE
              ANGLE(I,J) = (AHEAD(I) - ALOS(I,J)) - 2.* PI              5.487
            ENDIF
          ENDIF
011     CONTINUE
      RETURN
      END
```

5.3.4.4 *Subroutine DIRECT*

This subroutine complements the computations of DISTT by calculating the target aspect angle from an aircraft to the defense weapon sites denoted generically ANGLE in the subroutine. The procedure used is exactly the same as that of DIRECW with the exception

being the smaller size of the array containing the defense weapon site locations (i.e. one dimensional). Eqs. 5.488 through 5.494 assign the engagement to a particular geometry and note that the target aspect convention associates positive target aspect angles (ANGLE) with targets located starboard of the aircraft velocity vector direction.

```
      SUBROUTINE DIRECT (AHEAD, ALOS, AY, TY, NA, NP, PI, ANGLE)
C
      INTEGER NA, NP, I, J
      REAL  AY(NA), TY(NP), AHEAD(NA), ALOS(NA,NP), ANGLE(NA,NP),
     +        PI
      DO 011 I=1,NA
        DO 011 J=1,NP
          IF (AY(I) .GE. TY(J)) THEN                                    5.488
            IF (-PI .GE. (AHEAD(I)-ALOS(I,J))) THEN                     5.489
              ANGLE(I,J) = 2.*PI + (AHEAD(I) - ALOS(I,J))               5.490
            ELSE
              ANGLE(I,J) = AHEAD(I) - ALOS(I,J)                         5.491
            ENDIF
          ELSE
            IF (PI .GE. (AHEAD(I)-ALOS(I,J))) THEN                      5.492
              ANGLE(I,J) = AHEAD(I) - ALOS(I,J)                         5.493
            ELSE
              ANGLE(I,J) = (AHEAD(I) - ALOS(I,J)) - 2.* PI              5.494
            ENDIF
          ENDIF
011     CONTINUE
      RETURN
      END
```

5.3.4.5 Subroutine ATMOS

At least as partially the name implies this subroutine calculates the main parameters of the international standard atmosphere (ICAO 1962) from approximate close form equations (Roskam, 1981). Inputs to this procedure are the aircraft speed (SPEED) and altitude (ALT). Main outputs are aircraft mach number (MACHN), flight dynamic pressure (QA), temperature ratio (THE), pressure ratio (DEL), and density ratio (SIG). The atmospheric sea level static conditions conditions (SSL) are defined in Eqs. 5.495 through 5.499. A two layer atmospheric approximation is used to define the standard atmosphere according to Eqs. 5.500 through 5.509. These equations are just 5.409 and 5.410 of the previous model. The mach number and dynamic pressure are computed lastly in Eqs. 5.510 5.511, respectively.

```
      SUBROUTINE ATMOS (SPEED, ALT, MACHN, DEL, THE, SIG, RO,
     +     TZERO, PZERO, GAMA, NA, QA)
C
C       COMPUTES THE CHARACTERISTICS OF THE STANDARD ATMOSPHERE AT
C       ANY ALTITUDE (UP TO 20,000 METERS) AS WELL AS ESTIMATES THE
C       FLIGHT MACH NUMBER OF EACH AIRCRAFT.
C
      INTEGER NA, I, J
      REAL MACHN(NA), ALT(NA), SPEED(NA), DEL(NA), THE(NA), SIG(NA)
      REAL RO, PZERO, TZERO, LAM, GAMA, RCON, QA(NA)
C
      DO 008 I=1,NA
          RO    = 1.225                                                    5.495
          TZERO = 288.2                                                    5.496
          PZERO = 101300.                                                  5.497
          LAM   = .0065                                                    5.498
          GAMA  = 1.400                                                    5.499
          RCON  = 287.                                                     5.500
        IF (ALT(I).LE.11000.) THEN                                         5.501
          THE(I)  = 1 - LAM/TZERO * ALT(I)                                 5.502
          DEL(I)  = THE(I) ** 5.2561                                       5.503
          SIG(I)  = THE(I) ** 4.2561                                       5.504
        ELSE
          THE(I)  = .75189                                                 5.505
          DEL(I)  = .2234 * EXP (-(ALT(I)-11000.)/ 6340.64)                5.506
          SIG(I)  =  DEL(I) / THE(I)                                       5.509
        ENDIF
          MACHN(I) = SPEED(I) / SQRT(GAMA*RCON*THE(I)*TZERO)               5.510
          QA(I)    = 0.5 * PZERO * GAMA * DEL(I)* MACHN(I)**2              5.511
008     CONTINUE
      RETURN
      END
```

5.3.4.6 *Subroutine INTER*

This subroutine serves to interpolate linearly between a set of N values defined in the form of a table function. The table function is comprised of two inputs, a dependent variable (F) and an independent variable (X) which are generally defined in a set of data statements in the code. The value of the independent variable to be interpolated is defined as XVAL and its respective output (i.e. dependent variable value) is labeled FOUT. Input variable NI is associated with the array dimension of the interpolated value, while N is the number of points comprising the actual table function. Eq. 5.517 represents the interpolation formula for elements within the range of specified table values. Eqs. 5.512 and 5.514 clip XVAL either to the lowest or highest tabular value specified.

```
      SUBROUTINE INTER(X, F, XVAL, N, NI, FOUT)
      INTEGER N, NI
      REAL FOUT(NI), X(NI,N), F(NI,N), XVAL(NI)
C
```

```
      DO 001 I=1,NI
       IF (XVAL(I).LE.X(I,1)) THEN                                    5.512
          FOUT(I) = F(I,1)                                            5.513
       ELSE
          IF (XVAL(I).GE.X(I,N)) THEN                                 5.514
             FOUT(I) = F(I,N)                                         5.515
          ELSE
             DO 002 J=1,N
                IF (XVAL(I).GT.X(I,J)) THEN                           5.516
                   FOUT(I) = F(I,J) + (XVAL(I)-X(I,J))*
     +                (F(I,J+1)- F(I,J))/(X(I,J+1)-X(I,J))            5.517
                ELSE
                ENDIF
002             CONTINUE
          ENDIF
       ENDIF
001   CONTINUE
      RETURN
      END
```

5.3.4.7 Subroutine MATRIX

This subroutine simply finds the scalar product of an (I x J) matrix (A) and a column vector (B). Note that the value of A is initialized within the matrix (Eq. 5.518).

```
      SUBROUTINE MATRIX ( A, B, C, IC, JC)
      INTEGER  IC, J
      REAL A(IC), B(IC,JC), C(JC)
C
      DO 030 I=1,I
        A(I) = 0.0                                                    5.518
        DO 040 J=1,J
          A(I) = A(I) + B(I,J) * C(J)                                 5.519
040     CONTINUE
030   CONTINUE
      RETURN
      END
```

5.3.4.8 Subroutine LOADF

The purpose of this subroutine is to compute the maximum sustained (i.e. no loss in altitude) load factor that an aircraft can generate restricted by engine thrust considerations. Inputs to this subroutine are the aircraft dynamic pressure (QD), aircraft mass (AMAS), wing area (WA), wing span efficiency factor (WK), and aircraft zero-lift drag coefficient (DC). Eq. 5.521 represents the main expression to estimate the maximum sustained load factor (NF). Eq.

5.522 clips the value of NF to effectively 1 if the thrust available equals the drag. This in fact will be reflected in the aircraft dynamic equations as the start of a deceleration maneuver.

```
      SUBROUTINE LOADF (QD, AMAS, WA, WK, TH, DC, NA, G, NF)
      INTEGER  NA, I
      REAL QD(NA), AMAS(NA), WA(NA), WK(NA), TH(NA), DC(NA), NF(NA),G
C
      DO 070 I=1,NA
        IF (TH(I)/(QD(I)*WA(I)) .GT. DC(I)) THEN                          5.520
          NF(I) = QD(I) * WA(I) / (AMAS(I) * G) * SQRT (1/WK(I) *
     +              (TH(I)/(QD(I)*WA(I)) - DC(I)))                      5.521
        ELSE
          NF(I) = 1.01                                                    5.522
        ENDIF
070   CONTINUE
      RETURN
      END
```

5.3.4.9 *Subroutine YAWRTE*

Just as in the previous model, YAWRTE calculates the maximum sustained yaw rate (YAW) that an aircraft can experience subjected to a given load factor (LOAD). Inputs to this subroutine are the aircraft load factor (LOAD) estimated in previous subroutine, the aircraft speed (SPEED), and the number of aircraft for which the calculation is to be performed (NA).

```
      SUBROUTINE YAWRTE (LOAD, SPEED, NA, G, YAW)
      INTEGER  NA, I
      REAL  LOAD(NA), SPEED(NA), YAW(NA), G
C
      DO 080 I=1,NA
        YAW(I) = G * SQRT(LOAD(I)** 2 - 1)/ SPEED(I)                      5.523
080   CONTINUE
      RETURN
      END
```

5.3.4.10 *Subroutine PS*

This subroutine computes the aircraft specific excess power (PS) at any point in the mission. PS expressed in units of length over time (m/sec.) is a traditional metric associated with the potential maneuvering capabilities of a flight vehicle. It in fact represents the

instantaneous climb capability or else can be easily translated into acceleration/ deceleration performance. Inputs to estimate this maneuvering metric are the aircraft speed (SPEED), aircraft mass (AMAS), thrust available (TH), and aircraft total drag (D). The sole output is the specific excess power denoted for the subroutine purposes as APS (Eq. 5.524).

```
      SUBROUTINE PS (SPEED, AMAS, G, TH, D, NA, APS)
      INTEGER  NA, I
      REAL SPEED(NA), AMAS(NA), TH(NA), APS(NA), G, D(NA)
C
      DO 085 I=1,NA
       APS(I) = (TH(I) - D(I)) * SPEED(I) / (AMAS(I) * G)                5.524
085   CONTINUE
      RETURN
      END
```

5.3.4.11 *Subroutine YAW*

This subroutine constrains the aircraft heading angle (ψ) within 0 and 2 π. The inputs are the present aircraft heading angle (ANGLE), and the number of aircraft (NA). The single output is the corrected heading angle (NEWAN). Note that two alternate corrections arise as the heading angle could become either a large positive value (e.g. higher than 2 π) or a negative value. Eqs. 5.525 and 5.526 represent the conditional branching statements to check both of these conditions. Eqs. 5.527 and 5.529 correct the heading angle provided (ANGLE).

```
      SUBROUTINE YAW (ANGLE, NA, NEWAN, PI)
      INTEGER  NA, I
      REAL  ANGLE(NA), NEWAN(NA), PI
C
C     SUBROUTINE TO LIMIT THE YAW ANGLE WITHIN 0 AND 2 PI (RAD)
C
      DO 101 I=1,NA
       IF (ANGLE(I) .GE. 0) THEN                                        5.525
         IF (ANGLE(I) .GE. 2.*PI) THEN                                  5.526
           NEWAN(I) = ANGLE(I) - 2.*PI                                  5.527
         ELSE
           NEWAN(I) = ANGLE(I)                                          5.528
         ENDIF
       ELSE
         NEWAN(I) = 2.*PI + ANGLE(I)                                    5.529
       ENDIF
101   CONTINUE
      RETURN
      END
```

5.3.4.12 Subroutine INTE

This subroutine represents another example of interpolating algorithm with different array representation as that of INTER. In this particular case the output and the interpolated independent variable (FOUT and XVAL) are two dimensional arrays instead of one dimensional vectors used in INTER. The mechanics of the subroutine are exactly the same as those used in INTER including the low and high value clipping for extrapolated values.

```
      SUBROUTINE INTE (X, F, XVAL, NA, NT, NP, FOUT)
      INTEGER NA, NT, NP, I, J, K
      REAL FOUT(NA,NT), X(NA,NP), F(NA,NP), XVAL(NA,NT)
C
      DO 001 I=1,NA
       DO 001 J=1,NT
         IF (ABS(XVAL(I,J)) .LE. X(I,1)) THEN                          5.530
            FOUT(I,J) = F(I,1)                                         5.531
         ELSE
            IF (ABS(XVAL(I,J)) .GE. X(I,NP)) THEN                      5.532
               FOUT(I,J) = F(I,NP)                                     5.533
            ELSE
               DO 002 K=1,NP
                  IF (ABS(XVAL(I,J)) .GT. X(I,K)) THEN                 5.534
                     FOUT(I,J) = F(I,K) + (ABS(XVAL(I,J))-X(I,K))
     +                 * (F(I,K+1)- F(I,K))/(X(I,K+1)-X(I,K))          5.535
                  ELSE
                  ENDIF
002               CONTINUE
         ENDIF
       ENDIF
001   CONTINUE
      RETURN
      END
```

5.3.4.13 Subroutine DWKE

This subroutine is used to estimate the defense weapon kinematic envelopes. In principle the subroutine is yet another interpolating algorithm that reads tabular values from a DATA statement whose values define the boundaries of reach of a particular weapon. The independent variable X represents the downrange while the dependent variable (F) is associated altitude. Note that XVAL in this case represents the aircraft altitude and thus is represented in a one-dimensional vector. This in fact represents one difference between this

subroutine and INTE (previously defined). A second subtle difference is the clipping of the lower bound of FOUT (output) to zero since it is assumed that no weapon could conceivably reach a target beyond the outer boundary of the kinematic envelope (Eqs. 5.537 and 5.539).

```
      SUBROUTINE DWKE (X, F, XVAL, NA, NWE, NP, FOUT)
      INTEGER NA, NWE, NP, I, J, K
      REAL FOUT(NA,NWE), X(NWE,NP), F(NWE,NP), XVAL(NA)
C
      DO 001 I=1,NA
       DO 001 J=1,NWE
         IF (XVAL(I) .LE. X(J,1)) THEN                                    5.536
            FOUT(I,J) = 0.0                                               5.537
         ELSE
            IF (XVAL(I) .GE. X(J,NP)) THEN                                5.538
               FOUT(I,J) = 0.0                                            5.539
            ELSE
               DO 002 K=1,NP
                  IF (XVAL(I) .GT. X(J,K)) THEN                           5.540
                     FOUT(I,J) = F(J,K) + (XVAL(I)-X(J,K))
     +                 * (F(J,K+1)- F(J,K))/(X(J,K+1)-X(J,K))             5.541
                  ELSE
                  ENDIF
002            CONTINUE
         ENDIF
       ENDIF
001   CONTINUE
      RETURN
      END
```

5.3.4.14 *Subroutine DOUBL*

This subroutine interpolates values provided by a one dimensional vector and has as an output a two-dimensional array. The implementation of this subroutine is necessary when the values of the table function are not dependent upon any of elements of the engaging forces. Vectors X and F define the table function, XVAL is a two-dimensional array that represents the value of the dependent variable to be interpolated and FOUT is the output two-dimensional array. NA and NP are variable size array parameters.

```
      SUBROUTINE DOUBL(X, F, XVAL, NA, NT, NP, FOUT)
      INTEGER NA, NT, NP, I, J, K
      REAL FOUT(NA,NT), X(NP), F(NP), XVAL(NA,NT)
C
      DO 001 I=1,NA
       DO 001 J=1,NT
         IF (XVAL(I,J) .LE. X(1)) THEN                                    5.542
            FOUT(I,J) = F(1)                                              5.543
         ELSE
```

```
            IF (XVAL(I,J) .GE. X(NP)) THEN                                  5.544
               FOUT(I,J) = F(NP)                                            5.545
            ELSE
               DO 002 K=1,NP
                  IF (XVAL(I,J) .GT. X(K)) THEN                             5.546
                     FOUT(I,J) = F(K) + (XVAL(I,J)-X(K))                    5.547
     +                 * (F(K+1)- F(K))/(X(K+1)-X(K))                       5.548
                  ELSE
                  ENDIF
002               CONTINUE
            ENDIF
         ENDIF
001   CONTINUE
      RETURN
      END
```

5.3.4.15 *Subroutine DINV*

This subroutine converts a number from decibels to a ratio of two quantities. Arrays A and B (i.e. two-dimensional) are inputs to the subroutine. The single output is array RET whose dimensions are compatible with those of A and B as shown in Eq.

```
      SUBROUTINE DINV (A, B, NA, NT, RET)
      INTEGER  NA, NT
      REAL A(NA,NT), RET(NA,NT), B(NA,NT)
C
C     CONVERTS FROM DECIBELS TO A RATIO OF TWO QUANTITIES
C
      DO 086 I=1,NA
       DO 086 J=1,NT
         RET(I,J) = 10. ** (A(I,J) / (10. * B(I,J)))                        5.549
086   CONTINUE
      RETURN
      END
```

5.3.4.16 *Subroutine RATINV*

The purpose of this subroutine is to convert a ratio of two quantities to decibles. This subroutine is used extensively in computing the probability of radar detection as will become evident in the next section. Given two arrays A of size (NA x NT) and B of size (NA x NT) the idea is to calculate the ratio in decibles of these two (RET). Eq. 5.550 depicts the actual implementation of this subroutine. Note that in order to avoid the undefined form $\log_{10}(0)$ an

AMAX1 function has been used to clip the value of the function when the ratio of the two parameters is 0.001 or below.

```
      SUBROUTINE RATINV (A, B, NA, NT, RET)
      INTEGER  NA, NT
      REAL A(NA,NT), RET(NA,NT), B(NA,NT)
C
      DO 087 I=1,NA
       DO 087 J=1,NT
       RET(I,J) = 10.* ALOG10 (AMAX1 (A(I,J)/B(I,J) , 0.001))                    5.550
087   CONTINUE
      RETURN
      END
```

5.3.4.17 Subroutine PRADAR

One of the most involved subroutines used in this model involves the computation of the probability of radar detection. The methodology used here is that outlined by Brookner [1978] and also used in the ASALT I. The universal cumulative probability of radar detection curves for a multiple scatter target (i.e. Swerling I) is modeled according to Fig. 5.18 as a set of several table functions labeled PDRT and RCROT and passed to the subroutine as first and second arguments. Other inputs are two ratios whose importance is better appreciated in Example 5.1 of this dissertation. The ratio of the change in aircraft position per radar scan and the single-scan radar detection range is labeled DRDRO while that of the aircraft instantaneous position to the single-scan radar detection range is defined RCDR for the subroutine purposes. A qualitative significance of these two ratios is as follows. RCDR provides an indication of the closeness of the target to the radar antenna while DRDR complements this information by providing specifics about the target closing speed to the radar antenna. The two facts combined determine the number of times the target is illuminated by the radar signal and thus dictate the probability of target detection. Four integer numbers complement the inputs to the subroutine. NA is associated with the number of aircraft, NT with the number of radar installations, NR and NC define the number of entries of the universal cumulative probability of detection curves. The main algorithm then performs

a two-dimensional search to locate the instantaneous values of DRDR and RCDR in Fig. 5.18 and thus find the cumulative probability of detection. The search algorithm starts checking values of DRDR below 5.0 *db* as seen in Eq. 5.551 where branching occurs to either Eq. 5.552 for interpolation within the lowest DRDR curve or to Eq. 5.558 where a check is performed on DRDR for low closing speeds (i.e. high DRDR values). The third main choice of DRDR values are those lying between 5 and 25 decibels wich represent largely the values of interest for probability of radar detection. Eqs. 5.565 through 5.571 represent the two dimensional search for this particular range of DRDR and RCDR values. Notice that the first curve to be tested is that at DRDR of 5 decibels and then increasing the values by 5 decibels (i.e. curves available) by means of the recursion relation shown in Eq. 5.565. Once the value of DRDR has been located between two adjacent curves the algorithm proceeds the search in the RCDR direction (upwards in the curves) until the desired point of interest is located and an interpolated value of PDR (ordinate axis in Fig. 5.18) can be found.

```
      SUBROUTINE PRADAR (PDRT, RCROT, DRDR, RCDR, NA, NT, NR, NC, PDR)
      INTEGER NA, NT, NC, NR, I, J, K
      REAL DRDR(NA,NT), RCDR(NA,NT), PDR(NA,NT), PDRT(NR,NC)
      REAL  RCROT(NR,NC)
C
      DO 001 I=1,NA
       DO 001 J=1,NT
         IF (DRDR(I,J) .LE. 5.0) THEN                                    5.551
           IF (RCDR(I,J) .GE. RCROT(1,1)) THEN                           5.552
             PDR(I,J) = PDRT(1,1)                                        5.553
           ELSE
             IF (RCDR(I,J) .LE. RCROT(1,NC)) THEN                        5.554
               PDR(I,J) = PDRT(1,NC)                                     5.555
             ELSE
               DO 003 K=1,N3
               IF (RCDR(I,J) .LE. RCROT(1,K)) THEN                       5.556
                 PDR(I,J) = PDRT(1,K) + (RCDR(I,J) -
     +                   RCROT(1,K))*(PDRT(1,K+1)-PDRT(1,K))/
     +                   (RCROT(1,K+1)-RCROT(1,K))                       5.557
               ENDIF
003             CONTINUE
             ENDIF
           ENDIF
         ELSE
           IF (DRDR(I,J) .GE. 25.0) THEN                                 5.558
             IF (RCDR(I,J) .GE. RCROT(5,1)) THEN                         5.559
               PDR(I,J) = PDRT(5,1)                                      5.560
             ELSE
               IF (RCDR(I,J) .LE. RCROT(5,NC)) THEN                      5.561
                 PDR(I,J) = PDRT(5,NC)                                   5.562
               ELSE
                 DO 004 K=1,N
                 IF (RCDR(I,J) .LE. RCROT(5,K)) THEN                     5.563
                   PDR(I,J) = PDRT(5,K) + (RCDR(I,J) -
     +                   RCROT(5,K))*(PDRT(5,K+1)-PDRT(5,K))/
     +                   (RCROT(5,K+1)-RCROT(5,K))                       5.564
```

```
                ENDIF
004               CONTINUE
              ENDIF
            ENDIF
          ELSE
            DO 002 L=1,NR
              IF (DRDR(I,J) .GT. FLOAT(L+4*L)) THEN                    5.565
                IF (RCDR(I,J) .GE. RCROT(L,1)) THEN                    5.566
                  PDR(I,J) = PDRT(L,1)                                 5.567
                ELSE
                  IF (RCDR(I,J) .LE. RCROT(L,NC)) THEN                 5.568
                    PDR(I,J) = PDRT(L,NC)                              5.569
                  ELSE
                    DO 005 K=1,N
                    IF (RCDR(I,J) .LE. RCROT(L,K)) THEN                5.570
                     PDR(I,J) = PDRT(L,K) + (RCDR(I,J) -
     +                    RCROT(L,K))*(PDRT(L,K+1)-PDRT(L,K))/
     +                    (RCROT(L,K+1)-RCROT(L,K))                    5.571
                    ENDIF
005                  CONTINUE
                  ENDIF
                ENDIF
              ENDIF
002           CONTINUE
            ENDIF
          ENDIF
001   CONTINUE
      RETURN
      END
```

5.3.4.18 Subroutine PTF

This subroutine computes the probability of the defense weapon sites having sufficient time for firing (PTF). The probability of having sufficient time for firing as will be explained later in Section 5.3.8.3 of this dissertation is a complex function of several factors. Among them the aircraft speed, the aircraft flight path, the defense weapons kinematic envelopes, release of expendables, time available in the firing envelope, etc. All these factors can be captured in a single plot which considers as the independent variable the average tracking and flyout time of the propagator to the target aircraft (ARFOT) and the probability of sufficient time to (PTF) fire as the dependent variable. The role of this subroutine is then to take this curve and estimate the values of PTF given ARFOT. Previous interpolation subroutines cannot be used in this particular procedure because the event modeled is dependent upon the ground sites (N), the target aircraft (M), and the defense weapons (L) used resulting in at least a three dimensional transition array. Inputs to the subroutine are the propagator flyout time to the target (FOT), the time available in the firing envelope (TA), the table function relating PTF with

the ratio of FOT and TA denoted by pairs (X,F), the number of aircraft (NA), the number of weapon sites (NT), and the number of defense weapons (NWE). The single output is the value of the probability of having sufficient time for firing PTF.

```
      SUBROUTINE PTF (F, X, TA, FOT, NA, NT, NWE, NP, FOUT)
      INTEGER NA, NT, NWE, I, J, K, L
      REAL FOT(NA,NT,NWE), TA(NA,NT,NWE)
      REAL X(NP), F(NP), FOUT(NA,NT,NWE)
C
      DO 001 I=1,NA
       DO 001 J=1,NT
         DO 001 L=1,NWE
           IF (FOT(I,J,L)/(TA(I,J,L)+.001) .GE. X(1)) THEN                    5.572
              FOUT(I,J,L) = F(1)                                              5.573
           ELSE
              IF (FOT(I,J,L)/(TA(I,J,L)+0.001) .LE. X(NP)) THEN               5.574
               FOUT(I,J,L) = F(NP)                                            5.575
              ELSE
               DO 002 K=1,NP
                 IF (FOT(I,J,L)/(TA(I,J,L)+.001) .LT. X(K)) THEN              5.575
                   FOUT(I,J,L) = F(K) + (FOT(I,J,L)/
     +                 (TA(I,J,L)+.001)-X(K)) * (F(K+1) - F(K))/
     +                 (X(K+1)-X(K))                                          5.576
                 ENDIF
002             CONTINUE
              ENDIF
           ENDIF
001   CONTINUE
      RETURN
      END
```

5.3.4.19 *Subroutine SPECTR*

This subroutine calculates the effective infrared radiance (EFFR) of a gray body (e.g. target aircraft) given the spectral boundaries of infrared source (MU), the temperature of the body (TEMP), the number of radiant bodies (NA), the universal blackbody curves for infrared detection (see Appendix D) which is approximated by a table function comprising pairs of values (LTEM,REMIRT), and the body infrared radiance (JAY). JAY represents the perfect IR radiance throughout the entire IR spectrum of a radiating blackbody. However, aircraft targets are not necessarily "perfect radiators" and thus a correction has to be applied to JAY if one is to find the actual IR radiance received at the ground IR sensor which is also bounded in frequency response characteristics (i.e. finite bandwidth). MU represents a vector containing the boundary wavelenght values (in microns) of the IR radiation pattern to be corrected. NC

is the number of values contained in this vector and in general the radiation pattern can be bounded within two values of μ (see Appendix D). TEMP represents a time varying temperature value to be interpolated. It could represent, for example, the temperature of the aircraft skin surface, engine exhaust, or the afterburner plume. The algorithm shown in Eqs. 5.577 through 5.583 is in fact an integration of the normalized IR radiant emittance within a prescribed bandwidth. The internally defined vector REMIR contains the values of the lower and upper values of relative spectral radiance and finally they are subtracted in Eq. 583 to calculate the desired IR radiant energy.

```
      SUBROUTINE SPECTR (LTEM, REMIRT, TEMP, MUS, NA, NP, NC, JAY ,
     +     EFFR)
      INTEGER  NA, NP, NC, I, J
      REAL TEMP(NA), REMIR(2), REMIRT(NP), LTEM(NP), EFFR(NA)
      REAL MUS(NC), JAY(NA)
C
C     SUBROUTINE TO COMPUTE THE PROBABILITY OF INFRARED DETECTION.
C
      DO 001 I=1,NA
       DO 002 L=1,N
         IF (TEMP(I)*MUS(L) .LE. LTEM(1)) THEN                          5.577
           REMIR(L) = 0.0                                               5.578
         ELSE
           IF (TEMP(I)*MUS(L) .GE. LTEM(NP)) THEN                       5.579
              REMIR(L) = 1.0                                            5.580
           ELSE
              DO 003 K=1,NP
                IF ( TEMP(I)*MUS(L) .GT. LTEM(K) ) THEN                 5.581
                   REMIR(L) =  REMIRT(K) + (TEMP(I)*MUS(L)-
     +                 LTEM(K)) * (REMIRT(K+1) - REMIRT(K))/
     +                 (LTEM(K+1) - LTEM(K))                            5.582
                ENDIF
003           CONTINUE
           ENDIF
         ENDIF
002     CONTINUE
        EFFR(I) = JAY(I) * (REMIR(2) - REMIR(1))                        5.583
001   CONTINUE
      RETURN
      END
```

5.3.4.20 *Subroutine SINGL*

This subroutine constitutes another interpolation subroutine for cases where the input and output arrays are one dimensional. As before pairs (X,F) are specified in DATA

statements, XVAL constitutes the value of the independent variable to be interpolated (vector), NA is array size of XVAL and NP that of the table function values.

```
      SUBROUTINE SINGL (X, F, XVAL, NA, NP, FOUT)
      INTEGER I, J, NP, NA, NPP
      REAL FOUT(NA), X(NP), F(NP), XVAL(NA)
C
      DO 001 I=1,NA
       IF (XVAL(I) .LE. X(1)) THEN                                    5.584
          FOUT(I) = F(1)                                              5.585
       ELSE
         IF (XVAL(I) .GE. X(NP)) THEN                                 5.586
            FOUT(I) = F(NP)                                           5.587
         ELSE
            DO 002 J=1,NP
              IF (XVAL(I) .GT. X(J)) THEN                             5.588
                 FOUT(I) = F(I) + (XVAL(I)-X(J))*
     +                (F(J+1)- F(J))/(X(J+1)-X(J))                   5.589
              ELSE
              ENDIF
002           CONTINUE
         ENDIF
       ENDIF
001   CONTINUE
      RETURN
      END
```

5.3.4.21 *Subroutine SUM2*

This subroutine adds the outer most dimension elements of a two-dimensional array (B). The size of the original (B) and reduced arrays (A) are specified by integers N1 and N2.

```
      SUBROUTINE SUM2 (A, B, N1, N2)
      INTEGER I, J, N1, N2
      REAL A(N1), B(N1,N2)
C
      DO 001 I=1,N1
       A(I) = 0.0                                                     5.590
       DO 001 J=1,N2
         A(I) = A(I) + B(I,J)                                         5.591
001   CONTINUE
      RETURN
      END
```

5.3.4.22 *Subroutine SUM3*

This subroutine adds both, the outer most and the two outer most dimensions of a three-dimensional array (C). Inputs are array C and the respective dimensions of this array (N1, N2, and N3). The outputs are a two-dimensional array B (N1,N2) and a one dimensional array (N1) which are initialized in Eqs. 5.592 and 5.593, respectively. Eqs. 5.594 and 5.595 make the respective dimensional reductions.

```
      SUBROUTINE SUM3 (C, A, B, N1, N2, N3)
      INTEGER I, J, K, N1, N2, N3
      REAL A(N1), B(N1,N2), C(N1,N2,N3)
C
      DO 001 I=1,N1
       A(I) = 0.0                                              5.592
       DO 002 J=1,N2
         B(I,J) = 0.0                                          5.593
         DO 003 K=1,N3
           B(I,J) = B(I,J) + C(I,J,K)                          5.594
003      CONTINUE
       A(I) = A(I) + B(I,J)                                    5.595
002    CONTINUE
001   CONTINUE
      RETURN
      END
```

5.3.4.23 *Subroutine SUMACF*

This subroutine adds both, the middle and the two outer most dimensions of a three-dimensional array (C). Inputs are array C and the respective dimensions of this array (N1, N2, and N3). The outputs are a two-dimensional array B (N1,N3) and a one dimensional array (N1) which are initialized in Eqs. 5.596 and 5.597, respectively. Eqs. 5.598 and 5.599 make the respective dimensional reductions.

```
      SUBROUTINE SUMACF (C, A, B, N1, N2, N3)
      INTEGER I, J, K, N1, N2, N3
      REAL A(N1), B(N1,N3), C(N1,N2,N3)
C
      DO 001 I=1,N1
       A(I) = 0.0                                              5.596
       DO 002 K=1,N3
         B(I,K) = 0.0                                          5.597
         DO 003 J=1,N2
```

```
            B(I,K) = B(I,K) + C(I,J,K)                                    5.598
003         CONTINUE
          A(I) = A(I) + B(I,K)                                            5.599
002       CONTINUE
001     CONTINUE
        RETURN
        END
```

5.3.4.24 Subroutine SUMDWS

This subroutine adds the inner most dimension of a three-dimensional array C as well as the inner and outer dimensions of the same array. The outputs are B(N2,N3) and a one dimensional array A(N2) whose initialization take place in Eqs. 5.600 and 5.601 ,respectively.

```
        SUBROUTINE SUMDWS (C, A, B, N1, N2, N3)
        INTEGER I, J, K, N1, N2, N3
        REAL A(N2), B(N2,N3), C(N1,N2,N3)
C
        DO 001 J=1,N2
         A(J) = 0.0                                                       5.600
         DO 002 K=1,N3
           B(J,K) = 0.0                                                   5.601
           DO 003 I=1,N1
             B(J,K) = B(J,K) + C(I,J,K)                                   5.602
003        CONTINUE
         A(J) = A(J) + B(J,K)                                             5.603
002      CONTINUE
001     CONTINUE
        RETURN
        END
```

5.3.4.25 Subroutine DELAY3

This subroutine is used to introduce a "full" time delay to a three dimensional array variable. The word full has been used with the notion that most delays are, in general, approximations to a signal reconstruction process involved in generating a time delay [Smith, 1987]. The method adopted here is to artificially create a queueing array that stores the past history of the variable to be delayed and then recall the particular elements of the array that correspond to the instantaneous time delay to be introduced. One clearly perceives a drawback of the method being the large storage capacity associated with the "bookeeping"

of the reconstruction task. The method however, seems necessary due to large time variations in the eingenvalues of the processes modeled (i.e. propagators times of flight vary significantly).

The tradeoff that one can adopt is to size the queueing array based upon the largest expected time delay in the simulation and the most likely simulation step size used. Fortunately, the largest delays in this model are simply those associated with the attrition rate equations. Since the largest expected delays are in the order of 45 seconds for the long range weapons modeled (i.e. time to reach outer lethal envelope) and since the step size of 3 to 5 seconds would be used the storage needs for the queueing arrays will be around 15 to 9 cells. With this aspect in mind we can proceed to describe the subroutine. Inputs to the subroutine are the 3-dimensional variable to be delayed (VARIN), the corresponding integers defining the array size of VARIN (N1, N2,N3), the number of memory cells allocated for the delayed array (N), the delay time (MTOF), the simulation step size used (DT), and the dummy queueing array VAR which needs to be initialized outside the subroutine. Eqs. 5.604 and 5.606 perform the cycling of the elements of the queueing array (N - 1) times since first element to the queue is always the entering variable (VARIN). Eq. 5.605 loads the queueing array at the lowest cell (see Fig. 5.49) and proceeds backwards for convenience. The IF-THEN-ELSE structure shown in Eqs. 5.608 through 5.613 locates the position of the delayed variable when the time delay is equal to MTOF. Notice that two checks are performed to verify for very short time delays (Eq. 5.608) and longer delays than those capable of being generated with the current queueing array (VAR). Finally, linear interpolation is used to extract the current value of VAROUT (i.e. the delayed variable) if no cell matches exactly the value of the ratio MTOF/DT which is associated with the cell position for a delay of MTOF seconds. Notice that the array VAR has four dimensions in this particular subroutine since the array to be delayed is three-dimensional to start with. The size of VAR then should be used with caution in order to avoid excessive computational burden.

```
SUBROUTINE DELAY3 (VARIN, VAROUT, VAR, N1, N2, N3, N, MTOF, DT)
INTEGER I, J, K, N1, N2, N3, N, NP, DT, P
```

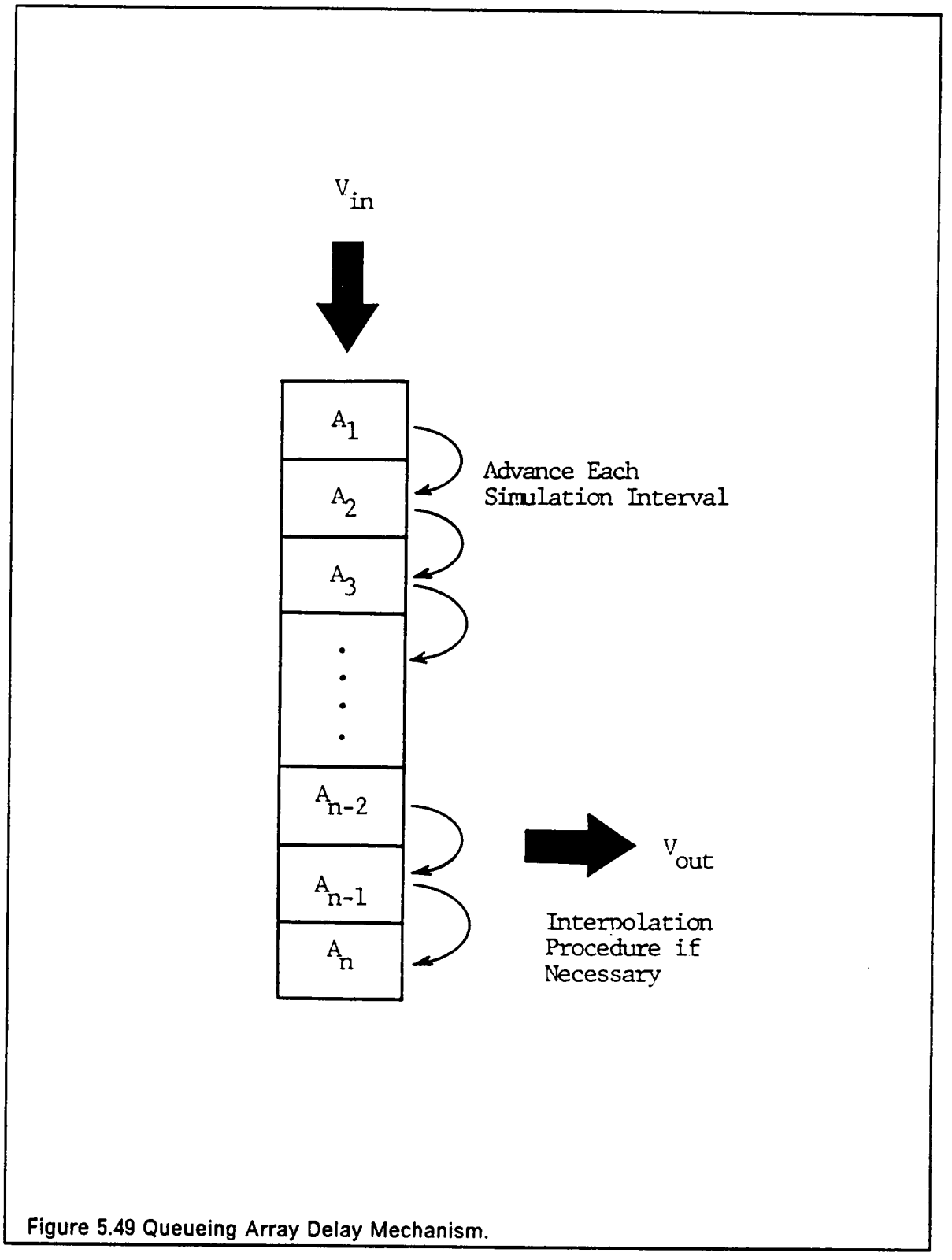


Figure 5.49 Queueing Array Delay Mechanism.

```
      REAL VARIN(N1,N2,N3), VAROUT(N1,N2,N3), VAR(N1,N2,N3,N)
     +  , MTOF(N1,N2,N3)
C
      NP = N - 1                                                    5.604
      DO 001 I=1,N1
      DO 001 J=1,N2
      DO 001 K=1,N3
      DO 004 P=1,NP
       M     = N + 1 - P                                          5.605
       VAR(I,J,K,M) = VAR(I,J,K,M-1)                              5.606
       VAR(I,J,K,1) = VARIN(I,J,K)                                5.607
       IF ( INT(MTOF(I,J,K))/DT . LE. 1 ) THEN                    5.608
         VAROUT(I,J,K) = VAR(I,J,K,1)                             5.609
       ELSE
          IF ( INT(MTOF(I,J,K))/DT . GE. N ) THEN                 5.610
             VAROUT(I,J,K) = VAR(I,J,K,N)                         5.611
          ELSE
             IF ( INT(MTOF(I,J,K))/DT . GE. P ) THEN              5.612
                VAROUT(I,J,K) = VAR(I,J,K,P) +
     +                  (INT(MTOF(I,J,K))/DT-P) *
     +                  (VAR(I,J,K,P+1) - VAR(I,J,K,P))          5.613
             ENDIF
          ENDIF
       ENDIF
004   CONTINUE
001   CONTINUE
      RETURN
      END
```

5.3.5 Model Initial Conditions

The model initial conditions are grouped into five important computational blocks that will be described in this section. The first one deals with the initialization of certain level variables that need to be used in subsequent computations in the initial conditions module or in the dynamic portion of the model. In the second, the mission fuel required is estimated through a mission phase decomposition scheme. The third block initializes the aircraft mass at the beginning of the dynamic simulation and computes secondary aircraft geometric parameters. In the fourth one time independent radar range parameter computations are performed outside the dynamic loop and finally, in the fifth block the initialization of dummy queuing arrays used in the delay of attrition equations takes place.

5.3.5.1 *Payload and Zero-Fuel Mass*

The number of air-to-surface (AS) weapons and electronic countermeasures equipment (ECM) are initialized in DATA statements at the beginning of the model code in DATA statements labeled ASWU and NEECM as well as the corresponding masses associated with each one of the various AS weapons (ASWUW) and that of the ECM pods (WEECM). The payloads due to weapons and ECM equipment are the scalar product of the mass vectors and the number of weapons matrix for each item as shown in Eqs.5.615 and 5.618. The aircraft zero-fuel mass is then computed in Eq. 5.619 as the sum of the aircraft operating empty mass (EMASS) which constitutes another input to the model, the weapons payload (PAYLD), and the ECM payload (ECMM). Eq. 5.620 defines a first pass guess of the mission fuel (EFUEL) which will be used in the fuel requirements iterative estimation to be described in next section. At this point the complete aircraft radar cross section (RCS) is estimated as the sum of the clean aircraft RCS and the contribution of the external stores and ECM equipment. Eq. 5.616 invokes subroutine MATRIX to calculate the total contribution of external stores per aircraft. Also defined here is parameter GAIN used in the proportional control algorithm of the throttle setting. The numerical value used seems to offer good response characteristics with little speed oscillations.

```
      GAIN = 1./10000.                                              5.614
      CALL MATRIX ( PAYLD, ASWU, ASWUW, M, KK)                      5.615
      CALL MATRIX (RCSW, ASWU, DRCSW, M, KK)                        5.616
C
C
      DO 050 I=1,M
        DECMCD(I) = NEECM(I) * ECMCDO(I)                            5.617
        ECMM(I)   = NEECM(I) * WEECM(I)                             5.618
        MASSZF(I) = EMASS(I) + PAYLD(I) + ECMM(I)                   5.619
        EFUEL(I)  = 5000.                                           5.620
        WINGK(I)  = 1 / (EFF(I) * AR(I) * PI )                      5.621
        RCS(I)    = RCSC(I) + RCSW(I)                               5.622
050   CONTINUE
C
C       PAYLD  - WEAPON PAYLOAD (KG)
C       ECMM   - EXTERNAL ECM EQUIPMENT PAYLOAD (KG)
C       DECMCD - INCREMENT CDO DUE TO EXTERNAL ECM POD (DIM)
C       MASSZF - AIRCRAFT ZERO FUEL MASS (KG.)
C       EFUEL  - FIRST ESTIMATE OF MISSION FUEL (KG.)
C       WINGK  - WINGSPAN EFFICIENCY FACTOR (DIM)
C       RCS    - RADAR CROSS SECTIONAL AREA (SQ. METERS)
```

5.3.5.2 *Aircraft Mission Fuel Requirements*

One of the most important parameters in aircraft operations is the estimation of the fuel required for a particular mission. The process used to estimate this parameter is iterative in nature since it is impossible to predict engine fuel consumptions under transient throttle conditions that are a function of aircraft speed, altitude, aerodynamic configuration (e.g. external stores, clean aircraft, etc.), thrust specific fuel consumption (TSFC), etc. without actually integrating the aircraft equations of motion for a particular environment. This of, course is prohibitive at this point because we only want to appraise the amount of fuel to be carried in order to fly a particular mission scenario. Note, also that a gross assumption of setting all mission conditions as constant is not acceptable since the variations in aircraft mass, drag, and thrust are large throughout the mission. An intermediate approach used here is to decompose the mission in stages such that an average value of mass, drag, altitude, speed, etc. can be obtained for each segment of the mission and hence a more refined fuel approximation found. Two stages with one or more segments are defined for our purposes: 1) a high altitude cruise phase and 2) the low altitude and high speed ingress and egress over hostile territory (see Fig. 5.50).

Cruise Fuel Requirements: The cruise phase is assumed to have one segment of length DISTC and flown at speed VCRS. For the baseline conditions a 150 Km. cruise segment is assumed to comply with the 400 Km. baseline mission radius (Fig. 5.50). The altitude of the cruise segment ALTCRS can also be specified with 6000 meters used as baseline value. The time spent in the cruise segment is computed in Eq. 5.625 where a factor of 2 is used in front to account for cruise-in and cruise-out conditions. The initial estimate of the aircraft takeoff mass (MASSTO) is done in Eq. 5.624 where the estimated fuel (EFUEL) is used in each pass. The iterative procedure is controled by the outer DO-LOOP structure which is executed three times to achieve convergence. The actual convergence of this procedure is extremely fast and it has been observed that after three iterations the difference between the fuel required (FUELW) and

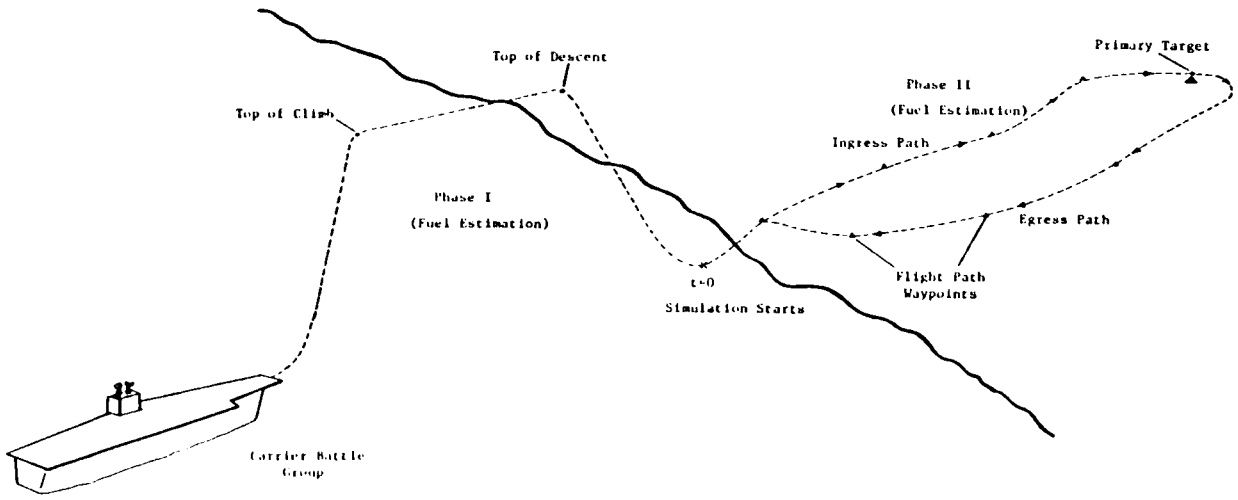


Figure 5.50 Aircraft Mission Fuel Phases.

that estimated (EFUEL) is on the order of 2 to 3 kilograms (i.e. 0.15 percent of a typical takeoff mass). Vector MFUEL defined in Eq. 5.623 is initialized to zero and it will be later used to process the fuel masses consumed per segment for each aircraft. Eqs. 5.626 through 5.631 invoke the aircraft performance subroutines to calculate atmospheric characteristics at cruise conditions (ATMOS), aerodynamic drag coefficients under those conditions (INTER and MATRIX), the total aircraft aerodynamic drag (DRAGF), the thrust specific fuel consumption at cruise altitude (INTER in Eq. 5.630), and finally the fuel consumed at cuise (MFUEL) by means of subroutine FUEL. Eq. 5.631 assigns the value of the dummy vector MFUEL to FUELCR which represents the fuel consumed during the cruise phase. Eq. 5.632 defines MASSEG as the current aircraft mass after the cruise segment whose value will be used as input to the next phase.

```
      DO 901 L=1,3
        DO 752 I=1,M
          MFUEL(I) = 0.0                                          5.623
          MASSTO(I) = MASSZF(I) + EFUEL(I)                        5.624
          TCRS(I) = 2. * DISTC(I) / VCRS(I)                       5.625
752     CONTINUE
        CALL ATMOS (VCRS, ALTCRS, MACH, DELTA, THETA, SIGMA, RHO
     +          , TO, PO, GAMMA, M, Q)                           5.626
          CALL INTER (MACHD, CDOM, MACH, 11, M, CDOB)             5.627
          CALL MATRIX (CDOWE, ASWU, ASCDO, M, KK)                 5.628
          CALL DRAGF (CDOB, MACH, Q, CDOWE, MASSTO, M, S, AR, EFF,
     +                PI, CDI, CD, CL, DRAG)                     5.629
          CALL INTER (MACHD, SNABT, MACH, 11, M, SFCU)            5.630
          CALL FUEL (DRAG, SFCU, TCRS, M, FFLOW, MFUEL, G)        5.631
        DO 880 I=1,M
          FUELCR(I) = MFUEL(I)                                    5.632
          MASSEG(I) = MASSTO(I) - FUELCR(I)/2.                    5.633
880     CONTINUE
```

Ingress and Egress Fuel Requirements: The procedure described before is also applicable to this section once the proper new aircraft altitudes, speeds, and waypoint distances are defined. Eq. 5.634 starts by defining the number of segments NH that will be used in the fuel requirement estimation procedure. The number of segments is dictated by the number of waypoints defining the aircraft flight path (W) as seen in the same equation. RFUEL and DISTS are matrices that represent fuel masses and distances, respectively for each segment (j) and aircraft (i) as defined by Eqs. 5.635 and 5.636. Following along, DISFX, DISFY, and DISFSE represent dummy variables that process the downrange, lateral range, and resultant range

between two adjacent waypoints. Note also the fact that these quantities are temporary in nature since every pass that the inner loop (DO 750) is executed their values change (Eqs. 5.639 through 5.641). The IF-THEN-ELSE structure shown in Eq. 5.638 is necessary to transition between ingress (XWIN,YWIN) and egress waypoints (XWOUT,YWOUT). For the baseline case six waypoints were used and thus five segments defined for the ingress path. Eq. 5.642 sets the aircraft average speed on the segment as the speed of the end waypoint defining that particular segment. The time to travel each segment (TSEG) is computed in Eq. 5.650 while Eqs. 5.651 and 5.652 record the fuel used and the aircraft mass at the end of each segment (RFUEL and MASSEG). This concludes the steps executed in the inner loop where the iteration count is sized according to the number of aircraft present in the simulation (I). The outer loop execution (i.e. loop with terminal value 751) continues with the invocation of the aerodynamic subroutines (Eqs. 5.653 through 5.660) used to estimate: 1) the atmospheric characteristics at the new low-penetration altitude (ALTS), 2) the zero-lift drag coefficient (CDOB), 3) the incremental zero-lift drag coefficient due to external stores carriage (CDOWE), 4) the total aircraft drag (DRAG), 5) the thrust specific fuel consumption (SFCU), and 5) the fuel mass consumed in the flight segment (MFUEL). This procedure is repeated NH times until the last egress segment is reached. In the next step one can add the fuel mass contributions of all the segments for each aircraft to know the total fuel expenditure FUELS (Eq. 5.661). The total fuel required for the mission (FUELW) is the sum of the cruise fuel mass (FUELCR) and the low-altitude penetration phase fuel mass (FUELS) as shown in Eq. 5.662. Note that a ten percent fuel reserve has been alloted in this expression. With knowledge of FUELW a new update is done for the estimated mission fuel (EFUEL) and the takeoff mission mass (MASSTO) according to Eqs. 5.664 and 5.665 before the next iteration is performed.

```
      NH = 2*W - 2                                                    5.634
      DO 751 J=1,NH
        DO 750 I=1,M
          RFUEL(I,J) = 0.0                                            5.635
          DISTS(I,J) = 0.0                                            5.636
          DISTS(I,1) = SQRT( ABS(XWIN(I,1)-XS(I))**2 +
     +               ABS(YWIN(I,1)-YS(I))**2)                         5.637
          IF (J .LE. 5) THEN                                          5.638
            DISFX    = ABS(XWIN(I,J+1) - XWIN(I,J))                   5.639
            DISFY    = ABS(YWIN(I,J+1) - YWIN(I,J))                   5.640
```

```
            DISFSE    = SQRT( DISFX**2 + DISFY**2)                          5.641
            DISTS (I,J)= DISTS(I,J) + DISFSE                                5.642
            VSEG(I)   = VTIN(I,J+1)                                         5.643
          ELSE
            K = J - 5                                                       6.644
            DISFX     = ABS(XWOUT(I,K+1) - XWOUT(I,K))                      5.645
            DISFY     = ABS(YWOUT(I,K+1) - YWOUT(I,K))                      5.646
            DISFSE    = SQRT( DISFX**2 + DISFY**2)                          5.647
            DISTS (I,J)= DISTS(I,J) + DISFSE                                5.648
            VSEG(I)   = VTOUT(I,K+1)                                        5.649
          ENDIF
          TSEG(I)   = DISTS(I,J)/VSEG(I)                                    5.650
          RFUEL(I,J) = RFUEL(I,J) + MFUEL(I)                                5.651
          MASSEG(I) = MASSEG(I) - RFUEL(I,J)                                5.652
750       CONTINUE
          CALL ATMOS (VSEG, ALTS, MACH, DELTA, THETA, SIGMA, RHO
     +              , TO, PO, GAMMA, M, Q)                                  5.653
          CALL INTER (MACHD, CDOM, MACH, 11, M, CDOB)                       5.654
          CALL MATRIX (CDOWE, ASWU, ASCDO, M, KK)                           5.655
          IF (J .LE. 5) THEN                                                5.656
            CALL DRAGF (CDOB, MACH, Q, CDOWE, MASSEG, M, S, AR,
     +            EFF, PI, CDI, CD, CL, DRAG)                             5.657
          ELSE
            CALL DRAGF (CDOB, MACH, Q, ZERO, MASSEG, M, S, AR,
     +            EFF, PI, CDI, CD, CL, DRAG)                             5.658
          ENDIF
          CALL INTER (MACHD, SNABT, MACH, 11, M, SFCU)                      5.659
          CALL FUEL (DRAG, SFCU, TSEG, M, FFLOW, MFUEL, G)                  5.660
751     CONTINUE
C
        CALL SUM2 (FUELS, RFUEL, M, 10)                                     5.661
C
        DO 782 I=1,M
          FUELW(I) = 1.1 * (FUELCR(I) + FUELS(I))                           5.662
          DELTAF(I) = ABS(EFUEL(I)-FUELW(I))                                5.663
          EFUEL(I) = FUELW(I)                                               5.664
          MASSTO(I) = MASSZF(I) + FUELW(I)                                  5.665
          ENDIF
782     CONTINUE
901   CONTINUE
C
C         MASSTO  - TAKEOFF MASS (KGS.)
C         MASSZF  - ZERO FUEL AIRCRAFT MASS (KGS.)
C         MASSEG  - MASS AT EACH FLIGHT SEGMENT OF FLIGHT PATH (KGS)
C         MASS    - AIRCRAFT CURRENT MASS (KGS.)
C         FUELR   - FUEL REMAINING ON THE MISSION (KGS.)
C         FUELW   - MASS OF FUEL CARRIED FOR THE MISSION (KGS.)
C         DELTAF  - DELTA MASS USED TO ESTIMATE FUEL REQUIREMENT
C         EFUEL   - FIRST ESTIMATE OF MISSION FUEL FUEL (KGS.)
C         ALTCRS  - CRUISE ALTITUDE (METERS)
C         VCRS    - CRUISE SPEED (HIGH ALTITUDE SEGMENT) IN METERS
C         FUELCR  - FUEL MASS CONSUMED IN CRUISE SEGMENT (KGS.)
C         TCRS    - TIME SPENT IN CRUISE SEGMENT (SECONDS)
```

Aircraft Initial Steady-State Parameters: The approach taken in ASALT II is to simulate dynamically and explicitly only those portions of the mission were combat interactions are likely to occur between the aircraft and the ground threat. For this reason the dynamic simulation starts with aircraft already in flight at 250 Km. from the main target area as depicted in Fig. 5.50. The mass of each aircraft at the beginning of the simulation is computed according to Eq. 5.666.1. Another variable that is included here is the fuel mass remaining on

each aircraft (FUELR). This one can effectively be used to calibrate the mission fuel requirements with trial runs at various conditions. Other variables are the steady-state aircraft lift coefficient at the beginning of the simulation (CL) shown in Eq. 5.668, the aircraft wingspan (B), and the aircraft wetted area estimation (AS) according to Eqs. 5.669 and 5.670, respectively. Eqs. 5.670.1 through 5.670.4 calculate the steady-state aerodynamic parameters for the aircraft at the starting point of the simulation. Note that this is necessary in order to have equilibrium of aerodynamic forces to start with. Eq. 5.670.5 computes the corresponding throttle setting (TSS) for this level non-accelerated flight condition.

```
      CALL ATMOS (VSEG, ALTS, MACH, DELTA, THETA, SIGMA, RHO
     +     , TO, PO, GAMMA, M, Q)                                    5.666
C
      DO 009 I=1,M
        FUELR(I)  = FUELW(I) - FUELCR(I) / 2.                        5.666.1
        MASS(I)   = MASSTO(I) - FUELCR(I) / 2.                       5.667
        CL(I)     = MASS(I) * G / (Q(I) * S(I))                      5.668
        B(I)      = SQRT (S(I) * AR(I))                              5.669
        AS(I)     = 10. ** (K1 + ALOG10 (MASS(I) ** K2)) * (10000./
     +            10.7584)                                           5.670
009   CONTINUE
C
      CALL INTER (MACHD, CDOM, MACH, 11, M, CDOB)                    5.570.1
      CALL MATRIX (CDOWE, ASWU, ASCDO, M, KK)                        5.570.2
      CALL DRAGF (CDOB, MACH, Q, CDOWE, MASSEG, M, S, AR,
     +     EFF, PI, CDI, CD, CL, DRAG)                               5.570.3
      CALL INTER(MACHD, THNAB, MACH, 11, 2, TRUST)                   5.570.4
C
      DO 048 I=1,M
        TSS(I) = DRAG(I) / (TRUST(I)* NE(I)*G*SIGMA(*)*1.1111)       5.570.5
009   CONTINUE
```

Radar Range Time Invariant Parameters: An explicit model for each one of the radar sites is used in the estimation of the probability of radar detection. This approach allows the analyst to explore changes in radar technology that might have leverage in the the final outcome of the mission simulated. Fortunately, many of the physical radar characteristics such as the size of the radar antenna, the radar average power, temperature losses, etc. remain constant throughout the mission and thus need not to be simulated dynamically. A quick glance at the radar range equations described in detail in Appendix E of this dissertation shows that in general the aircraft radar cross section area (RCS) is the only variable that changes with time. An argument can be raised about the variability of the scan time for different radar operation

modes but the changes are small and thus not considered for simplification purposes. This section calculates the so-called radar range parameters represented by Eqs. E.10, E.13, and E.14 in Appendix E for three ECM environments. Eqs. 5.674 through 5.676 represent the radar range parameters for ground radar operation with no jamming (RRPNJ), self-screening jamming (RRPSSJ), and stand-off jamming (RRPSOJ) mode. Equations 5.671 and 5.672 define the characteristics of the jammers used in terms of the effective power radiated by the jammer (JD). Lastly, Eq. 5.673 defines the radar beam scanning area (OMEGA) in terms of azimuth and elevation angle constraints THETAA and THETAE, respectively.

```
      JDSSJ = PSSJ * GSSJ / BWSSJ                                          5.671
      JDSOJ = PSOJ * GSOJ / BWSOJ                                          5.672
C
      DO 018 J=1,N
      OMEGA(J) = THETAA(J) * THETAE(J)                                     5.673
        RRPNJ(J) = (PAVE(J) * RAREA(J) * TS(J) / (16.* KB * TE(J) *
     +          LOSS(J) * SNR(J) * OMEGA(J))) **.25                        5.674
        RRPSSJ(J) = (32. * PAVE(J) * TS(J) / (PI * OMEGA(J) * JDSSJ
                                                                                +
* LOSS(J))) ** .5  5.675
        RRPSOJ(J) = (32. * PAVE(J) * TS(J) / (PI * OMEGA(J) * JDSOJ
     +          * LOSS(J))) ** .25                                         5.676
  018  CONTINUE
```

Initialization of Queuing Arrays: The process of delaying a variable was fully explained in Section of this dissertation. It was noted that dummy arrays were used in order to maintain the history record of the variable until delayed. These arrays in turn need to be initialized only once since their elements are cycled dynamically once the simulation has started (see Fig. 5.50). Eqs. 5.677 and 5.678 perform this initialization.

```
      DO 098 I=1,M
        DO 098 J=1,N
          DO 098 L=1,LL
            DO 098 K=1,10
              CBFQUE(I,J,L,K) = 0.0                                        5.677
  098  CONTINUE
C
      DO 101 I=1,M
        DO 101 J=1,N
          DO 101 K=1,KK
            DO 101 L=1,10
              DWSQUE(I,J,K,L) = 0.0                                        5.678
  101  CONTINUE
```

5.3.6 Computation of Auxiliary Variables

5.3.6.1 Engagement Geometry Description

In order to effectively asses the mechanisms that lead to the engagement and interaction between two enemy forces is necessary to know the geometry of the combatants at any point in the simulation. The initial aircraft and defense weapons states are known from data provided as inputs to the program. Altough the weapon sites are considered fixed for our purposes the aircraft dynamics are sufficient to add plenty of synergism to the engagement. It should be realized that from this module on we are in the realm of a long dynamic process that is to be executed thousands of times in order to estimate the outcome of the mission for both forces. Before the geometry of the engagement is carried out two important checks concerning the current position of the aircraft with respect to the primary target area and the carrier battle group have to be made in order to update the navigation algorithm. Eqs. 5.679 through 5.682 pertain to the event of the aircraft reaching the last ingress navigation waypoint, XWIN(I,W). This constitutes a transition point in the navigation algorithm as will be seen later. Note that only one component of the waypoint position vector (XWIN,YWIN) is necessary in this check. The second check is that of all the aircraft reaching the last egress navigation waypoint XWOUT (Eq. 5.683) marking the end of the simulation as all aircraft have reached a safe position with respect to the ground sites precluding further interactions. Notice that variables RTIMER and RTIM constitute dummy rate variables that become "active" as the two previously explained events take place in the simulation. Variable SRTIM is used to exit the simulation dynamic loop when its value equals the number of original aircraft at the start of the simulation (M).

```
C       CHECK IF TARGET AREA ( XWIN(I,W) ) HAS BEEN REACHED
C
        DO 021 I=1,M
          IF (XS(I) .GE. XWIN(I,W)) THEN                          5.679
            RTIMER(I) = 1                                         5.680
```

```
          ELSE
            RTIMER(I) = 0                                          5.681
          ENDIF
          TIMER(I) = TIMER(I) + RTIMER(I)                          5.682
021     CONTINUE
C
C       CHECK IF STARTING POINT OF DYNAMIC SIMULATION HAS BEED REACHED
C
        DO 022 I=1,M
          IF (XS(I) .LT. XWOUT(I,W)) THEN                          5.683
            RTIM(I) = 1                                            5.684
          ELSE
            RTIM(I) = 0                                            5.685
          ENDIF
022     CONTINUE
C
        CALL SUM1 (SRTIM, RTIM, M)                                 5.686
C
        DO 245 I=1,M
          IF (SRTIM . GE. M) GOTO 1000                             5.687
245     CONTINUE
C
C         TSSR  - THROTTLE SETTING RATE OF CHANGE (1/SEC)
C         LFSR  - LOAD FACTOR FOR AIRCRAFT (G'S)
C         TSS   - THROTTLE SETTING (DIM)
C         LFS   - AIRCRAFT INSTANTANEOUS LOAD FACTOR (G'S)
```

The geometry of the engagement is fully defined when the target aspect angles measured from the aircraft to the ground sites (ATN) and those measured fom the ground sites to the aircraft (TAA) are known. Fig. 5.51 illustrates graphically the geometry of a typical engagement. A one versus three geometry is shown for the sake of clarity although in general the model being dealt here is of M versus N order.

The first task is to estimate the distances between the aircraft and the ground sites and this is accomplished with the invocation of subroutine DISTT shown in Eq. 5.688. The important outputs are derived from this subroutine: 1) the resultant horizontal distance between the aircraft and each target site (ARTT) and 2) the direction of the instantaneous vector line-of-sight joining them (LOSATT) as depicted in Fig. 5.51. Eqs. 5.689 through 5.691 calculate the slant range between the aircraft and each ground site (SRL), the elevation angle (ELEV), and the angular size of the aircraft (in radians) as "seen" by an observer standing at ground level at each site (TSIZE). This latter parameter will be used in the estimation of the probability of visual detection. Eq. 5.692 finds the target aspect angle (ATN) between the aircraft and the target sites with the use of subroutine DIRECT (see section 5.). The direction of the line-of-sight vector from the ground sites to the aircraft (LOSTAA) is evaluated in Eqs. 5.693 through 5.695. Lastly in this sequence the rate of change of the line-of-sight vector

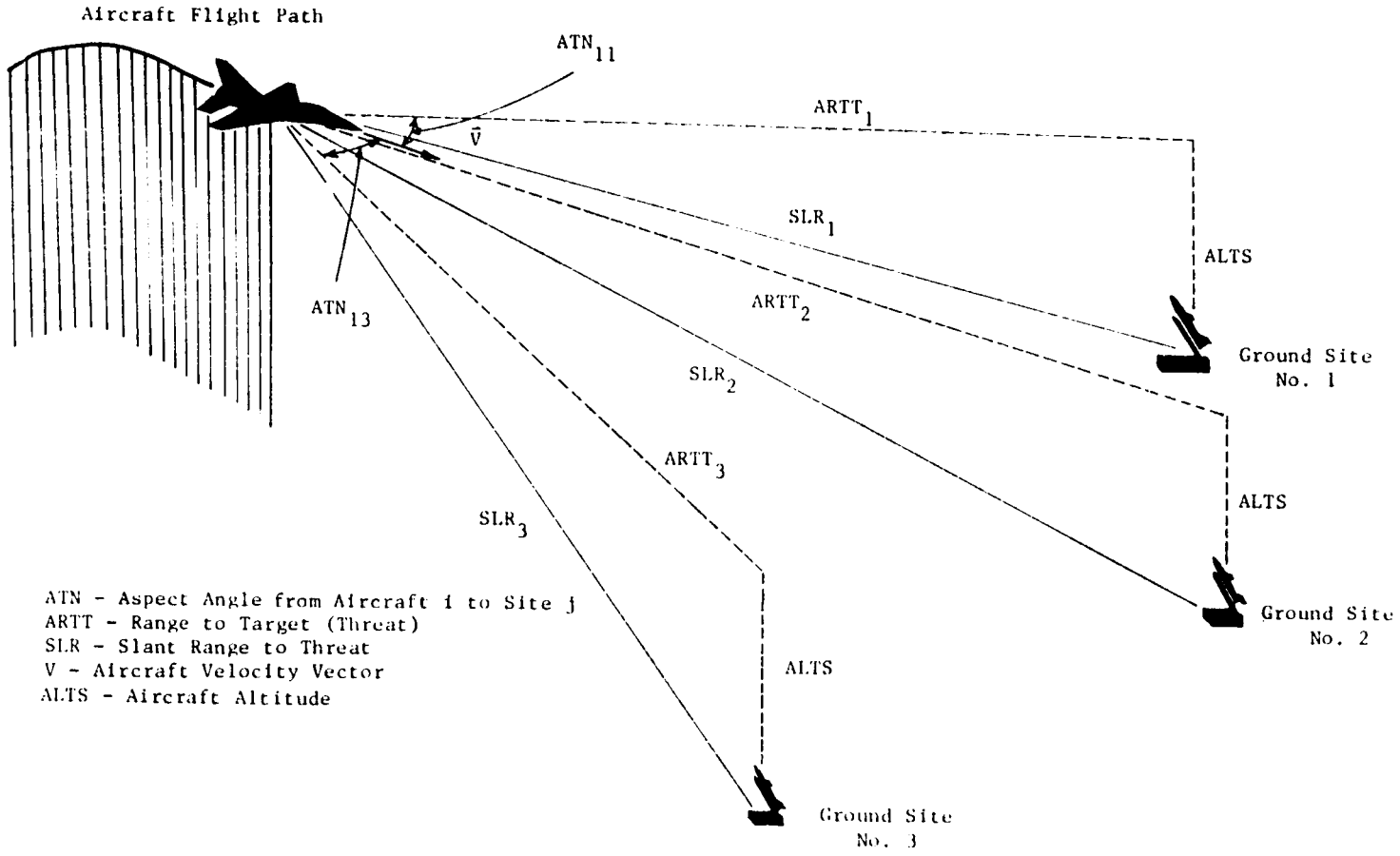


Figure 5.51 Engagement Geometry Definition.

(ATND) is evaluated according to expression 5.698. Notice that the radial and tangential aircraft velocity vector components (VAPPR and VAPPT) are computed in Eqs. 5.696 and 5.697 prior to the evaluation of ATND.

```
      CALL DISTT (XS, YS, XDWS, YDWS, ARTTX, ARTTY, ARTT, M, N,
     +          LOSATT, PI)                                          5.688
C
C         ARTTX  - AIRCRAFT DOWNRANGE TO TARGET (METERS)
C         ARTTY  - AIRCRAFT LATERAL DOWNRANGE TO TARGET (METERS)
C         ARTT   - AIRCRAFT RANGE TO TARGET (METERS)
C
        DO 017 I=1,M
          DO 017 J=1,N
            SRL(I,J)   = SQRT (ARTT(I,J)**2 + ALTS(I)**2)           5.689
            ELEV(I,J)  = ARCOS (ARTT(I,J)/SRL(I,J))                 5.690
            TSIZE(I,J) = ATAN (B(I)/SRL(I,J))                       5.691
017     CONTINUE
C
C         SRL    - SLANT RANGE (METERS)
C         ELEV   - ELEVATION ANGLE (RADIANS)
C         TSIZE  - TARGET ANGULAR SIZE (RADIANS)
C
        CALL DIRECT (HEADS, LOSATT, YS, YDWS, M, N, PI, ATN)        5.692
C
C         LOSATT - LOS VECTOR FROM AIRCRAFT TO TARGET (RADIANS)
C         HEADS  - AIRCRAFT HEADING (RADIANS)
C         ATN    - AIRCRAFT TARGET ASPECT ANGLE (RAD.)
C
        DO 024 I=1,M
          DO 024 J=1,N
            IF (LOSATT(I,J) .GE. PI) THEN                           5.693
               LOSTAA(I,J) = LOSATT(I,J) - PI                       5.694
            ELSE
               LOSTAA(I,J) = PI + LOSATT(I,J)                       5.695
            ENDIF
            VAPPR(I,J) = VS(I) * COS(ATN(I,J))                      5.696
            VAPPT(I,J) = VS(I) * SIN(ATN(I,J))                      5.697
            ATND(I,J)  = ATAN(VAPPT(I,J) / SRL(I,J))                5.698
024     CONTINUE
C
C         ATND   - RATE OF CHANGE IN AIRCRAFT LOS VECTOR (RAD/SEC.)
C         VAPPR  - AIRCRAFT RADIAL APPROACHING SPEED TO TARGET
C         VAPPT  - AIRCRAFT TANGENTIAL "APPROACHING" SPEED TO TARGET
```

Parallel to the calculation of target aspect angle ATN, the navigation algorithm used in this simulation requires the knowledge of the bearing angle (ABA) from an aircraft to the various waypoints defining the flight trajectory. Eq. 5.699 defines the number of flight segments flown (NW) during the two low-level attack phases (i.e. ingress and egress). The decision statement 5.700 branches to the proper waypoint since the ingress and egress activities are disaggregated. Eqs. 5.701 and 5.702 find out the distance and direction of the vector line-of-sight to a waypoint (LOSAWO). The navigation procedure for egress waypoints is executed in Eqs. 5.702 through 5.708. STVDA stands for the aircraft steering vector direction

to the next waypoint while DELTAV represents the differential speed between the target speed at the waypoint (VTIN) and that of the aircraft (VS). This parameter is used later to implement the throttle setting control algorithm. An identical procedure is repeated for the ingress portion of the flight as shown in Eqs. 5.709 through 5.716.

```
      NW = W - 1                                                          5.699
      DO 012 I=1,M
        IF (TIMER(I) .GE. 1) THEN                                         5.700
          CALL DISTW (XS, YS, XWOUT,YWOUT,ARTWOX, ARTWOY, ARTWO,
     +          M, W, LOSAWO, PI)                                       5.701
          CALL DIRECW (HEADS, LOSAWO, YS, YWOUT, M, W, PI
     +          , ABAOUT)                                               5.702
          IF (XS(I) .GT. XWOUT(I,1)) THEN                                 5.703
            STVDA(I) = ABAOUT(I,1)                                        5.704
            DELTAV(I) = VTOUT(I,1) - VS(I)                                5.705
          ELSE
            DO 013 J=1,NW
              IF (XS(I) .LT. XWOUT(I,J)) THEN                             5.706
                STVDA(I) = ABAOUT(I,J+1)                                  5.707
                DELTAV(I) = VTOUT(I,J+1) - VS(I)                          5.708
              ENDIF
013           CONTINUE
          ENDIF
        ELSE
          CALL DISTW (XS, YS, XWIN, YWIN, ARTWIX, ARTWIY, ARTWI
     +          , M, W, LOSAWI, PI)                                     5.709
          CALL DIRECW (HEADS, LOSAWI, YS, YWIN, M, W, PI, ABAIN)          5.710
          IF (XS(I) .LT. XWIN(I,1)) THEN                                  5.711
            STVDA(I) = ABAIN(I,1)                                         5.712
            DELTAV(I) = VTIN(I,1) - VS(I)                                 5.713
          ELSE
            DO 016 J=1,NW
              IF (XS(I) .GT. XWIN(I,J)) THEN                              5.714
                STVDA(I) = ABAIN(I,J+1)                                   5.715
                DELTAV(I) = VTOUT(I,J+1) - VS(I)                          5.716
              ENDIF
016           CONTINUE
          ENDIF
      ENDIF
012   CONTINUE
C
C       ARTWIX  - AIRCRAFT DOWNRANGE TO WAYPOINT (METERS)
C       ARTWIY  - AIRCRAFT LATERAL DOWNRANGE TO WAYPOINT (METERS)
C       ARTT    - AIRCRAFT TO WAYPOINT (METERS)
C       LOSAWI - LOS VECTOR FROM AIRCRAFT TO WAYPOINT (RADIANS)
C       HEADS  - AIRCRAFT HEADING (RADIANS)
C       STVDA  - STEERING VECTOR DIRECTION (TO NEXT WAYPOINT)
C       DELTA  - DIFFERENTIAL SPEED FROM TARGET WAYPOINT SPEED
C       VTOUT  - EGRESS WAYPOINT TARGET SPEED (M/SEC.)
C       VTIN   - INGRESS WAYPOINT TARGET SPEED (M/SEC.)
C       ABAIN  - AIRCRAFT BEARING ANGLE TO INGRESS WAYPOINT (RAD)
C       ABAOUT - AIRCRAFT BEARING ANGLE TO EGRESS WAYPOINT (RAD)
```

5.3.6.2 *Dynamic Model Atmospheric Characteristics*

This section implements the same subroutine ATMOS used before in the estimation of fuel requirements and the calculation of steady-state parameters within the dynamic module. This is necessary as one would expect because the dynamic changes in the aircraft parameters throughout the mission (e.g. speed, altitude, drag, etc.).

```
      CALL ATMOS (VS, ALTS, MACH, DELTA, THETA, SIGMA, RHO,
     +   TO, PO, GAMMA, M, Q)                                    5.717
C
C       VS    - AIRCRAFT VELOCITY (MAGNITUDE) IN M/SEC.
C       ALTS  - AIRCRAFT ALTITUDE (METERS ABOVE MSL)
C       MACH  - AIRCRAFT MACH NUMBER (DIM)
C       DELTA - ATMOSPHERIC PRESSURE RATIO (DIM)
C       THETA - ATMOSPHERIC TEMPERATURE RATIO (DIM)
C       SIGMA - ATMOSPHERIC DENSITY RATIO (DIM)
```

5.3.6.3 *Aircraft Performance Characteristics*

The aircraft is represented as a point mass with dynamics defined explicitly in two degrees of freedom, roll and yaw and implicitly in pitch. The equations of motion of this system are defined in Eqs. 5.160 through 5.164 of the previous model. As can be appreciated this is a fourth order dynamic system where no rotational aircraft dynamics have been included. A fifth differential equation is included in order to account for the mass variations through the mission. The goal of the modeling approach has been to provide a simple yet realistic model of the aircraft aerodynamic forces, thrust and drag and couple them with the powerplant model to estimate basic performance parameters and thus the potential aircraft maneuvering capabilities such as sustained turn rate, maximum sustained yaw rate, specific excess power, etc. The two more important aerodynamic characteristics to be evaluated in any design are lift and drag. Lift and drag information for conceptual design must take the form of educated guesses (based upon previous designs and expected technology improvements) since little is known about the ultimate aircraft configuration. For the purposes

of this model a typical parabolic drag behavior is assumed. The modeling concept do not includes wave drag computations since it is considered that most of the attack missions take place in the high subsonic or low transonic region where wave drag effects can, in general, be neglected. It should be realized that wave drag effects make up roughly 35 percent of the total drag for modern supersonic fighters in the supersonic regime and that when a more complete assessment is desired the model will have to be updated [Covert, 1985]. Drag is modeled as having two principal contributions: 1) skin friction or lift-independent drag and 2) the drag due to lift usually expressed terms of nondimensional coefficients CDO and CDI, respectively. The evaluation of the zero lift drag coefficient (CDO) is performed in two stages. The first one is to define the clean aircraft zero-lift drag coefficient CDOB (Eq. 5.719) and then add the contributions of the external stores and ECM equipment (Eq. 5.722). As before, the contribution of weapons to drag is done through subroutine MATRIX (Eq. 5.720) which performs the matrix multiplication of the number of air-to-surface weapons (ASWU) and the drag increment due to weapons (ASCDO).

Induced drag (CDI) is computed as a parabolic function of the lift generated through the use of subroutine DRAGF (Eq. 5.723) . The lift during the first pass has been initialized in section 5. value which later will be recalculated to allow steady maneuvers such as high-g The aircraft geometric characteristics are modeled as fixed values for the purpose of this model although some degradation or improvement in the the lift curve slope (CLALP) is modeled at various flight speed regimes as shown in Eq. 5.718 where the values of CLALP are read from a table function defined as input to the program through pairs (MACHD,CLALPT). The calculation of the thrust parameters takes place in Eqs. 5.724 through 5.730. Two nearly identical segments separated by a decision statement (Eq. 5.724) are observed. The first one is executed when the normalized throttle setting (TSS) is above 0.9 which correspond to afterburning operation. The second set of equations (5.727 through 5.730) correspond to thrust values in the maximum military regime. Eqs. 5.731 through 5.734 complement the powerplant parameters by computing the thrust specific fuel consumption at the selected throttle setting and aircraft altitude (SFCU), the total fuel flow (FFLOW), the potential thrust available

(PTRUST), and the aircraft stagnation temperature (STGTEM). The altitude corrections to to thrust and specific fuel consumption are based upon rules of thumb which are familiar to the author throughout his years of readings in aviation engine data analysis from several well documented sources [Oates, 1969 and Roskam, 1986]. A more detailed analysis of this corrections would necessarily mean an in-depth analysis of the internal components of the engine (e.g. compressor, turbine, burners, etc.). Following in this sequence, the maximum sustained load factor constrained by thrust and drag considerations (NFAC), its corresponding yaw rate (YAWR), and the available specific excess power (PSA) are calculated in Eqs. 5.734 through 5.737 with the use of subroutines LOADF, YAWRTE, and PS respectively.

```
      CALL INTER(MACHD, CLALPT, MACH, 11, 2, CLALP)                    5.718
      CALL INTER(MACHD, CDOM, MACH, 11, 2, CDOB)                       5.719
      CALL MATRIX (CDOWE, ASWU, ASCDO, M, KK)                          5.720
C
      DO 015 I=1,M
        ALP(I)  = CL(I) / CLALP(I) + ALPO(I)                           5.721
        CDO(I)  = CDOB(I) + CDOWE(I) + DECMCD(I)                       5.722
        CALL DRAGF (CDOB, MACH, Q, CDOWE, MASSTO, M, S, AR, EFF,
     +              PI, CDI, CD, CL, DRAG)                             5.723
        IF (TSS(I).GT.0.9) THEN                                        5.724
          CALL INTER(MACHD, THAB, MACH, 11, 2, TRUST)                  5.725
          CALL INTER(MACHD, SABT, MACH, 11, 2, SFCU)                   5.726
          THRUST(I)  = TSS(I)*TRUST(I)*NE(I)*G*SIGMA(I)                5.727
        ELSE
          CALL INTER(MACHD, THNAB, MACH, 11, 2, TRUST)                 5.728
          CALL INTER(MACHD, SNABT, MACH, 11, 2, SFCU)                  5.729
          THRUST(I)  = TSS(I)*TRUST(I)*NE(I)*G*SIGMA(I)*1.1111         5.730
        ENDIF
        TSFC(I)  = SFCU(I) * SIGMA**0.75
        FFLOW(I)  = THRUST(I) * TSFC(I) / ( G * 3600)                  5.732
        PTRUST(I) = TRUST(I)*G*NE(I)                                   5.733
        STGTEM(I) = THETA(I) * TO * ( 1 + R * (GAMMA - 1)/ 2 *
     +            MACH(I) )                                            5.734
015   CONTINUE
C
C     DRAG  - TOTAL AIRCRAFT DRAG (NEWTONS)
C     CDOWE - INCREMENTAL DRAG COEFFICIENT DUE TO WEAPONS
C     TSS   - AIRCRAFT THROTTLE SETTING (DIM)
C     NE    - NUMBER OF ENGINES PER AIRCRAFT (UNITS)
C     Q     - DYNAMIC PRESSURE (PASCALS)
C     S     - AIRCRAFT WING AREA (SQUARE METERS)
C     THRUST - COMMANDED ENGINE THRUST (NEWTONS)
C     TRUST  - MAXIMUM AVAILABLE ENGINE GROSS THRUST AT SEA LEVEL
C     SFCU   - UNCORRECTED SPECIFIC FUEL CONSUMPTION (KG/HR/KG)
C     3600   - CONVERSION FACTOR FROM HOURS TO SECONDS
C
    CALL LOADF (Q, MASS, S, WINGK, PTRUST, CDO, M, G, NFAC)            5.735
    CALL YAWRTE (NFAC, VS, M, G, YAWR)                                 5.736
    CALL PS (VS, MASS, G, PTRUST, DRAG, M, PSA)                        5.737
pf
```

The performance of the aircraft is intimately related with the guidance algorithm used in the model as can be seen in the diagram shown in Fig. 5.46 which is also valid for this model.

The purpose of this block of equations (5.738 through 5.750) is to further constraint the aircraft performance by introducing human and structural limitations which constitute exogenous variables to the the model. The maximum load factor (NAMAX) is found in Eq. 5.738 as the minimum of the maximum sustained aerodynamic load factor (NFAC), the maximum structural load factor (NSTRUC) and the maximum tolerance load factor value (NCREW). At this point the aerodynamic lift coefficient is redefined in order to account other than one-g conditions according to Eqs. 5.739 and 5.740 to yield a maximum usable load factor (NUS). The corresponding yaw rate capability is computed in 5.742 and the commanded load factor (NCOM) in terms of the commanded yaw rate (SAICO) is evaluated in Eq. 5.749. A final evaluation of the lift coefficient (CL) is necessary in Eq. 5.750 since in many instances reduced turn performance capabilities will be needed in order to intercept the desired heading towards the next navigation waypoint.

```
      DO 014 I=1,M
        NAMAX(I) = AMIN1(NFAC(I), AMIN1(NCREW(I), NSTRUC(I)))          5.738
        CLNAX(I) = NAMAX(I)*MASS(I)*G / (Q(I)*S(I))                    5.739
        CLUS(I)  = AMIN1(CLNAX(I), CLMAX(I))                           5.740
        NUS(I)   = AMAX1(Q(I)*S(I)*CLUS(I)/(MASS(I)*G), 1.0001)        5.741
        SAIRUS(I)= G * SQRT(NUS(I)** 2 - 1)/ VS(I)                     5.742
C       CALL SVECT (SAIRUS, STVDA, M, PI, SAICO, DT)                   5.743
          IF (ABS(STVDA(I)). LE. SAIRUS(I)*FLOAT(DT)) THEN             5.744
              SAICO(I) = - STVDA(I) / DT                               5.745
          ELSE
              IF (STVDA(I). GE. 0) THEN                                5.746
                 SAICO(I) = - SAIRUS(I)                                5.747
              ELSE
                 SAICO(I) = SAIRUS(I)                                  5.748
              ENDIF
          ENDIF
        NCOM(I)  = SQRT(1 + (ABS(SAICO(I)) * VS(I) / G)**2)            5.749
        CL(I)    = NCOM(I)*MASS(I)*G / (Q(I)*S(I))                     5.750
014   CONTINUE
```

5.3.7 Threat Systems Effectiveness

Threat system effectiveness is used to describe a number of the essential functions that must be performed by the threat in order to inflict damage or destroy the attacking aircraft. The essential elements of threat system effectiveness are: the aircraft being in line-of-sight,

aircraft detection and tracking, weapons launch, weapons guidance, and weapons detonation. In order to understand these five basic aspects it is necessary to consider a probability associated with each so as to be able to assess the probability of threat system effectiveness (PTSE) which is used to represent the lethality of the defensive system as a whole. The probability of line-of-sight (PALOS), the probability of aircraft detection (PAD), the probability of defense weapons launch (PDWL), the probability of successful guidance, and the probability of detonation (PDET) constitute the elements necessary to compute PTSE. Eq. shows the basic relationship and in the following sections the individual elements of threat system effectiveness will be discussed in detail. Threat system effectiveness is quantified as a three dimensional matrix with one dimension corresponding to the aircraft (I), one devoted to each weapon site location (J), and the last one to the type of weapon used (L) at that particular ground site location. In terms of the probability of threat systems effectiveness (PTSE) this can be interpreted as the probability that the *j th* weapon has to inflict damage to the *i th* aircraft using weapon *k*. The description of this portion differs from that of ASALT I because the automatic sorting capabilities of DYNAMO III allow one to adopt a "top-down" approach when describing the effectiveness functions. In FORTRAN 77 the aircraft and threat functions are described in a "bottom-up" fashion thus making the code slightly less readable.

5.3.7.1 Aircraft in Line-of-Sight

The probability that an aircraft is in line-of-sight (PALOS) is evaluated as a true or false condition by comparing the aircraft altitude (ALTS) with the critical altitude for a given slant range. The critical altitude constitutes the minimum altitude that a target should have in order to be "seen" from a distant observer located at ground level. Critical altitudes are expressed in table function form by the pairs (RLOST, ZLOST) which are the first and second arguments used to invoke subroutine DOUBL. Numerically, the true condition is assigned a one whereas a zero is used for a false line-of-sight condition as shown in Eqs. 5.751 through 5.754.

```
      CALL DOUBL(RLOST, ZLOST, ARTT, M, N, 8, LOS)                    5.751
      DO 028 I=1,M
        DO 028 J=1,N
          IF (ALTS(I) .GT. LOS(I,J)) THEN                             5.752
            PALOS(I,J) = 1.0                                          5.753
          ELSE
            PALOS(I,J) = 0.0                                          5.754
          ENDIF
028     CONTINUE
```

5.3.7.2 *Aircraft Detection*

Aircraft detection is evaluated as the highest value of the three types of detection considered in this model: 1) visual, 2) infrared and 3) radar detection. Qualitatively these detection mechanisms are evaluated in terms of probabilities and each of the defense weapons is assumed for the baseline model to be associated with a detection mechanism. The following paragraphs describe some of the important assumptions and calculations necessary to arrive to the probabilities of radar, infrared, and visual detection.

Aircraft Radar Signatures and Radar Jamming Characteristics: The main parameter used to describe the radar signature (RF) of a target is its radar cross section (RCS). There are several methodologies to estimate the radar cross section of complex bodies such as those of aircraft and missiles. Theoretical, dynamical, and static approaches have been used with certain limitations by the aerospace community according to Crispin [1969]. It is, however, beyond the scope of this modeling effort to utilize these cumbersome techniques and simplification has been exercised in the computation of RCS. The model considers RCS to be a level variable having two influences that dictate the rate of change of RCS with time. These are aspect angle variations and the time varying number of external stores which could significantly to the total RCS of the aircraft if poor airframe-weapons integration is present [Bore, 1987]. Two aspect angle multipliers, RCSAM and RCSEM, are used to vary the complete aircraft and weapons variations of RCS with azimuth and elevation changes,

respectively (Eqs. 7.755 and 5.756). The effective aircraft RCS is evaluated according to expression 5.757. The initial value of the clean aircraft RCS is represents an singled value input to the model and corresponds to the aircraft frontal RCS. The multipliers RCSAM and RCSEM represent exogenous inputs that are peculiar to each aircraft and will in general be derived from signatures testing performed in anechoic chambers with real aircraft models. The result of this type of testing are usually presented in the form of Fig. 5.5 of this dissertation. Variations of RCS with radar threat parameters (e.g. radar emission frequency) are not accounted since these parameters were assumed constant for the threat. The variations in RCS due to weapons release and number of externally mounted ECM equipment are heavily dependent upon the type of offensive weapons used and the scattering characteristics of the ECM equipment installed (i.e. conformal, pylon, or internal ECM installations). The values chosen were considered typical for medium range missiles and for the 220 kg. smart bombs modeled as will be discussed in Section 5. which discusses the rate variables of the model. The following DO-LOOP block computes some of the dynamic radar parameters such the change in target position between radar scans (DR) and the distance between the stand-off jammer to the target aircraft (RJSOJ) as shown in Eq. 5.762.

There are several mechanisms used as countermeasures against radar detection. Two classes of countermeasures are passive and active devices. The former ones are usually expendables (e.g. rapid bloom chaff) which create unwanted radar returns thus decreasing the probability of detection. Active countermeasures, on the other hand modify the actual RF signal (e.g. creation of noise) conceal the target. Hovanessian [1984] identifies three techniques typically used in noise jamming with non-expendables. These are stand-off jamming, escort jamming, and self screening jamming. The three techniques can be readily implemented in ASALT II an some results will be explored with these variations. The jamming technique is selected by the analyst as an input to the model through variable NRADPO. For no jamming employed the baseline model assumes NRADPO as unity. Stand-off and self-screening jamming techniques can be selected assigning values of 2 and $x > 2$, respectively. Eqs. 5.764 through 5.767 compute the corresponding radar ranges for these

three cases. The values of the radar parameters RCDRO and DRDRO are defined in Eqs. 5.768 ans 5.769.

```
      CALL INTE(ATNT, RCSAMT, ATN, M, N, 5, RCSAM)                    5.755
      CALL INTE(ELEVT, RCSEMT, ELEV, M, N, 5, RCSEM)                  5.756
C
      DO 056 I=1,M
        DO 056 J=1,N
          ERCS(I,J) = RCS(I) * RCSAM(I,J) * RCSEM(I,J)                5.757
056   CONTINUE
C
      DO 027 I=1,M
        DO 027 J=1,N
          DR(I,J)   = ABS (VAPPR(I,J) * TS(J))                        5.758
          DXSOJ(I)  = AMAX1(XS(I)-XSOJ,XSOJ-XS(I))                    5.759
          DYSOJ(I)  = AMAX1(YS(I)-YSOJ,YSOJ-YS(I))                    5.760
          DZSOJ(I)  = AMAX1(ALTS(I)-ZSOJ,ZSOJ-ALTS(I))                5.761
          RJSOJ(I)  = SQRT(DXSOJ(I)**2 + DYSOJ(I)**2 +
     +                DZSOJ(I)**2)                                    5.762
027   CONTINUE
C
      DO 630 I=1,M
        DO 630 J=1,N
          IF (NRADPO .EQ. 1) THEN                                     5.763
            DRO(I,J)  = RRPNJ(J) * ERCS(I,J)**.25                     5.764
          ELSE IF (NRADPO .EQ. 2) THEN                                5.765
            DRO(I,J)  = RRPSOJ(J) * ERCS(I,J)**.25 *
     +                RJSOJ(I) ** 0.5                                 5.766
          ELSE
            DRO(I,J)  = RRPSSJ(J) * ERCS(I,J)**.50                    5.767
          ENDIF 630      CONTINUE
C
C     COMPUTATION OF RANGE AND RANGE RATE PARAMETERS USED IN
C     THE ESTIMATION OF THE PROBABILITY OF RADAR DETECTION
C
      CALL RATINV (SRL, DRO, M, N, RCDRO)                             5.768
      CALL RATINV (DRO, DR, M, N, DRODR)                              5.769
C
C       SRL   - AIRCRAFT TO TARGET SLANT RANGE (METERS)
C       DRO   - SINGLE SCAN RADAR RANGE (METERS)
C       RCDRO - RATIO OF AIRCRAFT-TO-TARGET RANGE TO DRO RANGE
C
```

Aircraft Radar Detection: The radar detection used in the model is based on the method used by Brookner [1978] to evaluate the cumulative probability of detection using the universal detection curves. The target model selected for the universal curves was a Swerling 1 Model which considers the aircraft as a large number of scatters with a similar radar cross sectional area. As it was mentioned before in the section devoted to the subroutine PRADAR the use of the universal radar detection curves requires the knowledge of two important range parameters. The first one is the ratio of the baseline radar range (DRO) and the distance covered by the aircraft in one radar antenna scan (DR) and defined as DRODR. The second

parameter is the ratio between the aircraft slant range from radar site (SRL) and the radar range (DRO) denoted by RCDRO. The computational procedure is straight forward once the mechanics of subroutine PRADAR are understood.

```
      CALL PRADAR(PRDTT, RCROTT, DRODR, RCDRO, M, N, 5, 7, PRAD)          5.770
C
C       PRAD  - PROBABILITY OF RADAR DETECTION
C       PRDTT - TABLE CONTAINING VALUES OF PROB. OF DETECTION FOR
C               SWERLING I MODEL (SEE BROOKNER)
C       RCDRO - RATIO OF SLANT RANGE TO AIRCRAFT AND SINGLE SCAN
C               RADAR RANGE (DRO)
```

Infrared Detection: The infrared mechanism used in the model follows the same sequence as the radar detection described in previous section. The aircraft is modeled as an imperfect radiator (i.e. gray-body) with a known infrared radiation bandwidth. The procedure used here is to decompose the main aircraft contributions to the infrared radiance (J) and then sum their influences to obtain an equivalent single radiator [Hudson, 1969 and Young, 1986]. This decomposition is necessary since each contribution to the total aircraft radiance will have, in general, different IR spectral radiant intensity spectral characteristics.

Infrared Signature: Three main contributions to the IR spectral radiant intensity spectrum are predominant in our simple infrared model: 1) the aircraft skin temperature, 2) the aircraft engine exhaust nozzle parts, and 3) the aircraft engine exhaust plume. These three contributions are estimated using the same procedure and fully described in Appendix F. Eqs. 5.780 through 5.782 estimate the IR spectral radiant intensity for each one of the three IR sources. Note that the only difference in these expressions is the temperature factor associated with each IR source. For example, the skin stagnation temperature (STGTEM) with the JS which represents the infrared radiance of the aircraft skin at a particular mach number and altitude. In the case of the engine exhaust parts and plume the reference temperature EGT is the same. Note however, that for the plume case EGT has been reduced according to a perfect isentropic expansion in the exhaust nozzle [Hudson, 1969]. Another important difference between the three contributions is the different spectral wavelengths conforming

the IR radiation pattern. The IR radiation spectrum is specified with the values of μ as shown in Eqs. 5.783, 5.784, 5.786, 5.787, 5.789, and 5.790 for each one of the three radiation sources. Eq. 5.785, 5.788, and 5.791 integrate the IR radiant flux according to the procedure described in Appendix F and the IR spectral radiant intensity source contributions are added in 5.792 to find the total IR aircraft radiance (JTOTE). A final correction to JTOTE is necessary to account for the influence of various azimuth and elevation angles. This is accomplished with the introduction of two multipliers IRSAM and IRSEM. These multipliers represent exogenous variables that are specified in the form of table functions. Just as in the case of those used to correct the aircraft radar signature IRSEM and IRSAM constitute the IR "fingerprint" of a particular aircraft. The model also accounts for atmospheric propagation effects in the form of the atmospheric transmittance IR flux ratio (TAU) as shown in 5.797. Finally the IR radiance (HT) and the IR signal-to-noise ratio is estimated in Eqs. 5.798 and 5.799.

```
      CALL INTER (TSTAP, TSAPT, TSS, 6, M, TSAPM)                    5.771
      CALL INTER (TSTEGT, TSEGTT, TSS, 6, M, TSEGTM)                 5.772
      CALL INTER (TSTAE, TSAET, TSS, 6, M, TSAEM)                    5.773
C
    DO 039 I=1,M
      AE(I)  = AEB(I) * TSAEM(I) * NE(I)                             5.774
      EGT(I) = EGTB(I) * TSEGTM(I)                                   5.778
      AP(I)  = APB(I) * TSAPM(I) * NE(I)                             5.779
      JE(I)  = EMM * SIG * EGT(I) ** 4. * AE(I) / (4.*PI)            5.780
      JP(I)  = 0.5 * SIG * (0.85 * EGT(I)) **4. * AP(I)
   +          / (4.*PI)                                             5.781
      JS(I)  = EMM * SIG * STGTEM(I) ** 4. * .25 * AS(I)
   +          / (4.*PI)                                             5.782
039  CONTINUE
C
C        AE    - AIRCRAFT ENGINE EXHAUST AREA (SQ. CM)
C        EGT   - AIRCRAFT ENGINE EXHAUST GAS TEMPERATURE (D.K)
C        AP    - AIRCRAFT ENGINE EXHAUST PLUME AREA (SQ. CM)
C        AS    - AIRCRAFT WETTED AREA (SQ. CM)
C        NE    - NUMBER OF AIRCRAFT ENGINES (UNITS)
C
C       SKIN FRICTION INFRARED SIGNAL
C
C        JSEFF  - EFFECTIVE SKIN FRICTION IR RADIANCE (W/SR)
C        JS     - AIRCRAFT SKIN IR RADIANCE (W/SR)
C        BLACKT - TABLE VALUES FOR UNIVERSAL BLACKBODY CURVES
C        STGTEM - AIRCRAFT STAGNATION TEMPERATURE (DEG. KELVIN)
C        MUSKIN - SKIN FRICTION IR SPECTRAL EMISSION BAND
C                 VALUES (MICRONS)
C
C                 MULOW  = MUSKIN(1)                                  5.783
C                 MUHIHG = MUSKIN(2)                                  5.784
C
      CALL SPECTR (LTEMT, BLACKT, STGTEM, MUSKIN, M, 15, 2, JS,
   +   JSEFF)                                                         5.785
C
C       ENGINE EXHAUST PLUME INFRARED SIGNAL
C
```

```
C          JPEFF  - EFFECTIVE ENGINE PLUME IR RADIANCE (W/SR)
C          JP     - PLUME IR RADIANCE (W/SR)
C          MUPLUM - ENGINE PLUME IR SPECTRAL EMISSION BAND
C                   VALUES (MICRONS)
C
C                    MULOW  = MUPLUM(1)                              5.786
C                    MUHIHG = MUPLUM(2)                              5.787
C
       CALL SPECTR (LTEMT, BLACKT, EGT, MUPLUM, M, 15, 2, JP,
     +   JPEFF)                                                       5.788
C
C          ENGINE EXHAUST INFRARED SIGNAL
C
C          JEFF   - EFFECTIVE ENGINE EXHAUst IR RADIANCE (W/SR)
C          JE     - ENGINE EXHAUST IR RADIANCE (W/SR)
C          MUENG  - ENGINE EXHAUST IR SPECTRAL EMISSION BAND
C                   VALUES (MICRONS)
C
C                    MULOW  = MUENG(1)                               5.789
C                    MUHIHG = MUENG(2)                               5.790
C
       CALL SPECTR (LTEMT, BLACKT, EGT, MUENG, M, 15, 2, JE,
     +   JEFF)                                                        5.791
C
       DO 055 I=1,M
            JTOTE(I) = JEFF(I) + JPEFF(I) + JSEFF(I)                 5.792
055     CONTINUE
C
C          AZIMUTH AND ELEVATION ANGLE CORRECTIONS TO IR SIGNAL
C
      CALL INTE (IRATNT, IRSAMT, ATN, M, N, 7, IRSAM)                5.793
      CALL INTE (IELEVT, IRSEMT, ELEV, M, N, 7, IRSEM)               5.794
      CALL SINGL (ALPHT, ALTALP, ALTS, M, 6, ALF)                    5.795
C
       DO 043 I=1,M
          DO 043 J=1,N
             JA(I,J)    = JTOTE(I) * IRSAM(I,J) * IRSEM(I,J)        5.796
             TAU(I,J)   = EXP(- ALF(I) * SRL(I,J)/1000.)             5.797
             HT(I,J)    = JA(I,J) * TAU(I,J) / ( SRL(I,J) *
     +                    100.) ** 2                                 5.798
             SNOISE(I,J) = HT(I,J) / NEI(I)                          5.799
043     CONTINUE
C
      CALL DOUBL (IRNOIT, IRPDT, SNOISE, M, N, 12, PDIR)             5.800
C
C          IRNOIT - INFRARED NOISE TABULAR VALUES ASSOCIATED WITH
C                   CURVES OF PROBABILITY OF IR DETECTION (DIM.)
C          IRPDT  - TABULAR VALUES FOR PROB. OF IR DETECTION (DIM.)
C          PDIR   - PROBABILITY OF INFRARED DETECTION (DIM.)
C          SNOISE - INFRARED SIGNAL-TO-NOISE RATIO (DIM.)
C          HT     - IR RADIANCE (W/SQ. CM)
C          TAU    - RATIO OF TRANSMITTED RADIANT FLUX (DIM.)
```

5.3.7.3 *Aircraft Visual Detection*

The probability of visual detection (PVDET) is based upon the assumption that the ground observer has previous knowledge of the intruders either based on radar observations or IR sensor data. It is generally recognized the fact that under most circumstances the probabilities of radar and infrared detection of an aerial target are far greater than PVDET. This then tells

us that optical tracking is somewhat conditioned to other means of detection. Subroutine DOUBL is used to estimate the probability of visual detection. AS one might expect the target size (TSIZE) is the main input to this subroutine. The values of PVDET are defined in a DATA statement at the beginning of the code in the usual table function form. Pairs (TSIZET,VISPD) represent the values of the probability of visual detection curve versus angular target size. The numerical values are adapted from Rolfes and Staples [1986] for typical background luminance of 260 cd/m^2 and 0.3 seconds of initial exposure.

```
      CALL DOUBL (TSIZET, VISPDT, TSIZE, M, N, 11, PVDET)                5.801
C
C        TSIZE  - TARGET SIZE (RADIANS)
C        VISPDT - VALUE OF PROBABILITY OF VISUAL DETECTION FOR A
C                 GIVEN CONTRAST (DIM.)
C        PVDET  - PROBABILITY OF AIRCRAFT VISUAL DETECTION (DIM.)
C
      DO 123 I=1,M
        DO 123 J=1,N
          PAD(I,J) = AMAX1( PRAD(I,J) ,AMAX1( PDIR(I,J),
     +                PVDET(I,J)))                                         5.802
123     CONTINUE
C
C        PRAD   - PROBABILITY OF AIRCRAFT RADAR SELECTION (DIM.)
C        PDIR   - PROBABILITY OF AIRCRAFT INFRARED DETECTION (DIM)
C        PVDET  - PROBABILITY OF AIRCRAFT VISUAL DETECTION (DIM.)
```

5.3.8 Defense Weapons Launch

There are three conditions to be satisfied in order for the defense weapon units to fire a terminal propagator (i.e. an RF-guided missile, IR-guided missile, and anti-aircraft artillery). First, the aircraft must be within the defense weapon kinematic envelopes. Second, the aircraft must be accurately tracked, and finally the defense weapon system (DWS) must have sufficient time to fire at it. Each of these necessary conditions or functions is represented in the model as a probability. Thus PAFE represents the probability of the aircraft being within the flying envelope of a particular type of defense weapon; PT is the probability of the aircraft of being tracked successfully; and finally PSTF is the probability that the defense weapons sites have

sufficient time to fire. The following three subsections describe in some detail each one of these elements.

5.3.8.1 *Probability of Aircraft Target Tracking*

The probability of target tracking (PT) is disaggregated into three categories as there are three types of defense weapons each one with different tracking mechanism. The probabilities of the aircraft being tracked are essentially dependent upon the probabilities of detection and the angular rate capabilities of the tracking devices used. The simplifying assumptions are: 1) tracking only occurs above certain probability of detection threshold and 2) below the angular tracking and slew rate capabilities of the defense weapons (TRACK).

```
      DO 072 I = 1,M
        DO 072 J = 1,N
          IF (PRAD(I,J) .GE. 0.9 .AND. ATND(I,J) .LT. TRACK(1)) THEN      5.803
            PT(I,J,1) = 1.0                                               5.804
          ELSE
            PT(I,J,1) = 0.0                                               5.805
          ENDIF
072   CONTINUE
C
      DO 178 I = 1,M
        DO 178 J = 1,N
          IF (PDIR(I,J) .GE. 0.9 .AND. ATND(I,J) .LT. TRACK(2)) THEN      5.806
            PT(I,J,2) = 1.0                                               5.807
          ELSE
            PT(I,J,2) = 0.0                                               5.808
          ENDIF
178   CONTINUE
C
      DO 083 I = 1,M
        DO 083 J = 1,N
C         IF (ATND(I,J) .LT. TRACK(3)) THEN                               5.809
            PT(I,J,3) = PVDET(I,J)                                        5.810
          ELSE
            PT(I,J,3) = 0.0                                               5.811
083   CONTINUE
```

5.3.8.2 *Defense Weapon Kinematic Envelopes*

There are three types of kinematic weapon firig envelopes defined in the model, corresponding to three types of weapons modeled: 1) radar-guided surface-to-air missiles

(RFSAM), 2) infrared-guided surface-to-air missiles (IRSAM), and 3) anti-aircraft artillery shells (AAA). The envelopes are three dimensional in nature and they are representative of modern weaponry. Altitude (ADWFE) and downrange (DWFET) are used to define pairs of numerical values that constitute the outer boundaries of the kinematic envelopes (Fig. 5.52). It is also assumed in the baseline model that the shape envelopes remains the same in azimuth although the weapons are constrained in line-of-sight rate.

5.3.8.3 Probability of the Defense Weapon Sites Having Sufficient Time to Fire

The probability of the defense weapon sites having time to fire, PTSF, is modeled as a table function whose independent variable is the ratio of acquisition-tracking-flyout time (ATFOT) to the time the aircraft is in the firing envelope (TAIE). This relationship is defined in a DATA statement at the beginning of the program and the numerical values are shown in Fig. 5.53

The term ATFOT comprises the average acquisition and tracking time (AATT) and the average flyout time (ARFOT). The first term, AATT, is the time that takes the defense facilities to establish positive identification of the intruder (i.e. aircraft) that is initial acquisition and identification functions are considered (Eq. 5.812). The second term (ARFOT) is the time that takes the propagators to reach the target aircraft (Eq. 5.815).

A more refined approach to compute the propagator flyout times would be use the equations of motion for a missile in order to determine basic flight parameters (i.e. downrange position, speed,altitude, etc.) using a given guidance and navigation scheme such as proportional, lead angle, pursuit, or 3-point navigation scheme. This refined approach is exemplified in Appendix J of this dissertation to illustrate how off-line studies can be readily incorporated into the model. A potential extension to the model is the inclusion of passive countermeasures in this section since AATT will realistically be a function of the number and sequence of expendable

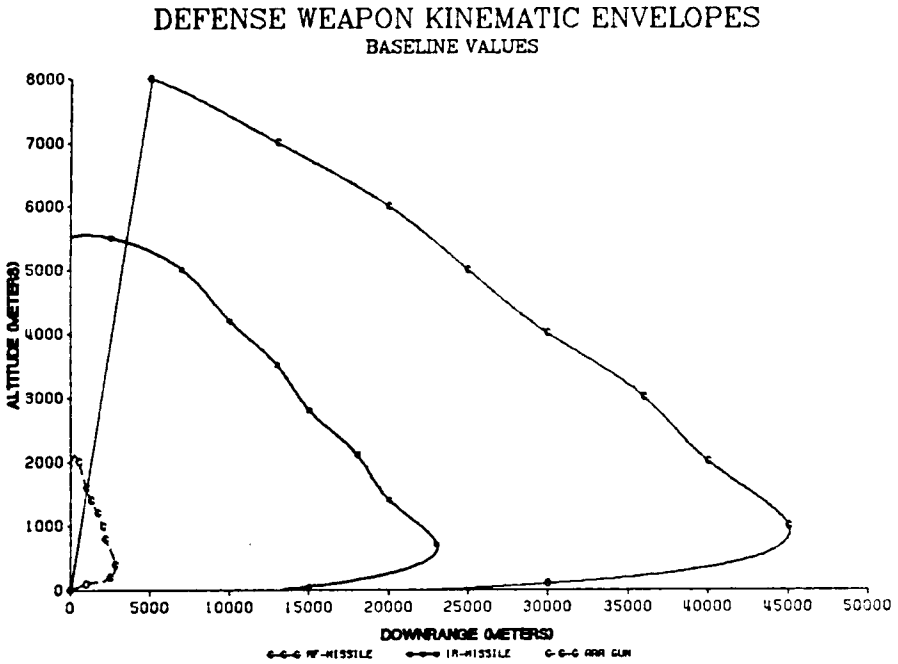


Figure 5.52 Defense Weapons Firing Envelopes.

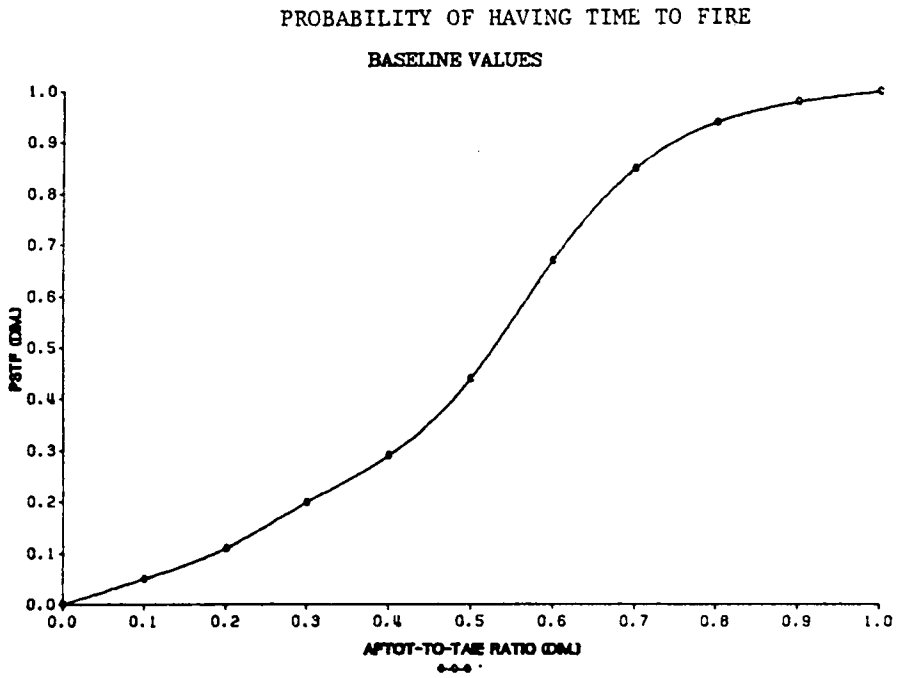


Figure 5.53 Probability of Defense Weapon Sites Having Sufficient Time to Fire.

cartridges used. The time available in firing envelope (TAIE) is defined in Eq. 5.814 as the ratio of the distance traveled in the firing envelope (DEDWFE) and the aircraft speed (VS). Note that DEDWFE is estimated in Eq. 5.813 according to simple geometry and assuming that the aircraft maintains its present heading and speed. Subroutine PTF is invoked in Eq. 5.817 to evaluate PSTF.

```
      DO 034 I=1,M
        DO 034 J=1,N
          DO 034 L=1,LL
            AATT(I,J,L)   = 10.0                                          5.812
            DEDWFE(I,J,L) = 2. * RDWFE(I,L) * COS (ABS(ATN(I,J)))         5.813
            TAIE(I,J,L)   = DEDWFE(I,J,L) / VS(I)                         5.814
            ARFOT(I,J,L)  = SRL(I,J) / (APS(L) + VAPPR(I,J))              5.815
            ATFOT(I,J,L)  = ARFOT(I,J,L) + AATT(I,J,L)                    5.816
034     CONTINUE
C
      CALL PTF (PSTFT, TEAFT, TAIE, ATFOT, M, N, LL, 11, PSTF)            5.817
```

5.3.8.4 *Probability of the Aircraft in the Defense Weapon Firing Envelopes*

The probability that the aircraft is in the defense weapons firing envelope (PAFE) is modeled as a binary function (i.e. zero or one). The idea is to ascertain whether the target aircraft is within the firing envelope of the defense weapons or not. PAFE takes a value of 1.0 when the aircraft is in range and the elevation angle (ELEV) is below the elevation angle firing limitations of the defense weapon (DWELL), zero otherwise. The shape and numerical values of the weapon envelopes are shown in Fig. 5.53.

```
      DO 071 I=1,M
        DO 071 J=1,N
          DO 071 L=1,LL
            IF (SRL(I,J) .LE. RDWFE(I,L)) THEN                            5.818
              PAFE(I,J,L) = 1.0                                           5.819
            ELSE
              PAFE(I,J,L) = 0.0                                           5.820
            ENDIF
          PDWL(I,J,L) = PT(I,J,L) * PAFE(I,J,L) * PSTF(I,J,L)             5.821
071     CONTINUE
C
      CALL SUMACF (PDWL, S1PDWL, S2PDWL, M, N, LL)                        5.822
C
```

5.3.8.5 *Passive Countermeasures*

Passive countermeasures are used to reduce the guidance and lock-on capabilities of a propagator. The expendables modeled are assumed to be of two types: 1) IR flares used against IR-guided missiles and 2) rapid bloom chaff (RBC) used for radar-guided missiles. Some simplifying assumptions have to be made with respect to the number of expendables released since they are not modeled explicitly. It has been assumed that only ten releases are allowed per aircraft per sortie. Five of them corresponding to rapid bloom chaff and four to infrared countermeasure flares (IRCM). Gunston and Spick [1983] provide an excellent introductory discussion to passive countermeasures. Suffice to say that modern expendable canister systems hold between 40 to 60 IRCM or RBC cartridges typically released in "packs" of six to eight at a time. Variable EXPAND maintains the record of expendable releases made (Eq. 5.827) while EXPRAT represents a rate variable to register an actual release. Releases are scheduled only when the probability of weapons launch (PDWL) exceeds a threshold value of 0.9 as shown in Eq. 5.823.

```
C
      DO 644 I=1,M
        DO 644 L=1,LL
          IF (S2PDWL(I,L) .GT. 0.9 .AND. EXPAND(I,L) .GE. 1)          5.823
     +              THEN
            EXPRAT(I,L) = 1                                           5.824
          ELSE
            EXPRAT(I,L) = 0                                           5.825
          ENDIF
          EXPAND(I,L) = EXPAND(I,L) - EXPRAT(I,L)                     5.826
644     CONTINUE
```

5.3.8.6 *Probability of Defense Weapons Successful Guidance*

The defense weapons guidance is represented in the model as the probability of successful guidance (PSG) which in turn depends upon four important factors; the aiming error (AIME), threat homing avoidance capability (THAC), aircraft guidance countermeasures

capability (GCMC), and the propagator lock-on and homing capability (PLOHC). It is realized that successful guidance is dependent upon the geometry of the engagement, the aircraft energy maneuverability, aircraft countermeasures, threat seeker guidance and accuracy, etc. The aim in this section is to capture the essential threat guidance elements and those threat avoidance capabilities of the aircraft in order to estimate the probability of threat successful guidance. It should be realized that an explicit modeling of each threat trajectory is not possible at this level of modeling because good end-game resolution necessitates extremely low step sizes (one or two orders of magnitude below the one used in this macro-simulation) in order to estimate with precision the miss distance between a propagator and the target. A possible alternative to overcome this problem has been to implement the results of a realistic end-game simulation analysis explained in Appendix J. The results of this off-line simulation illustrates and justifies the use of some of the seemingly arbitrary multipliers used in this model. The reader should be aware that many of the trends followed by the multipliers used in this model should come from off-line studies such as the one shown in Appendix J bearing in mind the specificity of each trend for a particular weapon or aircraft.

Aiming and Tracking Errors: Aiming and tracking errors are two of the most frequent and undesirable elements associated witn any fire control system. The aiming error probability is the uncertainty that exists in positioning or aiming a threat to a desired direction while tracking errors are concerned with the inability of the tracking mechanism to determine the exact position of the target tracked [Ball, 1985]. Both, aiming and tracking errors are aggregated in to a single variable denoted PAIM and depicted in Eq. 5.833. A normal aiming-tracking error probability (PAIMB) is assumed for each of the three types of weapons representing the minimum expected error under a "static" engagement (i.e. small angular rates involved). This normal error is complemented by a time-varying error assigned according to the instantaneous angular rate of the target with respect of the weapon site (PAIMN) as shown in Eq. 5.833.

Threat Avoidance Capability: The threat avoidance capability comprises various aspects that dictate the aircraft capability to evade a launched propagator. Among these are: 1) the capability to recognize the threat after a launch (threat warning capability), 2) tha aircraft capability to maneuver expressed in terms of turn rate, specific excess power or any other valid metric, 3) the number and type of threat countermeasures available for each threat (although this particular subject is modeled independently), 4) the geometry of the engagement in terms of aircraft and threat initial states, and 5) the evasive maneuver used to avoid the threat. As one can appreciate the magnitude of this problem is immense if one considers the numerous variables intervening in the outcome.

Past studies by Kelley and Lefton [1973], Anderson [1981], Funk [1984], Ben-Asher [1985], and Imado and Susumu [1986] have tried to search "optimality" criteria for one-on-one encounters and serve to illustrate the potential difficulty in characterizing end-game solutions for even highly simplified vehicle dynamics. With this in mind our approach to this problem has been to use a simple, although realistic simulation program (MISSILE) to estimate the trends in threat avoidance capability considering certain aircraft state characteristics such as speed, altitude, range, etc. Note that this approach implicitly introduces aircraft energy maneuverability considerations since a given set of aircraft state variables have associated a corresponding energy status. An more detailed description of the modeling approach used here is given in Appendices K and J.

Threat avoidance capability (THAC) is modeled as the product of a baseline threat avoidance value (THACB) corresponding to a specific set of aircraft flight conditions and four multipliers that represent deviations from this reference condition. Aspect angle (THACA), altitude (THACL), aircraft speed (THACS), and range (THACR) are considered parameters used to characterize the outcome of the end-game avoidance capability. Eqs. 5.828 through 5.832 recall the numerical values of these multipliers invoking subroutines SINGL and DOUBL. Implicit in the end game simulation a threat warning capability parameter has been modeled as a time delay imposed on the pilot to initiate the evasive maneuver. Note that THAC is

defined as unity for the anti-aircraft artillery (i.e. weapon subscript $I = 3$) as no specific avoidance is possible for each particular artillery shell.

Guidance Countermeasure Capability: Another parameter used in the computation of PSG is the potential guidance countermeasure capability of the aircraft (PGCMC). The guidance countermeasure capability is modeled as a function of expendables released which were covered in previous section. It is also assumed that each release degrades the guidance capability by 75 percent of its nominal value. Note that in order to model this influence in a more analytical way we would have to make use of a detailed end-game model, such as the one described in Appendices K and J, plus the incorporation of a detailed missile lock-on mechanism and aircraft expendable model. Note also that the anti-aircraft artillery is not affected by the passive countermeasures mechanisms in their guidance.

Probability of Propagator Lock-on and Homing Capability: The probability of propagator lock-on and homing capabilities is modeled using a similar scheme with a normal propagator's lock-on and homing probability (PLOHCN). That is a baseline value (PLOHCB) is assigned to each propagator and then corrected for line-of-sight rate variations (PLOHCA) as seen in Eq. 5.838. As before, lock-on and homing capability for the artillery shells is reassigned a unit value since its is not subject to any lock-on mechanism per se. Eq. 5.831 invokes subroutine DOUBL to search the numerical value of PLOHCA. Lastly, Eq. 5.840 computes the probability of successful guidance (PSG) as the product of the PAIM, THAC, PGCM, and PLOHC.

```
C
      CALL DOUBL (RATHAC, THACRT, ARTT, M, N, 8, THACR)                5.827
      CALL SINGL (ALTHAC, THACLT, ALTS, M, 6, THACL)                   5.828
      CALL SINGL (SPTHAC, THACST, MACH, M, 6, THACS)                   5.829
      CALL DOUBL (ATTHAC, THACAT, AATN, M, N, 7, THACA)                5.830
      CALL DOUBL (ATTHAC, PLOHCT, AATN, M, N, 7, PLOHCA)               5.831
      CALL DOUBL (APAIM, PAIMNT, ATND, M, N, 6, PAIMN)                 5.832
C
      DO 078 I=1,M
        DO 078 J=1,N
          DO 078 L=1,LL
            PAIM(I,L)   = PAIMB(L) * PAIMN(I,J)                        5.833
            THAC(I,J,L) = THACB(L) * TAHCS(I) * THACL(I)
```

```
     +                    THACA(I,J) * THACR(I,J)                          5.834
               THAC(I,J,3)  = 1.0                                           5.835
               IF (EXPRAT(I,L) .EQ. 1) THEN                                 5.836
                  PGCMC(I,L)   = 0.5 * PGCMCB(I,L)                          5.836
               ELSE
                  PGCMC(I,L)   = PGCMCB(I,L)                                5.837
               ENDIF
               PLOHC(I,J,L) = PLOHCB(L) * PLOHCA(I,J)                       5.838
C              PLOHC(I,J,3) = 1.0                                           5.839
078       CONTINUE
C
          DO 073 I=1,M
            DO 073 J=1,N
              DO 073 L=1,LL
                PSG(I,J,L) = PAIM(I,L) * PTHAC(I,J,L) *
     +                     PGCMC(I,L) * PLOHC(I,L)                          5.840
073       CONTINUE
C
C           PAIM   - AIMING PROBABILITY (DIM.)
C           PTHAC  - PROBABILITY OF THREAT HOMING AVOIDANCE
C                    CAPABILITY (DIM.)
C           PGCMC  - PROBABILITY OF GUIDANCE COUNTERMEASURE
C                    CAPABILITY (DIM.)
C           PLOHC  - PROBABILITY OF LOCK-ON AND HOMING CAPABILITY
C
C           PAIM   - AIMING PROBABILITY (DIM.)
C           THAC   - PROBABILITY OF THREAT HOMING AVOIDANCE
C                    CAPABILITY (DIM.)
C           PGCMC  - PROBABILITY OF GUIDANCE COUNTERMEASURE
C                    CAPABILITY (DIM.)
C           PLOHC  - PROBABILITY OF LOCK-ON AND HOMING CAPABILITY
C           PSG    - PROBABILITY OF DWS WEAPON SUCCESSFUL GUIDANCE
C           THACR  - PROBABILITY OF THREAT HOMING AVOIDANCE VS. RANGE
C                    MULTIPLIER (DIM.)
C           THACS  - PROBABILITY OF THREAT HOMING AVOIDANCE VS. SPEED
C                    MULTIPLIER (DIM.)
C           THACA  - PROBABILITY OF THREAT HOMING AVOIDANCE VS. ASPECT
C                    ANGLE MULTIPLIER (DIM.)
C
```

5.3.8.7 Defense Weapons Detonation

Weapons detonation is the ultimate phase in the computation of the threat system effectiveness. The main objective of this section is to quantify the probability of weapons detonation (PDET). The baseline probability of detonation (PDETB) is treated as an exogenous variable as shown in 5.841. This baseline value is corrected by range considerations alone with the use of PDETR.

```
C
          CALL DOUBL (RAPDET, PDETRT, ARTT, M, N, 6, PDETR)                 5.841
C
          DO 175 I=1,M
            DO 175 J=1,N
```

```
            DO 175 L=1,LL
              PDET(I,J,L)  = PDETB(L) * PDETR(I,J)                    5.842
175     CONTINUE
C
C         PDET   - PROBABILITY OF WEAPONS DETONATION (DIM)
```

5.3.8.8 *Defense Weapons Launched and Threat System Effectiveness*

The number of weapons launched (DWPL) is computed as the product of the the maximum defense weapons launch rate capability (MDWLR), the number of sites firing (DWS), and the probability for these sites launching a weapon (PDWL) as shown in Eq. 5.843. Note that as weapons are exhausted the AMIN1 function constrains DWLP to use the last number of remaining weapons. The probability of threat system effectiveness (PTSE) is just the product of the five probabilities estimated before as defined in the Military Handbook 336-1 [1982].

```
C
      DO 075 I=1,M
        DO 075 J=1,N
          DO 075 L=1,LL
            DWPL(I,J,L) = AMIN1(DWS(J,L) / DT,
     +          MDWLR(L) * DWS(J,L) * PDWL(I,J,L) / 60.)              5.843
            PTSE(I,J,L) = PALOS(I,J) * PDWL(I,J,L) * PSG(I,J,L)
     +        * PDET(I,J,L)                                           5.844
075     CONTINUE
C
C         DWPL - DEFENSE WEAPON PROPAGATORS LAUNCHED (UNITS)
C         MDWLR - MAXIMUM DEFENSE WEAPONS LAUNCH RATE (UNITS/MIN.)
C         DWS  - NUMBER OF DEFENSE WEAPONS (UNITS)
C         PTSE - PROBABILITY OF THREAT SYSTEM EFFECTIVENESS (DIM.)
C         PALOS - PROBABILITY OF AIRCRAFT IN LINE OF SIGHT (DIM.)
C         PDWL - PROBABILITY OF DEFENSE WEAPONS LAUNCH (DIM.)
C         PSG  - PROBABILITY OF DWS WEAPON SUCCESSFUL GUIDANCE
C         PDET - PROBABILITY OF WEAPONS DETONATION (DIM)
C
```

A finite inventory of propagators at each site is assumed (DWS) for the purposes of this model. Table 5.1 represents the initial baseline defense weapon inventory and their location.

Table 5.1 Defense Weapons Allocation Matrix.			
Defense Weapon	Radar Guided Missiles	Infrared-Guided Missiles	AAA Ammunition
Ring 1	8	0	0
Ring 2	8	0	0
Ring 3	8	0	0
Ring 4	12	8	20000
Ring 5	12	8	20000

5.3.8.9 *Probability of Aircraft Kill*

The aircraft probability of kill is evaluated according to Eq. 5.338 if P_{ASE} is substituted by P_{TSE} which denotes the probability of threat system effectiveness. The evaluation of this probability involves the exogenous variable PSSCBF which defines the probability of aircraft kill given a single shot. This term represents the end-game effect of having the threat in the vicinity of the aircraft and is a function of the aircraft vulnerability and the lethality of the threat warhead. An extensive data base is available from SURVIAC [Vice, 1986] on the single shot kill probability for almost any conceivable threat which could be readily incorporated in this model. Note that this expression the disaggregation of the weapons is extremely important as the number of propagators launched constitutes the exponent of the second term in the right hand side.

```
      DO 77 I=1,M
        DO 77 J=1,N
          DO 77 L=1,LL
            PKCBF(I,J,L)  =  PTSE(I,J,L) - PTSE(I,J,L) *
     +                      (1. - PSSCBF(L)) ** DWPL(I,J,L)                    5.845
77    CONTINUE
C
C        PKCBF - KILL PROBABILITY OF CBF AIRCRAFT (DIM.)
C        PTSE  - PROBABILITY OF THREAT SYSTEM EFFECTIVENESS (DIM.)
C        DWPL  - DEFENSE WEAPON PROPAGATORS LAUNCHED (UNITS)
C        PSSCBF- PROBABILITY OF SINGLE SHOT CBF AIRCRAFT KILL (DIM)
```

5.3.9 Aircraft Systems Effectiveness

Aircraft systems effectiveness refers to the functions that need to be accomplished by the attacking aircraft in order to inflict damage on the defense weapon sites and thus fulfill their mission. These functions are: ground target in line-of-sight, air-to-surface weapons launch, guidance, and detonation. It is seen that these functions are just a mirror image of those of the defense weapon ground sites. The approach is then similar to that taken in ASALT I which was governed by the same set of differential equations.

5.3.9.1 Air-to-Surface Weapons Launch

There are three conditions to be satisfied in order for the aircraft to fire upon a defense weapon ground site: 1) the target must lie within the effective range of the air-to-surface weapon, 2) the ground site must be detected, identified, and tracked, and 3) man and machine must be ready for the actual launch, that fire control system must be "armed" and the pilot must have *confidence* in the weapons range. The third point it might be considered trivial at first glance but it entails several important crew behavioral aspects that will be described later.

Air-to-Surface Kinematic Envelopes: The first element of air-to-surface weapon launch to be described is the implementation of kinematic (or aerodynamic) envelopes for the air-to-surface weapons (ASW). The air-to-surface weapons modeled are of two types: 1) medium range air-to-surface missiles (ASM) and infrared guided bombs (IRGB). The treatment of the two types of weapons is somewhat different since obviously the bombs are restricted to near free-fall trajectories while the missiles possess flight sustaining capability. The air-to-surface maximum kinematic envelope range (ASMR) is defined in terms of a maximum baseline range (ASMRB) and corrected by the effects of speed (ASMRS), altitude

(ASMRA), and "off-boresight" conditions (ASMRO) as shown in Eqs. 5.846 through 5.848. The combination of these three multipliers and the baseline missile range (ASMRB) result in the missile range volumes shown in Fig. 5.54. Eqs. 5.755 and 5.756 calculate the bombs time of flight (TIM) and range based on simple free-fall principles with an implicit resisting force. Eqs. 5.849 through 5.855 represent the evaluation of the effective air-to-surface weapon ranges (EASMR). Note that the missiles are also constrained in off-boresight capability to a value represented by ANMR(I,6) as shown in Eq. 5.852. The times of flight associated with each one of these weapons are shown in Eqs. 5.856 and 5.857.

```
      CALL INTER(MACAS, ASMRST, MACH, 5, M, ASMRS)                    5.846
      CALL INTER(MACAL, ASMRAT, ALTS, 9, M, ASMRA)                    5.847
      CALL INTE(ANMR, EASMRT, ATN, M, N, 6, ASMRO)                    5.848
C
       DO 053 I=1,M
         DO 053 J=1,N
           ASMR(I,1)   = ASMRB(I,1) * ASMRS(I) * ASMRA(I)             5.849
           TIM(I)      = SQRT (2. * ALTS(I) / G)                      5.850
           ASMR(I,2)   = TIM(I) * VS(I) /2.                           5.851
           IF (ABS(ATN(I,J)) .GT. ANMR(I,6)) THEN                     5.852
             EASMR(I,J,1) = 0.0                                       5.853
           ELSE
             EASMR(I,J,1) = ASMR(I,1) * ASMRO(I,J)                    5.854
           ENDIF
         EASMR(I,J,2) = ASMR(I,2)                                     5.855
         ASFOT(I,J,1) = SRL(I,J) / ASWS(I,1)                          5.856
         ASFOT(I,J,2) = TIM(I)                                        5.857
053    CONTINUE
C
C        ASMR  - AIR-TO-SURFACE MISSILE RANGE (METERS)
C        ASMRA - AIR-TO-SURFACE MISSILE RANGE VS ALT. MULT.(METERS)
C        ASMRS - AIR-TO-SURFACE MISSILE RANGE VS SPEED (METERS)
C        TIM   - BOMB TIME OF FLIGHT (SECONDS)
C        ASBR  - BOMB ANTICIPATION DROP RANGE (METERS)
C        ASMRO - AIR-TO-SURFACE MISSILE RANGE VS. OFF-BORESIGHT
C                CAPABILITY MULTIPLIER (DIM)
C        EASMR - EFFECTIVE AIR-TO-SURFACE MISSILE RANGE (M.)
```

Threat Detection and Identification: Target detection and identification plays a predominant role in the success of any attack mission. Over the years target acquisition systems have evolved from the pilot's sight as the means of identification to the extremely sophisticated electroptical, radar, and infrared devices found today in modern fighters and attack aircraft. A great deal of information is usually required to model modern systems such as the Forward Looking Infrared Detection (FLIR) and Synthetic Aperture Radar systems (SAR) which are currently installed in several aircraft in the United States inventory.

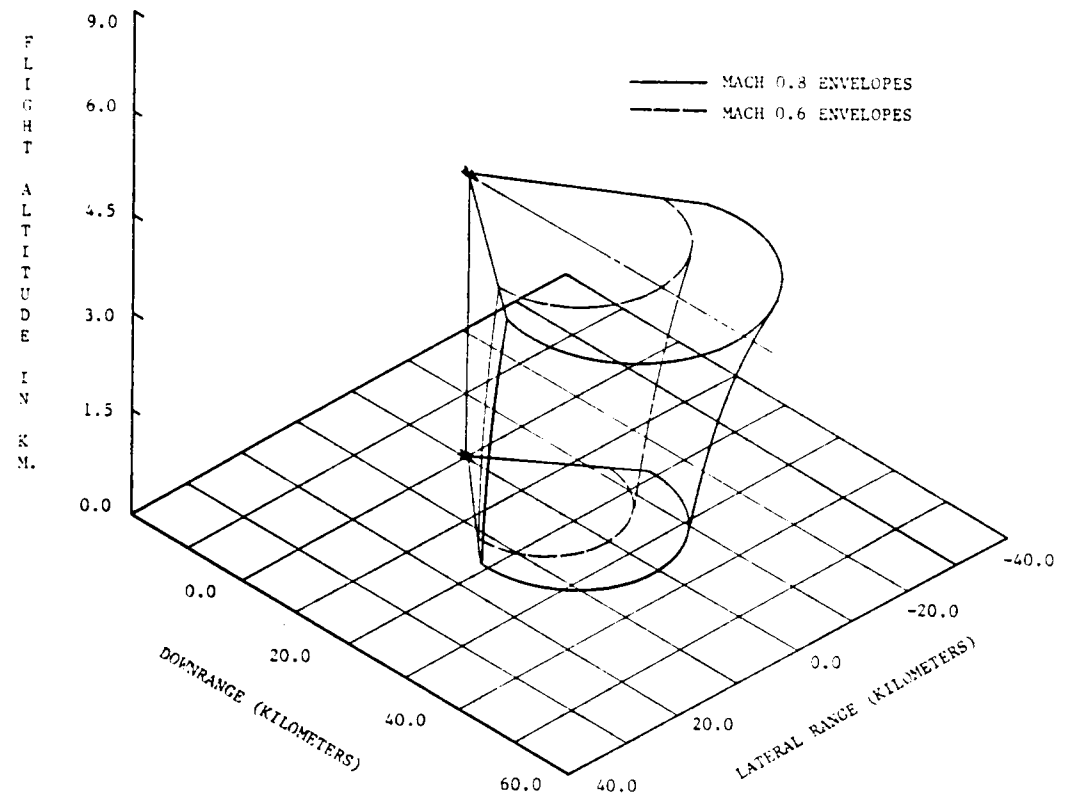


Figure 5.54 Air-to-Surface Weapon Three-Dimensional Modeling.

The approach adopted in this model to estimate the probability of threat detection and identification (TDI) is modest since no explicit description of a particular hardware is given. Instead, a typical search volume is generated in front of each aircraft simulating the target detection and identification capabilities of the system associated with a particular weapon. The search volume is subjected to aircraft parameter constraints such as speed (TDIS), altitude (TDIA), range (TDIR), and off-boresight conditions (TDIO) to add realism. These factors are modeled as multipliers that affect a baseline condition as seen in Eq. 5.863.

The multiplier values are addressed through subroutines SINGL and DOUBL as shown in Eqs. 5.858 through 5.861. These multipliers are depicted in graphical form in Fig. 5.55. Notice the fact that TDI is penalized at very low altitudes due to loss in the line-of sight and terrain effects, at higher speeds due to increased pilot attention devoted to terrain following navigation, and at large aspect angles due to azimuth beam loss shape factors [Stimpson, 1985]. The second point although disputable with respect to the numerical values used is, nonetheless, a fact even with the high levels of automation in today's cockpits due to the potential failures that might occur in the automatic terrain following control system necessitating a quick reversion to manual control.

Another important point accounted in the modeling is the complete disaggregation of the detection and identification mechanisms associated with each weapon. Eq. 5.863 estimates TDI to be used in the release of air-to-surface missiles while Eqs. 5.864 through 5.866 are associated with the bombs. It is assumed that the bomb IR guidance mechanism is effective up to eight kilometers from the desired target area as shown in Eq. 5.864.

```
C
      CALL DOUBL (RANTDI, TDIRT, SRL, M, N, 8, TDIR)                    5.858
      CALL SINGL (ALTTDI, TDIAT, ALTS, M, 8, TDIA)                      5.859
      CALL SINGL (ASPTDI, TDIST, MACH, M, 8, TDIS)                      5.860
      CALL DOUBL (OBTDI, TDIOT, AATN, M, N, 8, TDIO)                    5.861
C
      DO 201 I=1,M
        FIPTDI(I) = 0.0                                                 5.862
        DO 201 J=1,N
          TDI(I,J,1) = TDIR(I,J) * TDIA(I) * TDIS(I) * TDIO(I,J)        5.863
201   CONTINUE
C
      DO 203 I=1,M
        DO 203 J=1,N
          IF (SRL(I,J) .LE. 8000.) THEN                                 5.864
```

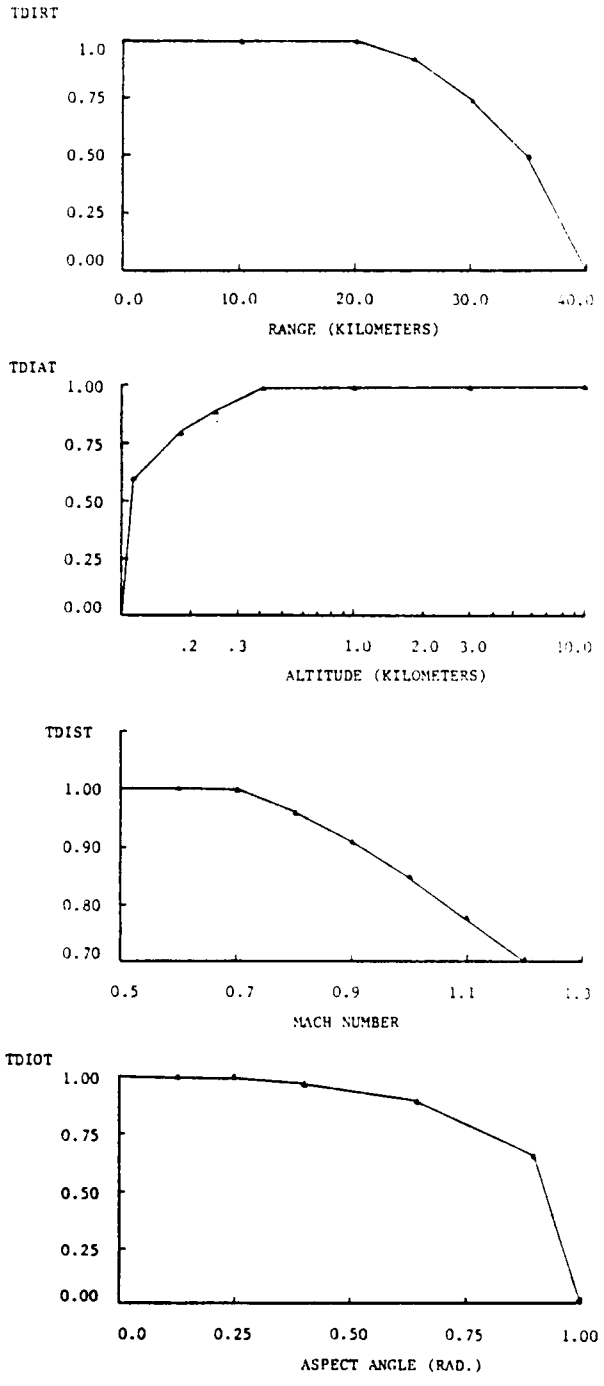


Figure 5.55 Target Detection and Identification Multipliers.

```
            TDI(I,J,2) = 1.0                                          5.865
          ELSE
            TDI(I,J,2) = 0.0                                          5.866
          ENDIF
203     CONTINUE
C
C         TDI  - PROBABILITY OF TARGET DETECTION AND
C              IDENTIFICATION (DIM.)
C         SRL  - SLANT RANGE TO TARGET (METERS)
C         TDIR - PROBABILITY OF TARGET DETECTION AND
C              IDENTIFICATION IN RANGE (DIM.)
C         TDIA - PROBABILITY OF TARGET DETECTION AND
C              IDENTIFICATION VS. ALTITUDE (DIM.)
C         TDIS - PROBABILITY OF TARGET DETECTION AND
C              IDENTIFICATION VS. SPEED (DIM.)
C         TDIO - PROBABILITY OF TARGET DETECTION AND
C              IDENTIFICATION VS. OFF-BORESIGHT CAPABILITY (DIM.)
```

Air-to-Surface Weapons Employment: Mission planning involves among other things the selection of one or several weapon employment doctrines. The one adopted in this model is to use the long range air-to-surface weapons for threat suppression and the bombs for the main target area (see Fig. 5.50). A target of opportunity policy is used for the air-to-surface missiles which implies that any ground site within the range of a particular aircraft weapons envelope is fired upon provided that the site has not been completely destroyed by the attacking force. Eqs. 5.867 through 5.870 define the air-to-surface weapon employment (ASWE) policy implemented in FORTRAN. Note that a threshold of five kilometers is used to activate the use of the bombs in the vicinity of the main target area (Eq. 5.867) while the missiles are assigned a unit value corresponding to indiscriminate use to surviving threats throughout the entire mission.

```
        DO 205 I=1,M
          DO 205 J=1,N
            IF (SRL(I,5) .LE. 5000.) THEN                             5.867
              ASWE(I,J,2) = 1.0                                       5.868
            ELSE
              ASWE(I,J,2) = 0.0                                       5.869
            ENDIF
          ASWE(I,J,1) = 1.0                                           5.870
205     CONTINUE
C
C         ASWE - PROBABILITY OF AIR-TO-SURFACE WEAPONS EMPLOYMENT
```

Air-to-Surface Weapons Launch Confidence Factor: The air-to-surface weapons launch confidence factor (ASWCF) constitutes a subjective way to establish crew preferences of when

to launch the medium range air-to-surface weapons available. ASWCF is a concept borrowed from air-to-air combat displays first described by Scott [1979] and later by Lutter [1981]. ASWFC is interpreted as the probability that the crew of an attacking aircraft launches a weapon with previous knowledge of the range capabilities of the weapon under a particular set of flight conditions. In practice all the information about range to target, aircraft speed, altitude, off-boresight capability, weapon maximum range, etc. is continuously monitored by an air data computer and a single numerical value for missile launch confidence factor displayed to the crew. The value of ASWCF varies then from zero to one depending upon previously define parameters. Zero is reserved for the outer boundary of the missile kinematic envelope while one is "recommended" at some intermediate point between the maximum range boundary and the target depending upon the particular performance characteristics of the weapon. For this model it is assumed that the inner boundary of launch is located at six tenths of the maximum range boundary. Eqs. 5.871 through 5.873 define the missile launch confidence factor while 5.874 through 5.876 accomplish the same for the guided bombs. Notice that in the latter case a parameter denoted BBC is introduced in Eq. 5.874 to constrain bomb releases within a narrow five degree aspect angle band in front of the aircraft. For the missiles this is not necessary as the parameter ASMRO (already described) constrains the off-boresight capability of these weapons. Finally in this segment, the air-to-surface weapon probability of launch (ASWL) is evaluated in Eqs. 5.877 through 5.879 as the product of TDI, ASWE, and ASWCF. Note that a check of the number of air-to-surface weapons available being greater than zero is performed prior to the computation of ASWL (Eq. 5.877).

```
      DO 210 I=1,M
        DO 210 J=1,N
          IF ( EASMR(I,J,1) .GT. 0.0 .AND. EASMR(I,J,1)
     +         .GE. ARTT(I,J)) THEN                                    5.871
             ASWCF(I,J,1) =  (EASMR(I,J,1) - ARTT(I,J)) / (
     +                    EASMR(I,J,1) - 0.8 * EASMR(I,J,1))          5.872
          ELSE
             ASWCF(I,J,1) = 0.0                                       5.873
          ENDIF
210     CONTINUE
C
      DO 211 I=1,M
        DO 211 J=1,N
          IF (ARTT(I,J) .LE. EASMR(I,J,2) .AND. ABS(ATN(I,J))
     +       .LE. BBC) THEN                                           5.874
```

```
            ASWCF(I,J,2) = 1.0                                          5.875
          ELSE
            ASWCF(I,J,2) = 0.0                                          5.876
          ENDIF
211     CONTINUE
C
        DO 221 I=1,M
          DO 221 J=1,N
            DO 221 K=1,KK
              IF (ASWU(I,K) .GT. 0.01) THEN                             5.877
                ASWL(I,J,K) = TDI(I,J,K) * ASWE(I,J,K) *
     +              ASWCF(I,J,K)                                        5.878
              ELSE
                ASWL(I,J,K) = 0.0                                       5.879
              ENDIF
221     CONTINUE
C
C         ARTT   - AIRCRAFT RANGE TO TARGET (METERS)
C         EASMR  - EFFECTIVE AIR-TO-SURFACE WEAPONS RANGE (METERS)
          ASWCF  - AIR-TO-SURFACE WEAPONS LAUNCH CONFIDENCE FACTOR
          ATN    - AIRCRAFT TO TARGET ASPECT ANGLE (RADIANS)
          ASWL   - AIR-TO-SURFACE WEAPONS LAUNCHED (UNITS)
```

5.3.9.2 *Probability of Air-to-Surface Weapon Successful Guidance*

The air-to-surface weapons guidance is modeled as the probability of aircraft successful guidance (PASG). PASG is dependent upon two flight parameters and the geometry of the launch. The flight parameters considered are: 1) aircraft speed (PASGS) and 2) aircraft altitude (PASGA) while the geometric characteristics considered are range to target (PASGR) and target aspect angle information (PASGO). Once again, four multipliers are used to represent typical trends that define performance and geometric constraints for the air-to-surface weapons.

```
        CALL DOUBL (RANTDI, PASGOT, SRL, M, N, 8, PASGR)                5.880
        CALL SINGL (ALTTDI, PASGAT, ALTS, M, 8, PASGA)                  5.881
        CALL SINGL (ASPTDI, PASGST, MACH, M, 8, PASGS)                  5.882
        CALL DOUBL (OBTDI, PASGOT, AATN, M, N, 8, PASGO)                5.883

        DO 223 I=1,M
          DO 223 J=1,N
            PASG(I,J,1) = PASGA(I) * PASGS(I) * PASGO(I,J) *
     +                  PASGR(I,J)                                      5.884
            PASG(I,J,2) = 0.55                                          5.885
223     CONTINUE

          PASG  - PROBABILITY OF AIRCRAFT WEAPONS SUCCESSFUL
                  GUIDANCE (DIM)
```

5.3.9.3 *Air-to-Surface Weapons Detonation*

Weapons detonation is the ultimate phase in the computation of the threat system effectiveness. The main objective of this section is to quantify the probability of weapons detonation (PDET). The baseline probability of detonation (PDETB) is treated as an exogenous variable as shown in 5.841. This baseline value is corrected by range considerations alone with the use of PDETR.

```
      DO 225 I=1,M
        DO 225 J=1,N
          PAWDET(I,J,1) = 0.80                                          5.886
          PAWDET(I,J,2) = 0.80                                          5.887
225     CONTINUE

        PAWDET - PROBABILITY OF AIR-TO-SURFACE WEAPONS DETONATION
```

5.3.9.4 *Probability of Aircraft System Effectiveness*

The probability of aircraft system effectiveness (PASE) is analogous to the probability of threat system effectiveness (PTSE) defined in equation 5.844. The interpretation of PASE is the probability of aircraft *i* inflicting damage to defense site *j* with weapon *k* PASE is evaluated in Eq. 5.888 as the product of the probabilities of the threat in line-of-sight (PALOS), tair-to-surface weapons launch (ASWL), air-to-surface weapons successful guidance (PASG), and the probability of air-to-surface weapons detonation (PAWDET).

```
      DO 226 I=1,M
        DO 226 J=1,N
          DO 226 K=1,KK
            PASE(I,J,K) = PALOS(I,J) * ASWL(I,J,K) * PASG(I,J,K)
     +                  * PAWDET(I,J,K)                                5.888
226     CONTINUE
C
C         PASE  - PROBABILITY OF AIRCRAFT SYSTEMS EFFECTIVENESS
C         PASG  - PROBABILITY OF AIRCRAFT WEAPONS SUCCESSFUL
C               GUIDANCE (DIM)
C         PAWDET - PROBABILITY OF AIR-TO-SURFACE WEAPONS DETONATION
```

5.3.9.5 *Number of Air-to-Surface Weapons Launched*

The number of air-to-surface weapons launched (ASULA) is computed as the product of the maximum weapons launch rate capability (ASWLR) and the probability of air-to-surface weapons launch (ASWL) as seen in Eq. 5.889. The use of a AMIN function in the same equation is to avoid launching more air-to-surface weapons than those available for a last last launch. Eq. 5.890 calculates the summation of air-to-surface weapons launched per aircraft (S1SULA).

```
      DO 235 I=1,M
        DO 235 J=1,N
          DO 235 K=1,KK
            ASULA(I,J,K) = AMIN1(ASWU(I,K)/DT, ASWLR(K)
     +                   * ASWL(I,J,K)/60.)                          5.889
235     CONTINUE
C
      CALL SUMACF (ASULA, S1SULA, S2SULA, M, N, KK)                  5.890
C
C       ASULA   - AIR-TO-SURFACE WEAPONS LAUNCHED (UNITS)
C       ASWL    - PROBABILITY OF AIR-TO-SURFACE WEAPONS LAUNCH
C       ASWU    - NUMBER OF AIR-TO-SURFACE WEAPONS (UNITS)
C       ASWLR   - MAXIMUM AIR-TO-SURFACE WEAPONS LAUNCH RATE
C                 (UNITS/MIN)
C       DT      - SIMULATION STEP SIZE (SECONDS)
```

5.3.9.6 *Probability of Surface Threat Kill*

The probability of kill of the defense weapons sites (PKDWS) is evaluated in an analogous way to that of the aircraft kill shown in Eq. 5.845. PSSDWS represents an exogenous parameter that stands for the single shot kill probability of a defense weapon site by a particular weapon. This parameter is a measure of the destruction capabilities of the weapon assuming that the weapon is has been successfully launched, guided, and detonated near the target. Obviously warhead size and fragmentation mechanisms are major contributors to PSSDWS. The usual analysis used to determine PSSDWS is through a detailed *vulnerability* assessment in which the target is modeled as a series of finite elements to study the damage inflicted by a weapon on each of them. This method is a "bottom-up" approach that estimates

the system operational capabilities after a weapon hit using a specialized failure mode effect and criticality analysis (FMECA) scheme renamed "kill tree" analysis by the survivability community.

```
      DO 236 I=1,M
        DO 236 J=1,N
          DO 236 K=1,KK
            PKDWS(I,J,K) = PASE(I,J,K) - PASE(I,J,K) *
     +                    (1. - PSSDWS(K)) ** ASULA(I,J,K)                    5.891
236   CONTINUE
C
C       PKDWS  - PROBABILITY OF DEFENSE WEAPONS KILL (DIM.)
C       ASULA  - AIR-TO-SURFACE WEAPONS LAUNCHED (UNITS)
C       PASE   - PROBABILITY OF AIRCRAFT SYSTEM EFFECTIVENESS
C       PSSDWS - PROBABILITY OF DEFENSE WEAPONS SINGLE SHOT KILL
```

5.3.10 Rate Variables

As their name imply rate variables constitute the rates of change in the state of the system. There are two types of rates variables: 1) those associated with the aircraft states (Eqs. 5.892 through 5.902) and 2) those linked to the defense weapon sites (Eqs. 5.903 through 5.907). Starting with Eq. 5.892 the aircraft acceleration (ACCS) in the direction of the velocity vector is evaluated in terms of the aircraft mass (MASS), thrust (THRUST), drag (DRAG), and angle of attack (ALP). Eqs. 5.893 and 5.894 calculate the rate of change in aircraft mass (DMASS) and the heading rate of change (SAIR) which constitutes a control variable. Note that DMASS encompasses changes due to the weapons released (DMASSW) and those due to fuel consumption (FFLOW). Next in the sequence is the determination of the radar cross section rate of change (RCSRW) due to azimuth and elevation angle changes as well weapons released. The second control variable, throttle setting (TSS), is affected by a single rate variable denoted as TSSR which is scheduled according to a simple proportional control algorithm shown in Eqs. 5.896 through 5.898. This algorithm increases or decreases the throttle setting as the difference between the aircraft speed (VS) and the target speed for a particular segment (DELTAV) increases or decreases accordingly. The factor GAIN represents a constant gain used to adjust the new value of the rate of change in throttle setting (TSSR).

Eqs. 5.899 through 5.902 calculate four variations of the CBF aircraft kill rate (CBFKR) based in previous knowledge of the probability of CBF aircraft kill (PKCBF) and the number of CBF aircraft in the simulation. Eqs. 5.899 and 5.900 represent the *nominal* and *delayed* kill three dimensional rates rates, CBFKR and CBFKRD, respectively. Eqs. 5.901 and 5.902 on the other hand are aggregated one dimensional kill rates that add the kill contributions of N defense sites and L surface-to-air weapons to each aircraft. Eq. 5.901 is in fact supplementary since it is not used in any other computation through the model. The only rates computed for the ground threat are the defense weapons kill rates, DWSKR and DWSKRD. Where DWSKR and DWSKRD are the *nominal* and *delayed* defense weapons kill rates, respectively. Eqs. 5.905 and 5.906 reduce the dimensionality of DWSKR and DWSKRD in order to estimate the number of defense weapons sites remaining (DWS) in subsequent section.

```
      DO 100 I=1,M
         ACCS(I) = (THRUST(I)*COS(ALP(I))-DRAG(I))/MASS(I)          5.892
         DMASS(I) = FFLOW(I) + dmassw(I)                            5.893
         SAIR(I) = SAICO(I)                                         5.894
100    CONTINUE
C
      CALL MATRIX (RCSRW, S2SULA, DRCSW, M, KK)                     5.895
C
      DO 005 I=1,M
      IF (TSS(I) .GE. 1.0) THEN                                     5.896
         TSSR(I) = 0.0                                              5.897
      ELSE
         TSSR(I) = DELTAV(I) * GAIN                                 5.898
      ENDIF
005    CONTINUE
C
      DO 112 I=1,M
        DO 112 J=1,N
          DO 112 L=1,LL
            CBFKR(I,J,L) = PKCBF(I,J,L) * CBFS(I)                   5.899
112    CONTINUE
C
      CALL DELAY3 (CBFKR, CBFKRD, CBFQUE, M, N, LL, 10, ARFOT, DT)  5.900
      CALL SUM3 (CBFKR, S1CBKR, S2CBKR, M, N, LL)                   5.901
      CALL SUM3 (CBFKRD, S1CBKD, S2CBKD, M, N, LL)                  5.902
C
      DO 113 I=1,M
        DO 113 J=1,N
          DO 113 K=1,KK
            DWSKR(I,J,K) = PKDWS(I,J,K) * NDWS(J)                   5.903
113    CONTINUE
C
      CALL DELAY3 (DWSKR, DWSKRD, DWSQUE, M, N, KK, 10, ASFOT, DT)  5.904
      CALL SUMDWS (DWSKR, S1DWKR, S2DWKR, M, N, KK)                 5.905
      CALL SUMDWS (DWSKRD, S1DWKD, S2DWKD, M, N, KK)                5.906
C
C       ACCS   - AIRCRAFT ACCELERATION (M/SEC-SEC)
C       THRUST - AIRCRAFT THRUST (KGS.)
C       DRAG   - AIRCRAFT DRAG
C       ALP    - AIRCRAFT ANGLE OF ATTACK (RADIANS)
C       SAIR   - RATE OF CHANGE IN HEADING ANGLE (RAD/SEC)
C       RCSRW  - RATE OF CHANGE IN RCS DUE TO WEAPONS DELIVERY
C              - (SQ. METERS/SEC)
C       DMASS  - RATE OF CHANGE IN VEHICLE MASS (KG/SEC.)
```

```
C       CBFKR  - CBF AIRCRAFT KILL RATE (AIRCRAFT/SEC.)
C       PKCBF  - PROBABILITY OF CBF AIRCRAFT KILL (DIM.)
C       CBFS   - NUMBER OF CBF AIRCRAFT (AIRCRAFT)
C       CBFKRD - DELAYED CBF AIRCRAFT KILL RATE (AIRCRAFT/SEC.)
C       ARFOT  - SURFACE-TO AIR WEAPON FLYOUT TIME (SEC.)
C       CBFQUE - DUMMY ARRAY TO HOLD TIME HISTORY OF CBFKR
C       DWSKR  - DEFENSE WEAPONS KILL RATE (UNITS/SEC.)
C       PKDWS  - DEFENSE WEAPONS PROBABILITY OF KILL (DIM.)
C       NDWS   - NUMBER OF DEFENSE WEAPONS PER SITE (UNITS)
C       DWSKRD - DELAYED DEFENSE WEAPONS KILL RATE (UNITS/SEC.)
C       ASFOT  - AIR-TO-SURFACE WEAPON FLYOUT TIME (SEC.)
C       DWSQUE - DUMMY ARRAY TO HOLD TIME HISTORY OF DWSKR
```

5.3.11 State Variables

5.3.11.1 Aircraft State and Control Variables

The aircraft state variables constitute a set of time varying parameters that describe the *state* of each aircraft at any point in the simulation. State variables include aircraft position coordinates (XS and YS), speed (VS), heading (SAI), mass (MASS), radar cross section (RCS), fuel status (FUELR) and number of air-to-surface weapons remaining (ASWU). Control variables on the other hand are the forcing function parameters that change the state of the aircraft at every point in time. These are: throttle setting (TSS) and the commanded load factor (NCOM) which is treated as an auxiliary variable since the rate change of NCOM with respect to time is quite fast and thus the level can be assumed to vary "instantaneously" (e.g. the throttle setting is a slow control) to a maximum value. Eqs. 5.907 through 5.922 define the aircraft state and control variables. Note that while computing CBFS and ASWU a check is necessary to insure that these variables have not been driven to zero as shown in Eqs. 5.915 and 5.920, respectively. Also the heading angle (SAI) is constrained within 0 and 2π with the use of subroutine YAW. Note that a simple first order integration method (Euler) is used in this model.

```
DO 200 I=1,M
   TSS(I)  = TSS(I)  + DT * TSSR(I)                          5.907
   VS(I)   = VS(I)   + DT * ACCS(I)                          5.908
   XS(I)   = XS(I)   + DT * VS(I)*COS(HEADS(I))              5.909
   YS(I)   = YS(I)   + DT * VS(I)*SIN(HEADS(I))              5.910
   SAI(I)  = SAI(I)  + DT * SAIR(I)                          5.911
```

```
            MASS(I) = MASS(I) - DT * DMASS(I)                          5.912
            RCS(I)  = RCS(I)  - DT * RCSRW(I)                          5.913
            FUELR(I) = FUELR(I) - DT * FFLOW(I)                        5.914
             IF (CBFS(I) .GT. 0.0) THEN                                5.915
               CBFS(I) = CBFS(I) - DT * S1CBKD(I)                      5.916
             ELSE
               CBFS(I) = 0.0                                           5.917
             ENDIF
200      CONTINUE
C
         CALL YAW (SAI, M, SAI, PI)                                    5.918
C
         DO 250 I=1,M
           DO 250 K=1,KK
             IF (ASWU(I,K) .GT. 0.0) THEN                              5.920
               ASWU(I,K) = ASWU(I,K) - DT * S2SULA(I,K)                5.921
             ELSE
               ASWU(I,K) = 0.0                                         5.922
             ENDIF
250      CONTINUE
C
C          CBFS   - NUMBER OF AIRCRAFT
C          TSS    - AIRCRAFT ENGINE THROTTLE SETTING (DIM.)
C          XS     - AIRCRAFT DOWNRANGE POSITION (METERS)
C          YS     - AIRCRAFT LATERAL DOWNRANGE POSITION (METERS)
C          HEADS  - AIRCRAFT HEADING (RADIANS)
C          RCS    - RADAR CROSS SECTION AREA (SQ. METERS)
C          FUELR  - AIRCRAFT FUEL REMAINING (KGS.)
```

5.3.11.2 *Defense Weapons State Variables*

The state of the defense weapon ground sites can be uniquely described by the number of defense weapons remaining at each site and time (DWS). An extra variable denoted NDWS is introduced here to aggregate the number of weapons at each site (e.g. *j* subscript). This is done to estimate the fraction of the defensive sites destroyed during a mission. Finally, Eq. 5.928 updates the simulation time.

```
         DO 302 J=1,N
           IF (NDWS(J) .GT. 0.0) THEN                                  5.923
             NDWS(J) = NDWS(J) - DT * S1DWKD(J)                        5.924
           ELSE
             NDWS(J) = 0.0                                             5.925
           ENDIF
302      CONTINUE
C
         CALL SUMDWS (DWPL, DWPL1, DWPL2, M, N, LL)                    5.926
         DO 301 J=1,N
           DO 301 L=1,LL
             DWS(J,L) = DWS(J,L) - DT * DWPL2(J,L)                     5.927
301      CONTINUE
C
           TIME   = TIME   + DT                                        5.928
C          DWS    - NUMBER OF DEFENSE WEAPON UNITS
C          DWPL2  - DEFENSE WEAPONS PROPAGATORS LAUNCHED (2-D ARRAY)
```

6.0 Use of the Models

The main goal of these models as it has been pointed out in Chapter 1 of this dissertation is to allow the user to perform survivability and lethality tradeoffs for typical naval fighter missions as described in section 1.2. Due to the multidisciplinary nature of models like these the reader needs to understand that the models should be viewed openly in the sense that some of the trends modeled might be the subject to detailed outside analysis that can be easily incorporated either in "look-up" table form or as explicit mathematical equations. The purpose of this chapter is to illustrate several tradeoff examples where aircraft systems characteristics and tactics are changed to appreciate their effects in the aircraft measures of effectiveness and survivability at the sortie level. Ideally, these tradeoffs should be incorporated in Block 2 of the survivability life cycle shown in Fig. 1.1 (Section 1.5 of this dissertation).

There are two types of measures of effectiveness (MOE) to be used in this analysis: 1) primary and 2) secondary measures of system effectiveness. Primary MOE's refer to those that directly quantify the outcome of an engagement such as the individual probabilities of survival per sortie for each aircraft. Secondary MOE's on the other hand are derived from primary MOE's and are used to estimate fleet effectiveness. In this category we find the average probability of aircraft survival per sortie P_{SAV} , the exchange ratio (ERATIO), and the

relative exchange ratio (RERATIO). These three secondary measures of aircraft effectiveness are defined as follows.

$$P_{S\,AV\,cbf} = \frac{1}{M} \sum_{i=1}^{M} P_{S\,i} \qquad P_{S\,AV\,agg} = \frac{1}{N} \sum_{j=1}^{N} P_{S\,j} \qquad \{6.1\}$$

$$ERATIO_s = \frac{N - AGG(t)}{M - CBF(t)} \qquad \{6.2\}$$

$$RERATIO_s = \frac{N - AGG(t)}{M - CBF(t)} \quad \frac{M}{N} \qquad \{6.3\}$$

where, M and N are the initial force sizes of the CBF and AGG fleets respectively, $P_{S\,AV\,cbf}$ and $P_{S\,AV\,agg}$ represent the average sortie survivabilities for the CBF and AGG forces, $P_{S\,i}$ is the individual CBF aircraft sortie survivability, $P_{S\,j}$ is the individual aggressor aircraft probability of sortie survival, *ERATIO* is the exchange ratio (favorable to the friendly force), and *RERATIO* is the relative exchange ratio of the sortie, and $CBF(t)$ and $AGG(t)$ are the aircraft remaining in combat at time t (e.g. at the end of a sortie). Notice that *RERATIO* is just ERATIO corrected by initial force size although it is an important measure of effectiveness at the campaign or mission level if one is to estimate the combat superiority of a force in terms of the initial force sizes. As an example take the current 5:2 fighter numerically superiority of the Soviet Union over N.A.T.O. forces in Europe. If a war were to occur, N.A.T.O. forces would have to achieve at least an exchange ratio (ERATIO) of $\frac{5}{2}$ in order to offset its numerical disadvantage. This would translate in a $\frac{1}{1}$ *relative exchange* ratio implying an even conflict for both sides.

6.1 Air Superiority Model (ASALT I)

The first portion Chapter 5 described in detail the equations comprised in the ASALT I simulation model emphasizing in the mechanics of each DYNAMOIII statement. The purpose of this section is to give more insight into the actual numerical values of some of the key variables of the model, to exemplify the versatility of the model by running several mission profiles and combat scenarios, and lastly to point out some of the precautions running the model and interpreting its results.

6.1.1 The Base Model

The baseline model refers to the version described in Chapter 5. It consists of parameter values that ideally would be used as a reference point in the calibration and fine tunning of the model.

The following discussion provides more insight into the key parameters of the model and their time histories in a sortie. One of the most important parameters in this model is the commanded load factor (NCOM and NCOMG) for the vehicles interacting in the combat. Fig. 6.1 represents a sample of the commanded load factors for two opposing aircraft during a 2 on 2 engagement. The combat takes place at 6.5 km and 3 tons of fuel are carried in the mission by both adversaries. The mission is that described at the begining of chapter three and lasts approximately 21 minutes (1200 sec.). From this figure it can be observed that the CBF aircraft acquires its opponent at around 220 seconds and starts its offensive maneuvers. The plot is characterized by a series of irregulars peaks and valleys which represent the abrupt changes of the commanded load factors occuring throughout the engagement in order to gain an advantageous firing position. An interesting detail observed in this graph is the fact that the altitude effect on engine performance can be observed from the commanded load

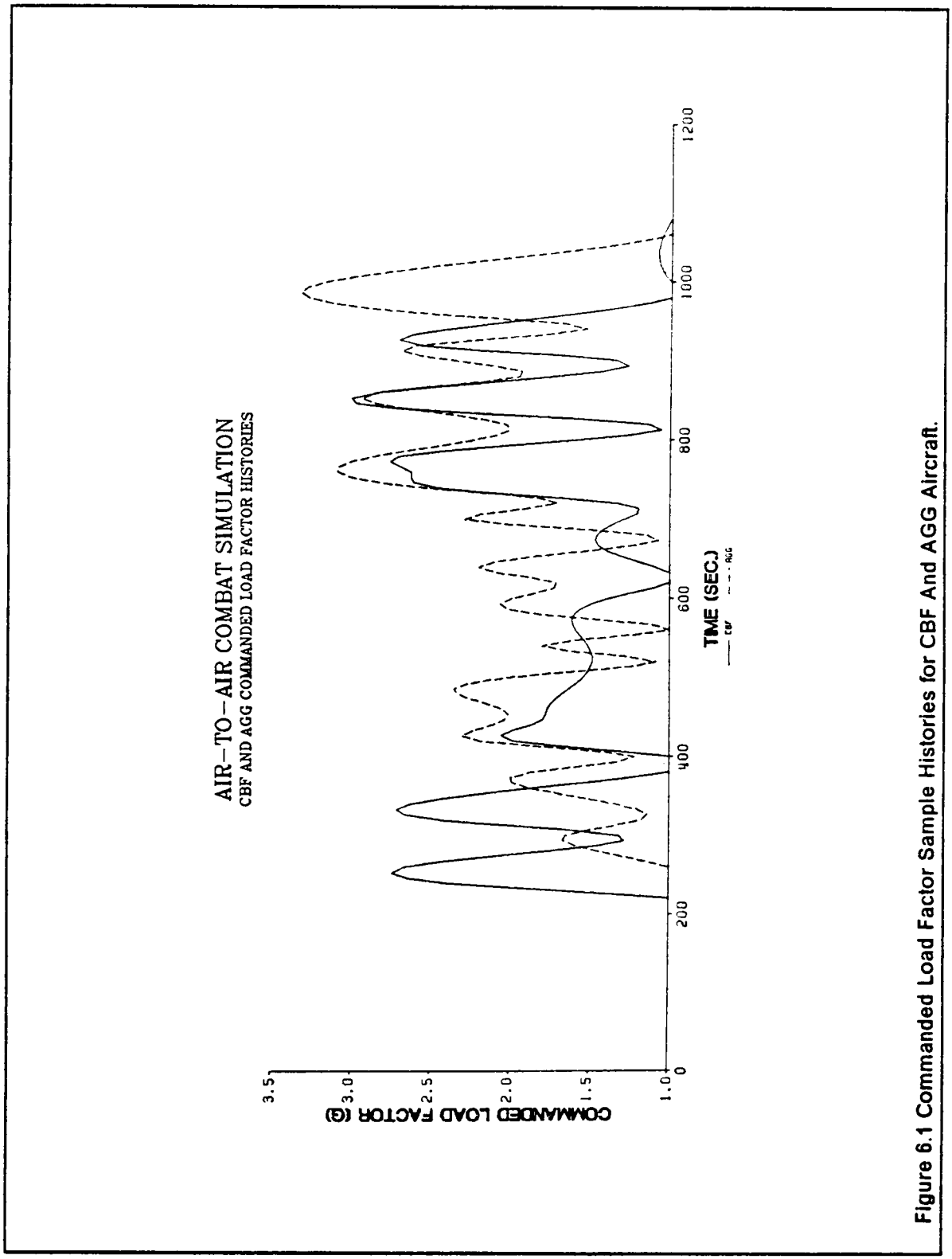


Figure 6.1 Commanded Load Factor Sample Histories for CBF And AGG Aircraft.

factors shown which seem to peak at approximately 3.5 g's. It should be recalled that engine thrust was assumed to vary proportionally with density ratio (Section 5.2.8).

Another important variable is the flight speed of each of the combatants. In this particular case the flight mach number is used as representative parameter and a sample of the variations in mach number through the mission can be observed in Fig. 6.2. From this figure it can be seen that both aircraft accelerate during the BVR phase of the combat (approximately starting at 300 seconds into the mission). Maximum speeds seem to occur at around 500 seconds and in both cases the aircraft engage each other in a supersonic fight following the control algorithms described in Section 5.2.5 of this dissertation.

The aircraft mass variations can be appreciated from Fig. 6.3. The plot shows a large expenditure of aircraft mass occuring in the interval 350-400 seconds associated with the launch of the long range weapons (LRAAM) which incidentally are heaviest ones. Note that the aggressor launches occur about 30 seconds later than those of the CBF aircraft due the more limited range of the weapons as well as those limitations imposed in the aggressor radar detection capability. Complementing the information presented in Figs. 6.1 and 6.2 it is possible to estimate the heading changes taking place during the combat. Fig. 6.4 shows typical heading histories for the same adversaries used in previous plots (i.e. 2 vs. 2 engagement). It is seen that the initial headings for the aggressor and CBF aircraft are 180 and 15 degrees, respectively. Again, a series of peaks and valleys starting at 230 seconds closely resemble those of Fig. 6.1. Not surprisingly should be recalled that the sustained turn rate, which influences the instantaneous aircraft heading, is a function of load factor and flight speed.

Finally in this sequence, it is possible to obtain great inside of the complete combat scenario by plotting the flight paths described by the aircraft taking part in the engagement. Figs. 6.5 and 6.6 depict two examples of aircraft flight paths generated by ASALT I for two near frontal attack and two even fleet size configurations (i.e. 2-on-2 and 4-on-4). The paths of the aggressors are marked with dotted lines while those of the CBF aircraft are solid lines. In Fig. 6.5 it is noticed that the CBF fleet initially flies in close formation dispersed echelon formation.

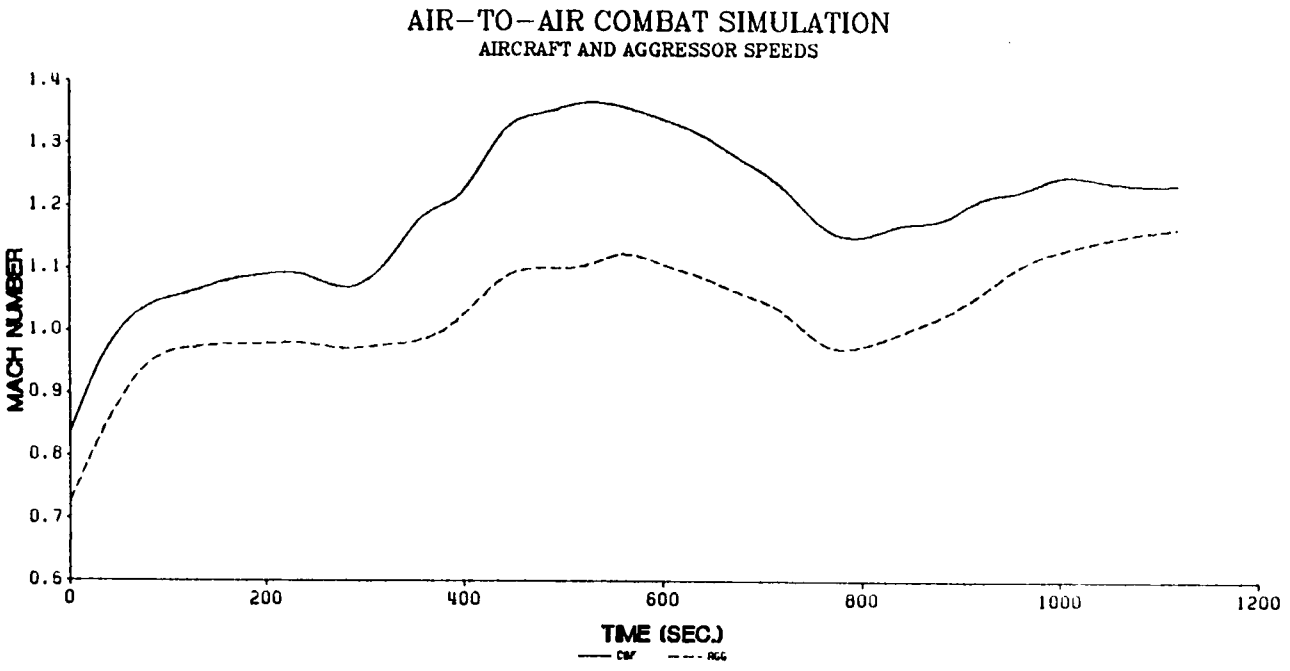


Figure 6.2 Flight Mach Number Histories for CBF and AGG Aircraft.

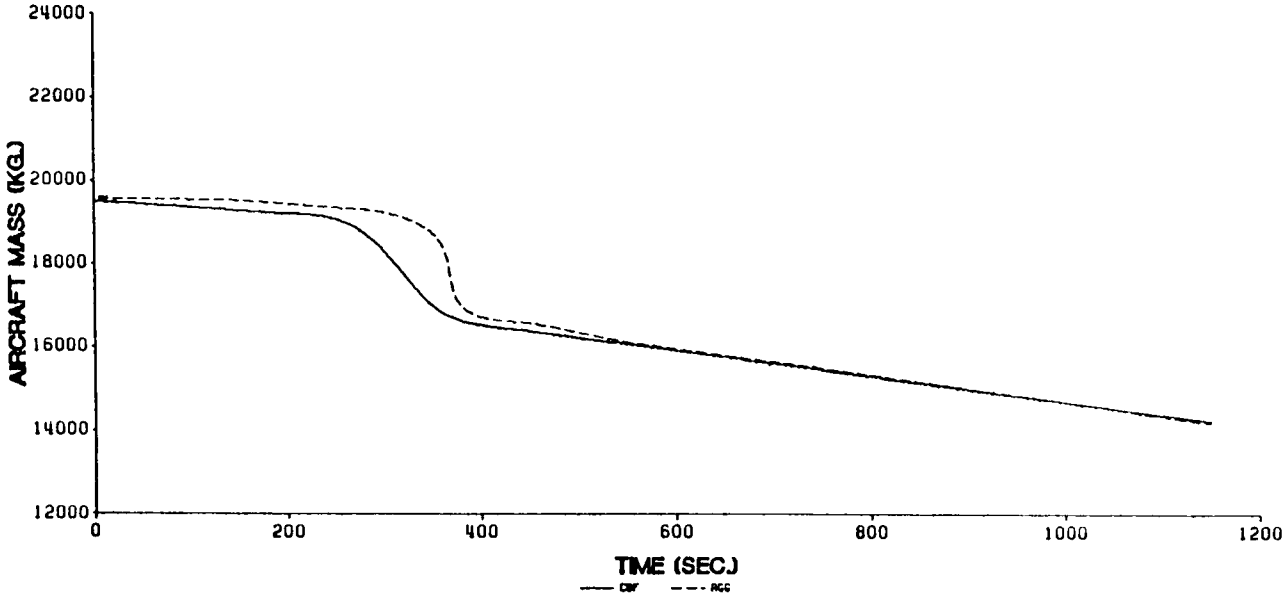


Figure 6.3 Typical CBF and AGG Aircraft Mass Histories Throughout an Engagement.

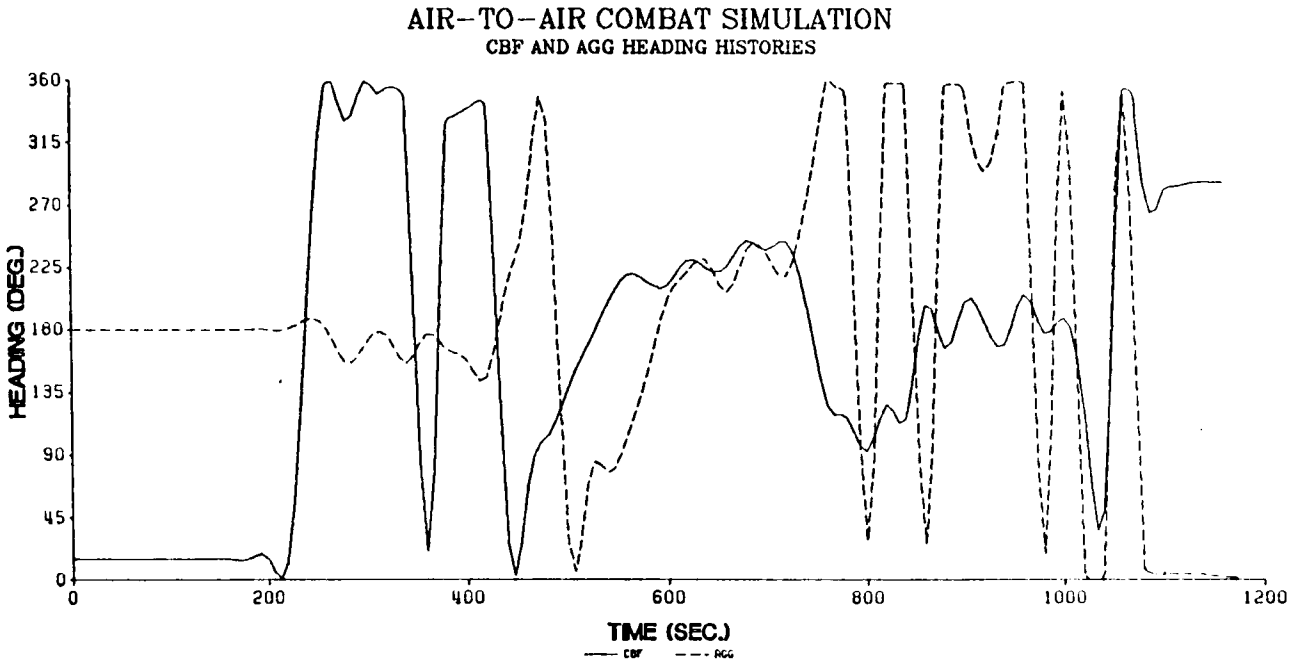


Figure 6.4 Typical CBF and AGG Aircraft Heading Angle Histories.

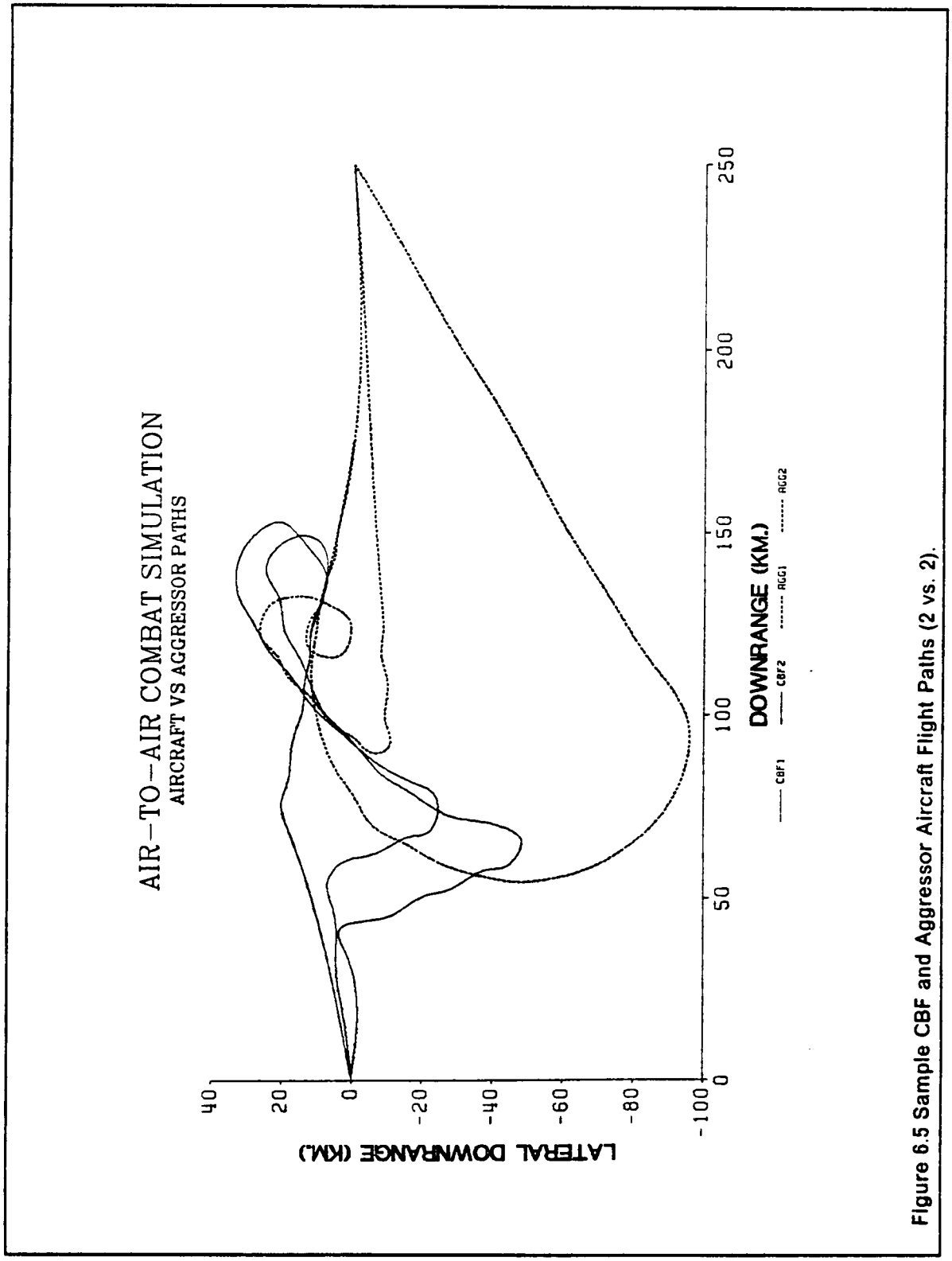


Figure 6.5 Sample CBF and Aggressor Aircraft Flight Paths (2 vs. 2).

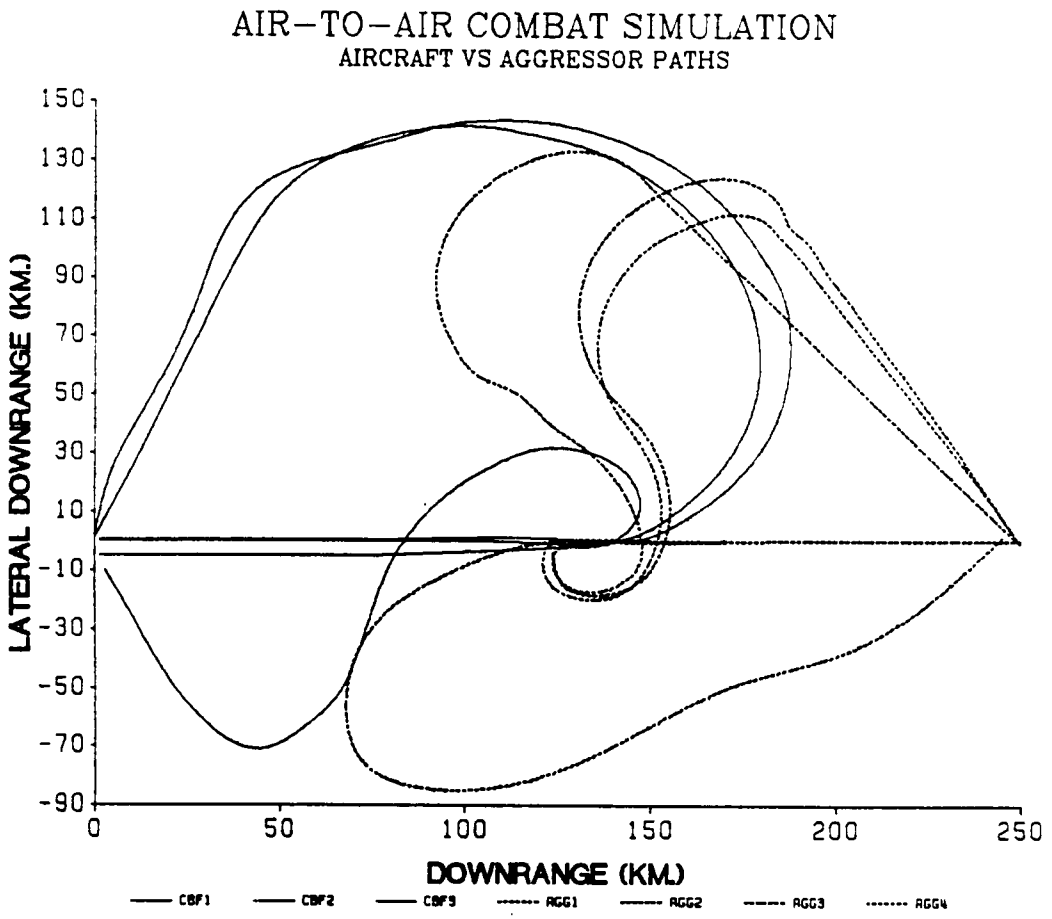


Figure 6.6 Sample CBF and Aggressor Aircraft Flight Paths (4 vs. 4).

A head-on pass takes place at about 125 kilometers downrange from the initial simulation starting point followed by a double pursuit of one of the aggressor aircraft by both CBF. Good firing opportunities develop for the second aggressor aircraft as well as the two aircraft CBF. The pursuit is ends in the lower left hand side quadrant due to weapon exhaustion on both sides. This particular mission favors the CBF fleet with an exchange ratio of 1.85 due to the effective employment of the long range weapons (130 km. max range) in the initial frontal pass. In Fig. 6.6 the CBF aircraft fleet starts in dispersed echelon formation (e.g. two distinct pairs are visible). Again, a frontal attack with long range use of the weapons takes place followed by multiple aircraft pursuits. The outcome of this engagement yield an exchange ratio of 2.5 favoring the CBF fleet.

6.1.2 Sensitivity Analysis

One of the most important questions arising in the survivability community is the role of technology in survivability. It has been argued that technologically superior fighters can be outnumbered by an opponent fleet and still be victorious. However, it is not evident at which point does this technological superiority ceases to exist unless a detailed analysis is performed and the exchange ratio can be estimated from a given set of engagement conditions. This statement if true cannot be taken lightly from a tactical and cost effectiveness point of view since small improvements in $P_{s/s}$ could result in large aircraft savings at the end of a campaign (i.e. a predeterminated number of sorties to achieve a tactical goal). For example, an increase of $P_{s/s}$ of only .3 % (say from .978 to .981) yields fractions of the escorting force remaining (FFR) of .513 and .562 respectively after a 30-sortie campaign, or a 9% increase in the number of aircraft available after 30 sorties. This suggests the importance of being able to assess even small changes in $P_{s/s}$ with force size as well as other key variables. Sensitivity analysis is performed around five key parameters in order to assess the results of the model as well as to test its usefulness as a conceptual design tool in estimating sortie

survivability/lethality of a given preliminary aircraft configuration. These parameters are aircraft radar cross section, electronic countermeasures, thrust-to-mass ratio, engagement geometry, and force-on-force variations.

6.1.3 Thrust-to-Mass Variations

Many aircraft designers envision future fighter designs with important technology breakthroughs incorporated in them in order to achieve high levels of performance to defeat and survive emerging threats. However, the question always arises as how much does a certain level of technology contributes to the survivability enhancement in a particular situation? There is no easy answer to this question since the outcome of an air-to-air engagement, for example, is highly dependent upon the particular scenario, tactics employed, etc.

As a first example consider the sizing of a baseline fighter aircraft around a series of "rubber" engines that could be in the development stage or already available at the time of the conceptual fighter aircraft design. Many parametric studies are usually conducted in order to match an engine to the planned airframe and it is very likely that several powerplants with different thrust ratings are tested to obtain the desired levels of performance within thrust constraints, fuel consumption, and range. The purpose of a tradeoff study is to estimate the changes in lethality and survivability of the carrier-based and aggressor aircraft when the engine thrust of a baseline fighter aircraft is varied and thus the thrust-to-mass ratio modified accordingly. The goal here is to choose the "best" airframe-powerplant configuration that yields the maximum relative exchange ratio (RERATIO) for the particular mission scenario as described in Chapter 5. Several assumptions have to be made in order to simplify the problem and they are as follows: 1) The main airframe geometric characteristics are kept constant except those associated with the inlet size to accommodate the various mass flow rate requirements associated with each particular powerplant installation to be studied. 2)

Aerodynamic drag characteristics are varied to account for changes in inlet drag. 3) Radar cross section (RCS) characteristics are also varied to account for changing inlet sizes. 4) Changes in aircraft mass are solely due to the different engines installed. The relevant characteristics of the CBF baseline design are given in Appendix H.

The first step to be performed in this tradeoff study is to determine the new physical engine characteristics of the modified aircraft in order to later on estimate radar cross section (RCS) and drag variations from those of the baseline design. For the purpose of preliminary engine sizing it is assumed that the modified powerplant area requirements can be estimated from the basic thrust equation for a turbojet/turbofan engine [Oates, 1986]. Defining T_{mod} and T_{base} as the modified and baseline thrusts, respectively; $\dot{m}_{mod}$ and $\dot{m}_{base}$ as the corresponding mass flow rates; also, A_{mod} and A_{base} are the modified and baseline engine compressor face areas. It can be shown that, for similar operating speed and pressure conditions,

$$\frac{T_{mod}}{T_{base}} \propto \frac{\dot{m}_{mod}}{\dot{m}_{base}} \propto \frac{A_{mod}}{A_{base}} \qquad \{6.4\}$$

from where an estimate of the compressor area requirements can be derived from either the mass flow rate or the thrust. The engine diameter can be readily estimated from which, ultimately, engine masses corresponding to each modification can be assessed. A useful relationship for these calculations is:

$$D_{mod} = D_{base}\sqrt{\frac{\dot{m}_{mod}}{\dot{m}_{base}}} \qquad \{6.5\}$$

where D_{mod} and D_{base} represent the engine diameters for the modified and the baseline aircraft, respectively.

Another important engine parameter considered in preliminary engine sizing is the length of the powerplant, L. According to Nicolai [1975] the following expression has been found applicable in current fighter designs.

$$L_{mod} = L_{base}\left(\frac{\dot{m}_{mod}}{\dot{m}_{base}}\right)^{n-\frac{1}{2}} \quad \{6.6\}$$

where L_{mod} and L_{base} are the modified and baseline engine lengths, respectively, and n is a scaling factor usually taken as unity for most practical purposes.

Regression analysis was performed for 11 current fighter aircraft engines in the same thrust category of the modifications sought in order to estimate trends in engine mass versus engine diameter [Drew et al, 1986]. This study showed good correlation (90%) and is used to estimate engine masses for all modifications; where the derived relationship is as follows:

$$w_{engine} = k_1 + k_2 D_{engine} \quad \{6.7\}$$

where k_1 and k_2 are regression constants, and D_{engine} is the engine diameter taken as reference. It follows that for a modified vs. a baseline engine,

$$w_{mod} \propto w_{base}\frac{D_{mod}}{D_{base}} \quad \{6.8\}$$

For added structural mass similar analogies are used -- starting with the added fuselage structural volume to support the modified powerplant. Assuming an average aircraft structural density and that the volume of the modified engine is proportional to the new required structural volume to support it, then expression 6.10 can be used to estimate the mass changes associated with the new powerplant.

$$\frac{V_{mod}}{V_{base}} = \frac{D_{mod}^2\ L_{mod}}{D_{base}^2\ L_{base}} \quad \{6.9\}$$

and,

$$M_{mod} = M_{base}\frac{V_{mod}}{V_{base}} \quad \{6.10\}$$

where, V_{mod} and V_{base} are the structural volumes of the modified and baseline aircraft, respectively; M_{mod} and M_{base} are the masses of the modified and baseline aircraft, respectively.

For the present analysis the baseline fuselage mass affected in the modification process is taken as 3500 kg for computational purposes. The final values of the mass changes for each modification are shown in Table 6.1.

Table 6.1 Dimension/Mass Variations for Aircraft Modifications.

Configuration	D (m)	L (m)	ΔM (kg)
Baseline	0.950	4.040	0.0
Mod. #1	0.760	3.250	-1698
Mod. #2	0.867	3.705	-828
Mod. #3	1.019	4.361	843
Mod. #4	1.073	4.590	1569

Another important issue is the drag increase associated with installation of a different engine for each modification. The simplifying assumption is that only additive drag is considered to increase CD_0 at a rate of 7.5 counts per 0.1 square meter of increased engine frontal area (one count of C_{D0} is 1/10000). The reasoning behind this seemingly arbitrary assumption is the fact that additive drag (spillage drag as sometimes referred) is very sensitive to the geometry of the particular inlet, information not available and beyond the scope of this simple example. The numerical results of drag changes for each configuration are in terms of the change in clean aircraft zero lift drag coefficient (CD_0).

The last parameter affected directly with the installation of a new engine is the radar cross section area (RCS) associated with it. Crispin [1968] offers a simple equation to approximate cavities such as that those characteristic of aircraft inlets as shown in Eq. 6.11.

$$\sigma \propto \frac{A_c^2}{\lambda^2} \qquad \{6.11\}$$

and for a constant λ:

$$\frac{\sigma_{mod}}{\sigma_{base}} = \frac{A_{mod}^2}{A_{base}^2} \qquad \{6.12\}$$

where σ_{mod} and σ_{base} represent the radar cross sectional areas of the modified and baseline aircraft, respectively; A_I is the engine area and λ is the radar wavelength. Finally it should be realized that the inlets only constitute one portion of the many radar reflecting surfaces found in an aircraft and for this matter it has been assumed that 60 % of the total aircraft radar cross section (RCS) is due to the inlets. The corresponding numerical results of the computation of RCS for each modification are shown in Table 6.2.

Table 6.2 Summary of Modifications for Baseline Aircraft.

	ALTERNATIVE A/C				
DESCRIPTION	BASE	MOD. 1	MOD. 2	MOD. 3	MOD. 4
1) Engine Thrust SSL (kg)	8131	5260	6840	9473	10525
2) Aircraft Mass (kg)	19300	17602	18473	20143	20869
3) Thrust/Weight	0.85	0.55	0.70	1.00	1.10
4) ΔC_{D0} (counts)	0.0	-30.60	-14.25	12.90	23.40
5) Engine Capture Area (sq. m)	0.363	0.472	0.567	0.653	0.723
6) Engine Diameter (m)	0.95	0.76	0.87	1.02	1.07
7) Radar Cross Section (sq. m)	5.00	3.23	4.08	5.98	6.88
8) Normalized RCS	1.00	0.646	0.816	1.196	1.376

Items 1,2,5, and 8 in Table 6.2 constitute the principal inputs to investigate the new survivability and lethality of each modified aircraft. The engine thrust is scaled down or up in the code according to the known values of engine thrust at sea level (item 1 in Table 6.2). A multiplicative scaling factor (TMULT) is introduced in the program to match the baseline sea level thrust (see Eq. 5.414) to the desired thrust for the new modification under the same conditions (i.e. sea level). The second input to the program is the aircraft mass. The masses shown in Table 6.2 correspond to the mission masses to be used for each run since it has been assumed that the only two sources of mass reduction/increase are different engine masses and the structural modifications to each aircraft. Values for ΔC_{D0} are also important to be incorporated into the model. This is done by adding a dummy variable (MULT) to

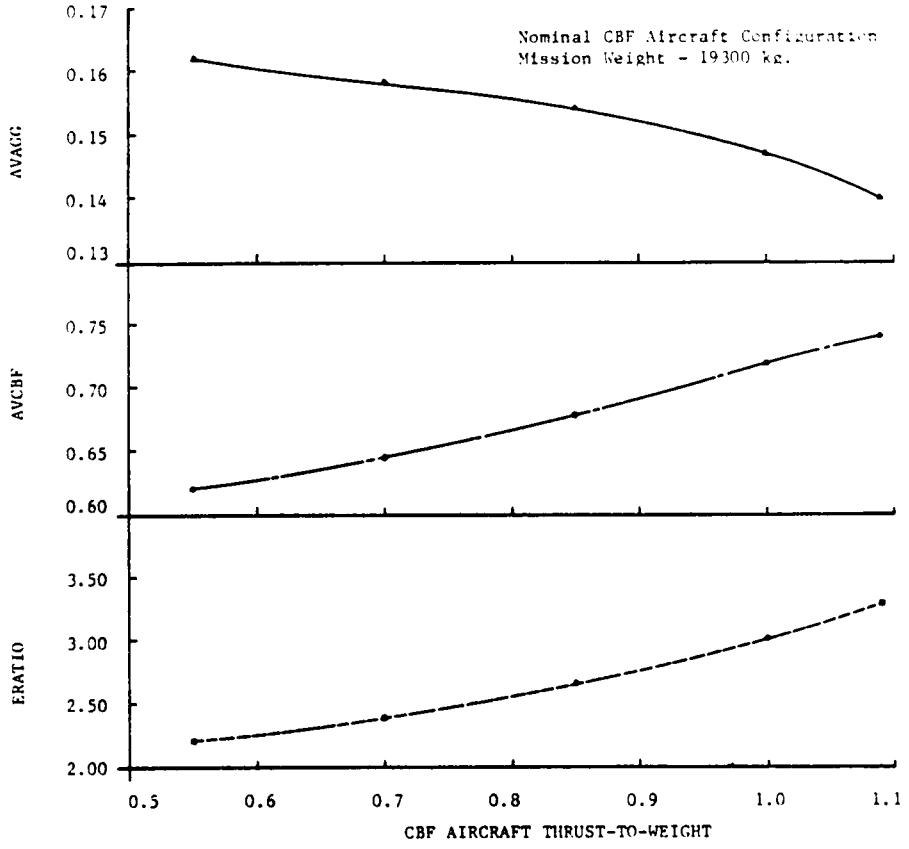


Figure 6.7 Survivability Related Measures for Various Engine Modifications.

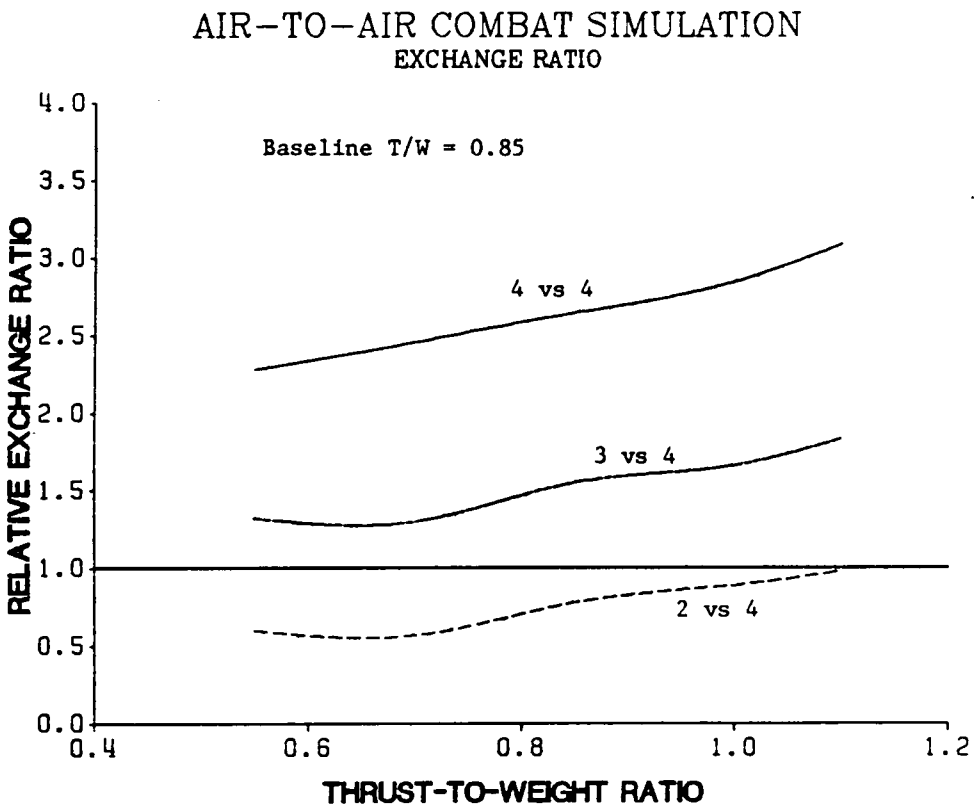


Figure 6.8 Relative Exchange Ratio for Various Engine Modifications.

account for ΔC_{D0} and adding it to the term CD0 (Eq. 5.439) which represents the clean aircraft zero-lift drag value. Lastly, the normalized RCS values shown in Table 6.2 correspond to the values of MULT2 (Eq. 5.268A) for each modification. It should be recalled that RCSAN is the clean aircraft radar cross section value.

Thrust-to-mass ratio (T/M) values ranging from 0.55 to 1.10 were tested in the program to determine the effects of this parameter on aircraft survivabilities (for both sides) and thus derive the corresponding values for the secondary MOE's. Fig. 6.7 shows a composite plot of the T/M as the independent variable and the average force survivabilities for the CBF and AGG aircraft (AVCBF and AVAGG), respectively. This study, by the way, was performed in a 4 on 4 force size configuration which incidentally is taken as the baseline case for comparative purposes. The behavior of the curve for exchange ratio is monotonic for the range of values tested. It should be realized that the CBF aircraft are more capable from the performance point of view as well as in the on board systems (i.e. weapons, radar, etc.). A quick glance at the nominal systems performance can be gained from Appendices G and H. As it might be recalled from Chapter 5, thrust palys a major role in the determination of aircraft acceleration and normal load factor. Fig. 6.8 depicts the relative exchange ratio (RERATIO) for three different force sizes. As one might expect, large RERATIO's were obtained for the engagements with even numerical strengths (4 vs. 4) ranging from 2.3 to 3.15. More moderate RERATIO's were observed for the the aggressor fleet having a 33% numerical advantage (3 vs. 4) and unfavorable results were seen for the case where the the aggressor force enjoyed an initial force size ratio of 2:1 (2 vs. 4). These results suggest that aircraft performance alone can only overcome numerical disadvantages in this particular scenario up to a well defined limit.

6.1.4 Weapon Technology Improvements

A second example to use this model is to explore the possible gains in aircraft lethality due to an improvement in the air-to-air weapons carried. The baseline values of the weapon capabilities for CBF and AGG aircraft are shown in Table 6.3. The tradeoff performed here is to vary the weapon ranges for the CBF aircraft from 0.4 to 1.4 of the nominal values shown in Table 6.3. Fig. 6.9 depicts the graphical results of this analysis. The results apply to a 4 vs. 4 frontal engagement and clearly indicate CBF superiority for values of the normalized range above .5 (approximately 65 km. maximum range). The variations in exchange ratio are significant and seem to confirm the tactic of using long range weapons in a stand-off fashion when their performance is significantly higher than that of the opponent. It is interesting to note that the equilibrium exchange ratio (i.e. that for equal sortie survivabilities) occurs near the normalized value that equates the weapon ranges thus implying that both aircraft configurations are fairly similar in performance aerodynamically under this particular conditions (i.e. specific excess energy levels are very close).

Table 6.3 Aircraft Weapon Ranges for Five Improvement Programs.

Configuration	Ranges (km)			
	LRAAM	MRAAM	SRAAM	GUNS
Baseline	130	47	7.5	2.5
Mod. #1	182	66	10.5	3.5
Mod. #2	156	57	9.0	3.0
Mod. #3	104	38	6.0	2.0
Mod. #4	78	28	4.5	1.5
Mod. #5	52	19	3.0	1.0

Fig. 6.10 depicts the relative exchange ratio (RERATIO) for three different force sizes and various weapons improvements. Just as with engine thrust variations, a definite improvement in the air-to-air weapons capabilities gives a decisive edge in aerial combat as seen in Fig. 6.10 for a numerically inferior force. It is noted though that the behavior of these curves show a much larger sensitivity of RERATIO to weapons than to aircraft performance variations.

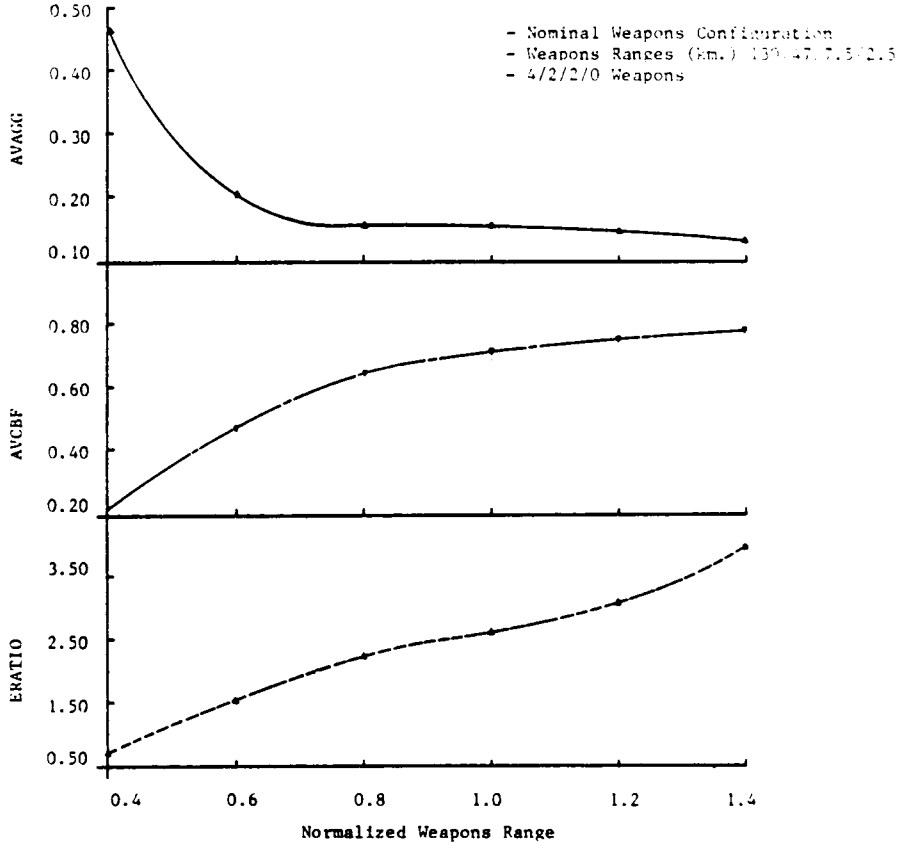


Figure 6.9 Average Survivability Parameters for Various Weapons.

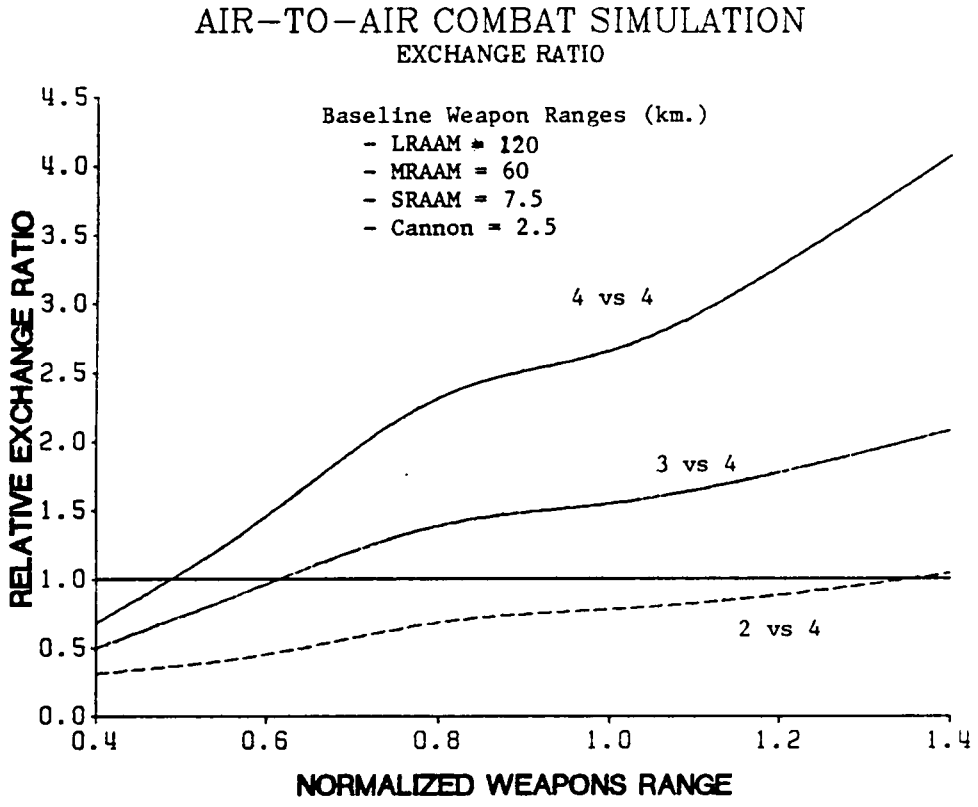


Figure 6.10 Relative Exchange Ratio for Various Weapon Improvements.

Notice that even for the even force size case (4 vs. 4) the CBF aircraft will eventually be at disadvantage for a normalized weapon range of 0.5 (i.e. baseline range is 130 Km.) which in fact corresponds very closely to the aggressor weapon range capabilities used as reference in all the program reruns.

6.1.5 Aircraft Signatures

Aircraft Signatures are becoming increasingly important elements in the design of combat aircraft as advances in electronic warfare seem to be changing the old fashioned concept of considering aircraft performance as the primary issue in survivability analysis. For example, the Rockwell International B-1B bomber has a radar cross section of just one tenth that of its more aerodynamic capable predecessor (i.e. the B-1A) while apparently retaining many of the fuselage external features [North, 1986]. This of course has been the result of a better engine-body integration in part due to the less stringent dash speed requirements of the B-1B contract. With this example then it is possible to appreciate the importance that a careful design can have in some parameters such as savethe radar signatures of an aircraft.
Signatures are modeled according to Eqns. 5.266 through 5.271. Aircraft radar cross section (RCS) variations for the purpose of sensitivity analysis are introduced in the model through the variable MULT2 which represents a multiplier affecting the CBF aircraft clean radar cross section, RCSAN, shown in Eq. 5.268A (see Appendix A of this report). The results of the sensitivity analysis performed around this parameter are shown in Fig. 6.11 and emphasize the importance of current tendency towards "stealth design" in order to achieve higher survivability levels. It is important however, to interpret Fig. 6.11 with caution since the plot assumes that only RCS is varied in the model keeping everything else constant. This then ignores possible tradeoffs that might accompany any change in RCS such as aircraft mass, size, changes in powerplant, etc.. The importance of the curves rests in the fact that there are various techniques available to the designer to reduce and "clean up" RCS of an aircraft with

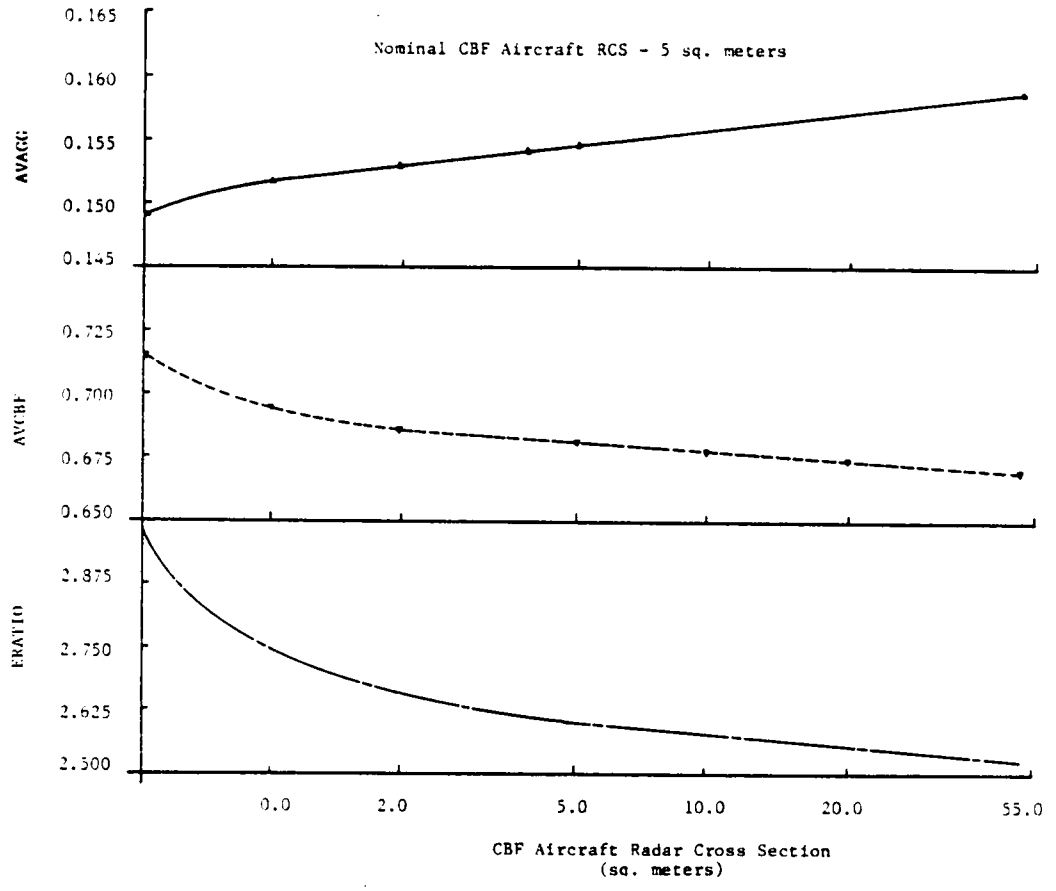


Figure 6.11 Average Survivability Parameters vs. Radar Cross Section.

little compromise to the aircraft aerodynamic performance such as the use of wave attenuation materials in the fuselage and engine inlets, cleaner control surfaces, engine-airframe integration, comformal ordnance, etc..

6.1.6 Electronic Countermeasures.

Jamming techniques and modeling were described in Section 5.6.1.2 There it was pointed out that there were two jamming doctrines modeled: 1) stand-off and 2) self screening jamming. The results of the various jamming doctrines is summarized in Table 6.4.

The first result of Table 6.4 correspond to the baseline case where no jamming on either side was applied. This baseline case, however, implies a boost in performance and weapon range capability for the CBF aircraft as detailed in Appendix H and as previous sections have detailed. The second and third jamming doctrines seen in Table 6.4 represent active jamming doctrines for the CBF aircraft *only*, while the last two cases (labeled *Reflex*) correspond to both sides making use of their jamming capabilities. It can be seen that the best results were achieved using the stand-off jammer whose location was assumed to be fixed throughout the simulation. The use of this jammer resulted in very small burn-through ranges (on the order of 24 km. for the aggressor radar) and thus gave a very decisive edge to the CBF aircraft fleet. Notice that high levels of lethality were also present with the self-screening technique presumably using the on-board CBF jammers for the task. Finally, much lower exchange ratios were obtained using the reflex doctrines were both aircraft fleets make use of their jammers (either SOJ or SSJ). The interesting conclusion about these last two results suggests that the aggressor gains some advantage in a total jamming environment since the period of launch opportunities is largely reduced for both, CBF and AGG, to the point that both aircraft fleets launch their weapons almost simultaneously at very short ranges.

Table 6.4 Noise Jamming Survivability Parameters.

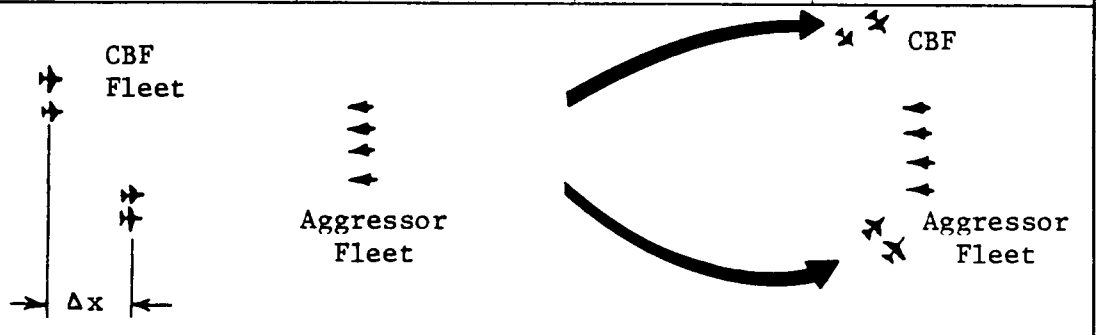
Configuration	AVAGG	AVCBF	ERATIO
No Jamming	0.155	0.682	2.659
Self-Screening	0.147	0.947	16.1
Stand-off	0.141	0.968	26.8
Reflex SSJ	0.114	0.657	2.584
Reflex SOJ	0.363	0.456	1.720

6.1.7 Variable Geometry Engagement Configurations

This section tries to capture the role of tactics in the exchange ratio between the two opposing forces. The main parameters considered in this analysis are the initial aircraft states (positions), and initial headings which define the geometry of the engagement. The effect of initial formation was first studied to see the effects of stagger and headings on the possible outcome of the combat. The results of this are shown in Table 6.5. It is noted that a "pincer" type tactic achieves by far the highest exchange ratio of the five formations tried. There was very little difference between a "finger four" and the large stagger formation (5km.). While the short stagger formation (2.5 km.) resulted in the lowest exchange ratio of all at 2.673. This value, however is still higher than that of the close formation used as baseline. The examples presented in this chapter constitute only a small portion of the many tradeoff analysis that can be carried out with ASALT II. The idea has been to provide the basis for more complex variations that will be developed in the last section of this chapter.

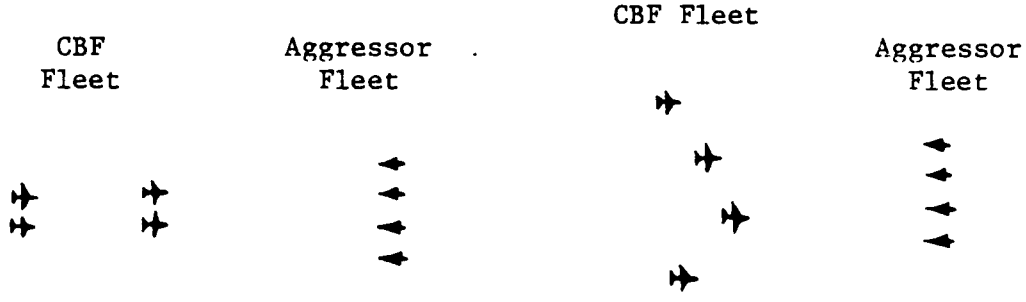
Table 6.5 Formation Influence on Survivability Parameters.

Configuration	$P_{S\,AV\,agg}$	$P_{S\,AV\,cbf}$	ERATIO
Staggered (5 km.)	0.157	0.690	2.720
Staggered (2.5 km.)	0.155	0.684	2.673
Pincer	0.189	.840	5.081
Column	0.157	0.691	2.730
Finger Four	0.156	0.689	2.716



Staggered Formation

Pincer Formation



Column Formation

Finger Four Formation

6.2 *Air-to-Surface Model (ASALT II)*

The goal of this section is to explain some of the basic results obtained with ASALT II. Just as in previous section the emphasis will be first in obtaining some "feel" for some of the most important variables and their variation as a function of time, then several sensitivity studies will be conducted in order to gain some understanding about the potential use of the model at the conceptual design level.

6.2.1 The Base Model

The first set of variables to be described here are the state variables for the aircraft and the defense ground sites. As previously mentioned (Section 5.3.11) each aircraft and ground site had associated several state variables (i.e. level variables in Systems Dynamics jargon) which represented the current condition of the aircraft and ground sites through the simulation. Fig. 6.12 depicts typical flight paths for the baseline condition where all the aircraft fly in close formation directly above the ground sites and over the target area. The maximum defense weapon sites are also identified to give an idea of the threat density (i.e. number of weapons per unit area). Notice that the concentric ellipses in all the sites represent three sets of weapons located at the same geographical position. Notice that the elliptical shape of the envelopes is due to dissimilar scales used for the horizontal and vertical axes. In reality, the envelopes constitute circles for all the weapons. It could be argued that this configuration might represent a worst case scenario for the attacking aircraft as their flight time inside the defensive weapon kinematic envelopes is maximized, however, it represents a valid case which will be used here to study the results of the simulation model. In general, any geometry selected by the analyst can be modeled in ASALT II as the program accepts as input data the waypoints defining each aircraft flight path independently. This flexibility is depicted in Fig.

6.13 where a dissagregated attack with four aircraft is shown. In this particular case the four aircraft perform the ingress portion of the flight in different paths to take advantage of the aligned location of the weapons. Notice that most of the anti-aircraft artillery fire is avoided except for aircraft labeled 3 which partially penetrates the AAA envelopes during the ingress portion of the flight. The eggress path is composed of two flight corridors located 15 kilometers north and south of the defensive weapon positions. This tactic takes all aircraft away from the reach of the AAA artillery (except at the main target area), however, this makes the aircraft more susceptible to radar-guided and infrared-guided weapons as their effective signatures increase with variations in azimuth. At the end of the sortie the probabilities of survival for aircraft 1, 2, and 4 are relatively higher (0.982-0.978) than that of aircraft 3 which achieves a mere 0.9757. Just as in the baseline run (see Fig. 6.12) the aircraft perform a maximum sustained performance turn (about 7 g's) shortly after the release of the bombs over the main target area, located 250 Km. from the starting point in the simulation.

Another important state variable which can be explicitly specified in the program is the aircraft speed at waypoint of the flight path (see Section 5.3.2). The throttle setting is then regulated accordingly to maintain the desired flight speed as close as possible according to the second order negative feedback loop depicted in Fig. 3.2. Fig. 6.14 shows the same simulation run of Fig. 6.14 depicting the time histories of the four attack fighters. It is noted that three distinctive speed changes are performed as the sortie progresses. Starting with a flight speed of mach 0.82 the aircraft accelerate as the ingress portion of the sortie takes place. Notice that maximum speed attained at the main target area is around mach 0.96 followed by a fast eggress at mach 0.88 to minimize exposure time to surface-to-air missiles. The speed histories for the baseline run is not shown here because a constant speed (Mach 0.8) is specified throughout the entire sortie making the plot extremely simple. It should be understood, however, that even if a constant aircraft speed schedule is assigned for all waypoints the throttle feedback control depicted Fig. 3.2 will perform continuous adjustments as the aircraft becomes aerodynamically "cleaner" as the sortie progresses due to the release of weapons.

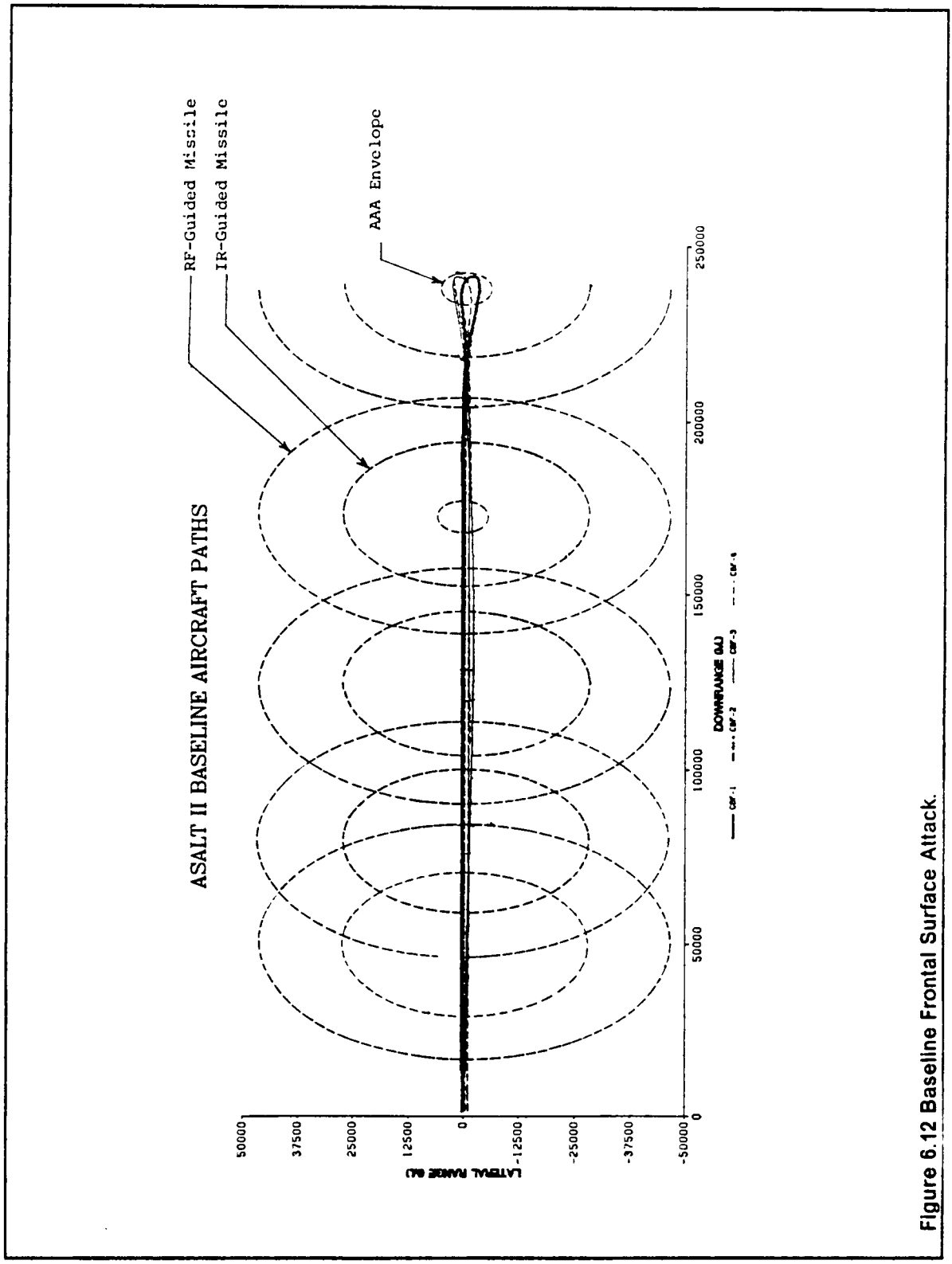


Figure 6.12 Baseline Frontal Surface Attack.

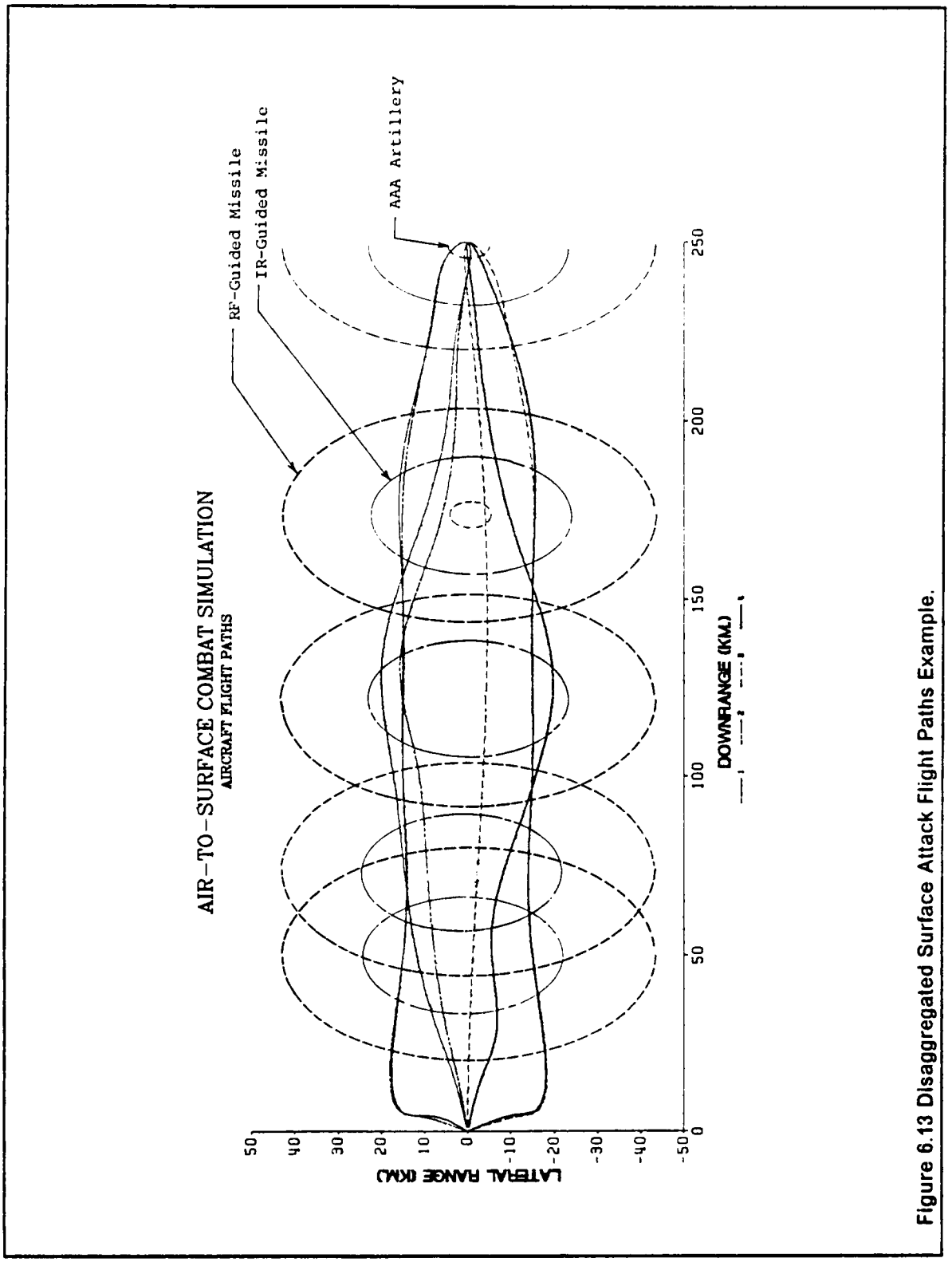


Figure 6.13 Disaggregated Surface Attack Flight Paths Example.

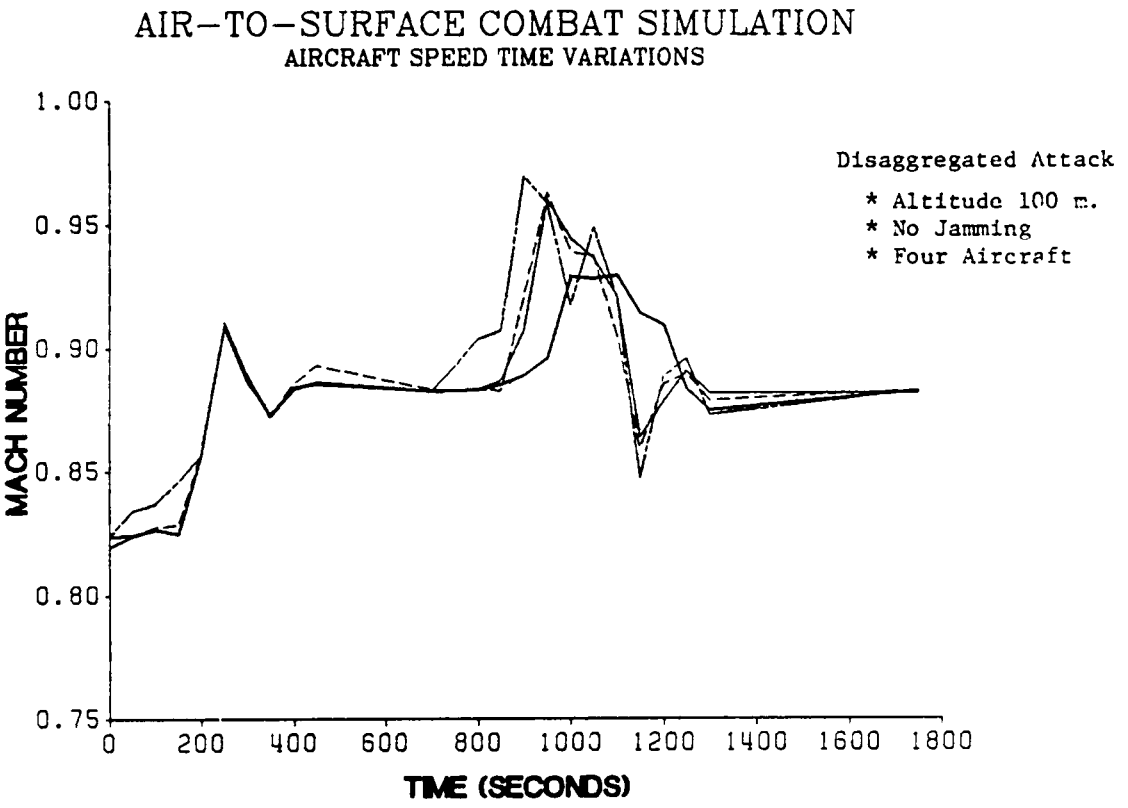
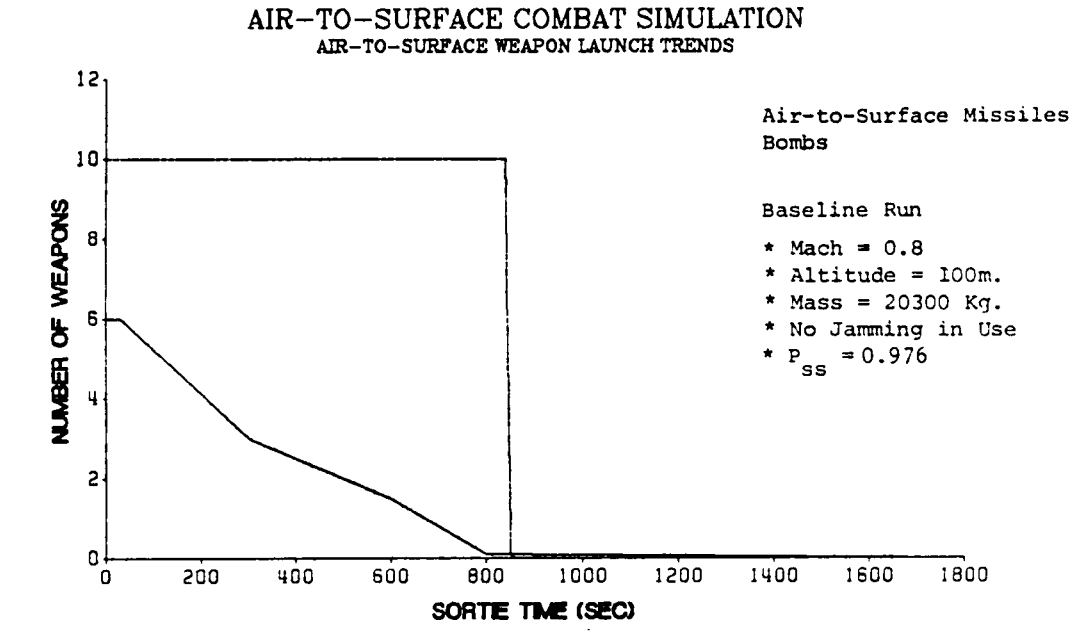


Figure 6.14 Flight Mach Number Variations for Typical Sortie.



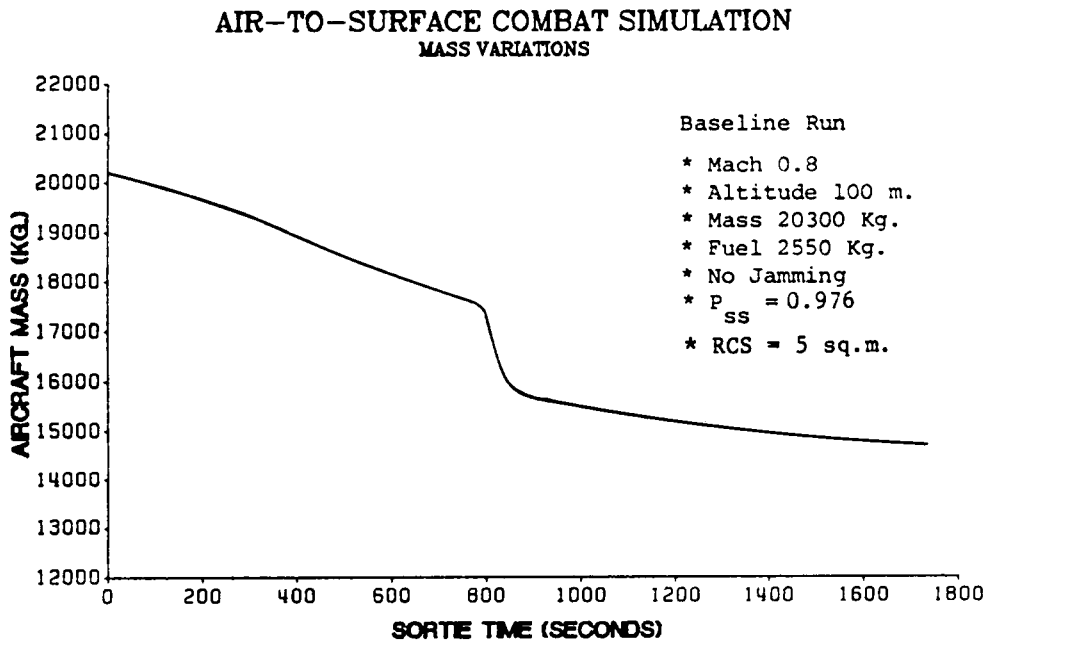


Figure 6.15 Typical Attack Aircraft Mass and Weapon Time Variations.

The aircraft mass variations can be depicted in Fig. 6.15. The plot shows a large expenditure of aircraft mass occuring at the end of the ingress phase occuring around 850 seconds into the simulation. This large mass expenditure is associated almost entirely with the launch of IR-guided bombs which as it might be recalled from Section 5.9.3.1 are allocated exclusively to the main target area. For the baseline scenario 2200 kgs. of bombs (i.e. 10 bombs) are released from each aircraft as can be seen in the composite plot 6.15. Notice also that the aircraft mass at the end of this run is about 14650 Kg. of which 350 Kg. will typically be employed in the high altitude cruise leg towards the aircraft carrier leaving approximately 300 kgs. of reserve fuel. In this baseline case the reserve fuel turned out to be 12 percent of the on-board total mission fuel (i.e. 2550 Kg.) which is very close the desired ten percent. These small discrepancies arise simply because the mission fuel planning algorithm uses only an average speed between waypoints (see Section 5.3.5.2) to estimate fuel consumption between waypoints. It also should be realized that the aircraft aerodynamic efficiency is continuously changing as weapons are being dropped fact that may be another important contributor for this small discrepancy.

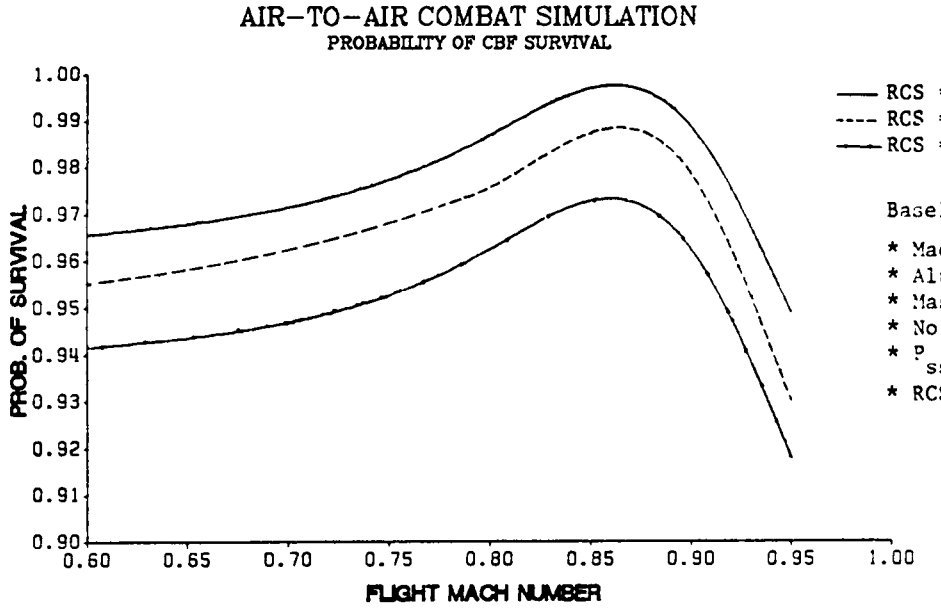
6.2.2 Sensitivity Analysis

Sensitivity analysis is performed around five key parameters in order to assess the results of the model as well as to test its usefulness as a conceptual design tool in estimating sortie survivability/lethality of a given preliminary aircraft configuration. These parameters are aircraft radar cross section, electronic countermeasures, thrust-to-mass ratio, engagement geometry, and force-on-force variations.

6.2.3 Aircraft Signatures

The importance of the aircraft signatures in the surface attack mission take prominent importance due to the static nature of the ground defenses. In fact, the entire success of a ground defense system depends upon the capability to timely detect attacking aircraft in order to effectively launch surface-to-air weapons. Recent conflicts (Viet Nam, Yom Kippur, Falklands, and Afghanistan) have demonstrated that ground forces are the predominant factor contributing to aircraft attrition and thus present goals towards a fully undetectable aircraft (stealth) seem to be justified. This simple sensitivity study is considers only variations in aircraft radar cross section (RCS). This parameter is chosen due to the important role played by radar detection in the outcome of a ground attack engagement. Values of aircraft radar cross section area were varied from 0.5 square meters (typical RCS for a small unmanned drone) up to 50 square meters which would be typical of a medium size bomber. The results of this study are shown in Figs. 6.16 and 6.17.

Fig. 6.15 depicts the probability of aircraft survival (top plot) for various RCS and flight mach numbers. The dotted line corresponds to the baseline design having a radar cross section area of 5 square meters, typical of modern small aircraft such as the cancelled Northorp F-20. Form this figure it is observed that significant variations in the probability of aircraft survival are attainable for this range of RCS values. The behavior of the three curves is about the same across the range of speeds since RCS was the *only* variable modified in the simulation. Although this might seem rather arbitrary it is possible to achieve large variations in RCS from nearly similar designs through careful airframe-powerplant integration and use of exotic materials. An important finding from the trends shown in Fig. 6.16 is that speed indeed plays an important role as one might suspect in the outcome of the engagement. Taking for example the baseline design it is observed that the probability of aircraft survival increases from 0.956 at mach 0.6 to about 0.987 at mach 0.87. This seemingly austere improvement would translate in more than 40 percent difference in the fraction of the force lost



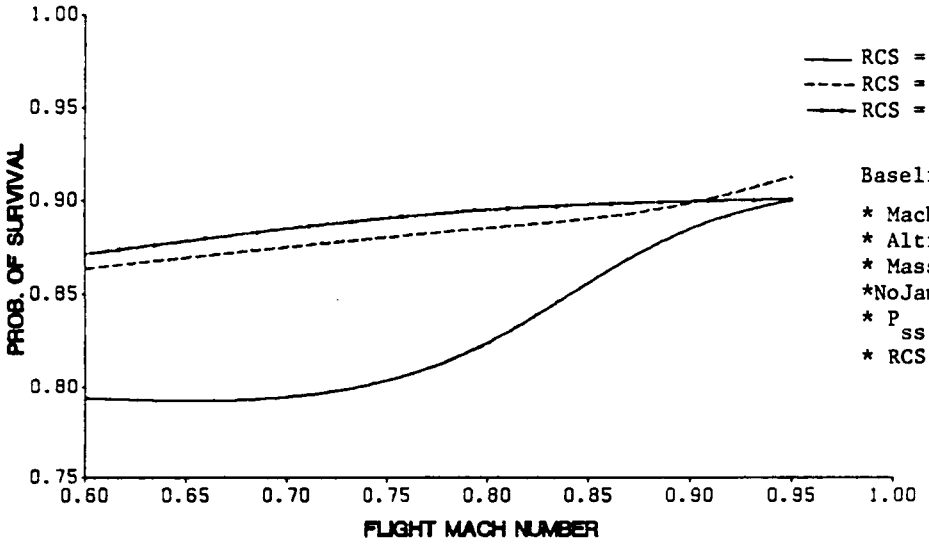


Figure 6.16 Survivability/Lethality for Various Aircraft Radar Signatures.

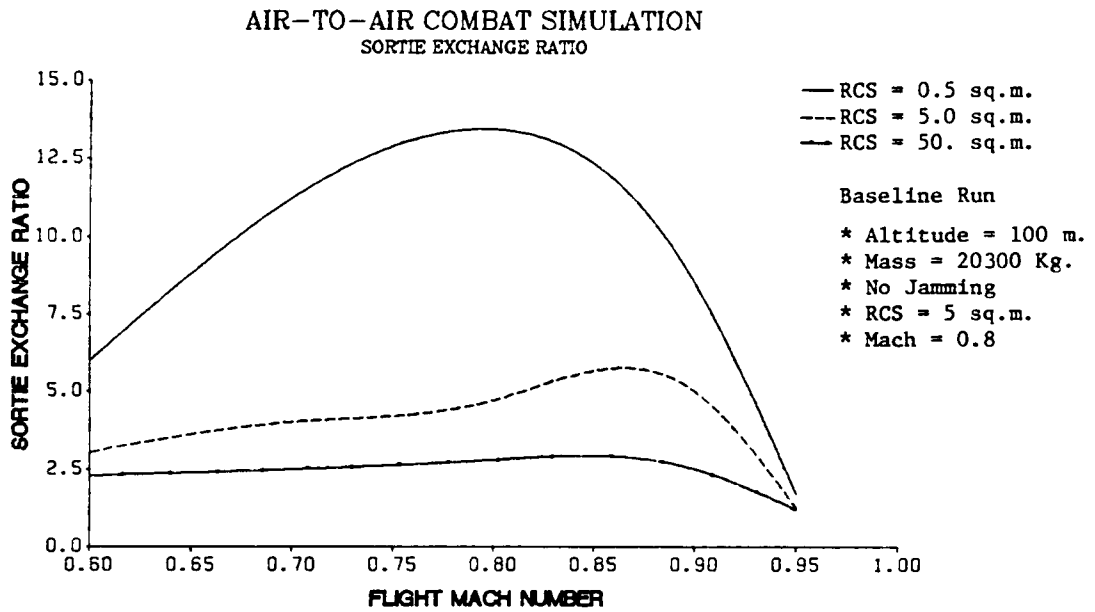


Figure 6.17 Exchange Ratio for Various Aircraft Radar Signatures.

after 30 sorties which would certainly please any pilot and field commander (i.e. campaign survivability will vary from 0.675 for the low RCS vehicle to 0.259 for the baseline design). A sharp drop in the survivability after mach 0.9 is also observed and this can be attributed to the aircraft reaching the drag divergence mach number (M_{DD}) which represents a large degradation in aircraft maneuverability due to a disproportionated increase in the drag coefficient C_{DO} as shown Fig. 5.45. It should be pointed out that Fig. 5.45 is representative of a current technology fighter such as the McDonnell Douglas F/A-18, however, large drag reductions in this speed range are expected to be incorporated in the next generation of fighter aircraft according to most observers [Sweetman, 1984; Parker, 1986].

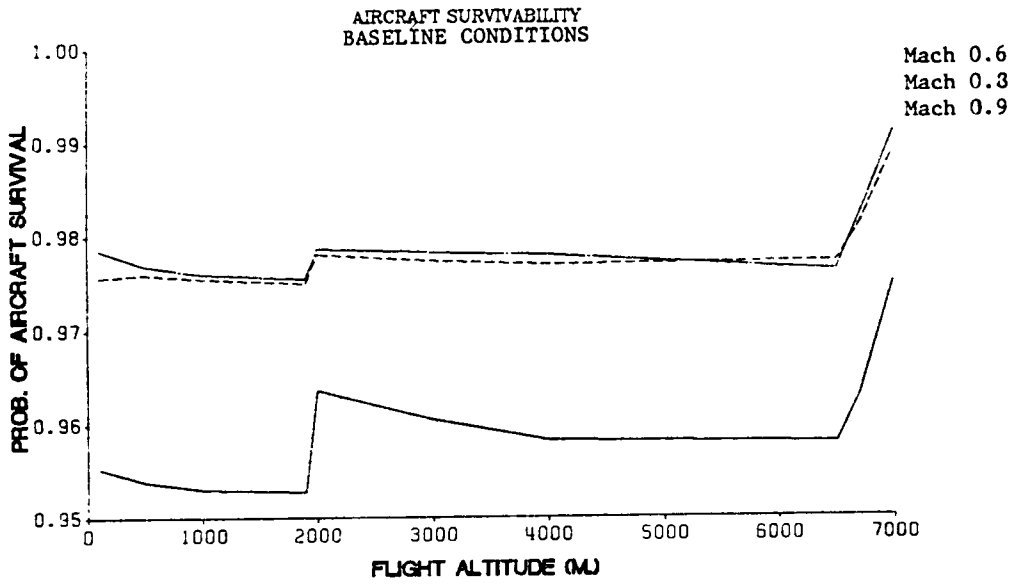
The second part of Fig. 6.16 depicts the CBF aircraft lethality, also labeled as the probability of DWS survival, for three different RCS as before. This plot shows clearly how effective stealth technology gains can be in achieving a high kill rate (i.e. low values of the ordinate) for even low mach numbers where the effectiveness of the weapons on both sides is higher. For speeds it is seen that performance constraints seem to dominate the outcome and the advantages of low RCS fade away above mach 0.95 where the aircraft maneuverability is highly reduced. These results of these two plots constitute average values for both, CBF aircraft and ground sites.

To finalize this discussion further insight can be obtained from Fig. 6.17 where the sortie exchange ratio (ERATIO) is plotted for the same three RCS variations and for various speeds. In this figure the effectiveness of the low RCS aircraft is observed to yield exchange ratios almost three times higher (e.g. 13 sites destroyed for each aircraft kill) than those achieved with current technology represented by the baseline aircraft configuration. From this plot it is also seen that the "optimum" attacking speeds vary between configurations with mach 0.8 being the best for the low vehicle with lowest RCS while mach 0.86 for moderate to high radar signatures.

6.2.4 Aircraft Flight Altitude

A second example to use this model is to explore the possible gains in aircraft survivability due to aircraft altitude variations. Altitude as one can perceive intuitively plays a major role in the outcome of an attack mission. Low level flying aircraft are less susceptible, however, it is at low altitudes where the majority of the weapons operate. This last point added to the fact that aircraft are restricted to fly above a certain altitude minimum due to terrain avoidance, and possibly handling quality considerations, constitutes a formidable problem for strategists and mission planners. Recent studies by Green [1986] and Davis and Green [1986] suggest the so called "high road" approach to attack missions where aircraft should fly as high as possible in order to confront a reduced number of weapons. The disadvantage of this approach is the obvious limitation of modern air-to-surface weapons to achieve even moderate lethalities from high altitude launches. A tradeoff is necessary in order to maximize exchange ratio. The idea of this study then is to gain understanding on how altitude affects survivability and lethality.

Figure 6.18 represents a composite plot where the survivability of the the CBF aircraft is investigated for various altitudes and three sortie speeds. Also in this plot, the lethality of the CBF aircraft (i.e. the survivability of the defense weapons sites) is shown in terms of the flight altitude. These results were obtained under the baseline assumption of four attacking aircraft, no jamming environment, and under the same takeoff gross mass (see Fig. 6.18). The altitudes selected for this study ranged from 100 to 7000 meters. It is important to mention that the defense weapons had maximum ceiling range thresholds of 2000, 6500, and 9000 meters for the AAA artillery, IR-guided missile, and RF-guided missile, respectively. Three representative mach numbers ranging from 0.6 up to 0.9 were used for this analysis and as one can see from the top plot that altitude has a stronger influence at low speeds (e.g. mach 0.6). Notice also that three "breaks" appear in the curves coinciding with the the maximum defense weapon envelopes. The important point is the fact that the probability of survival



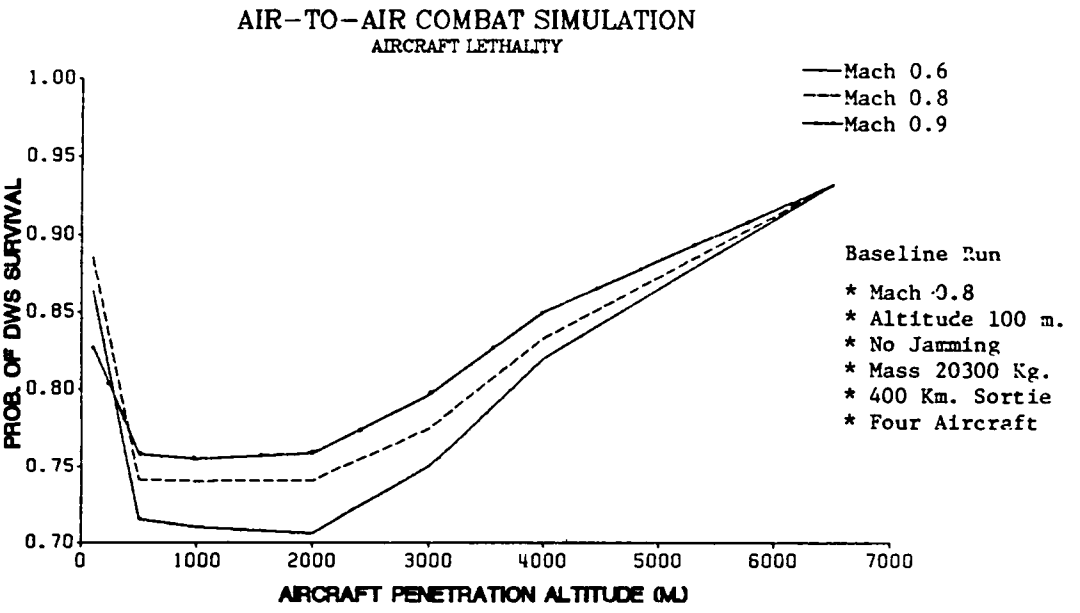


Figure 6.18 Survivability/Lethality for Various Flight Altitudes.

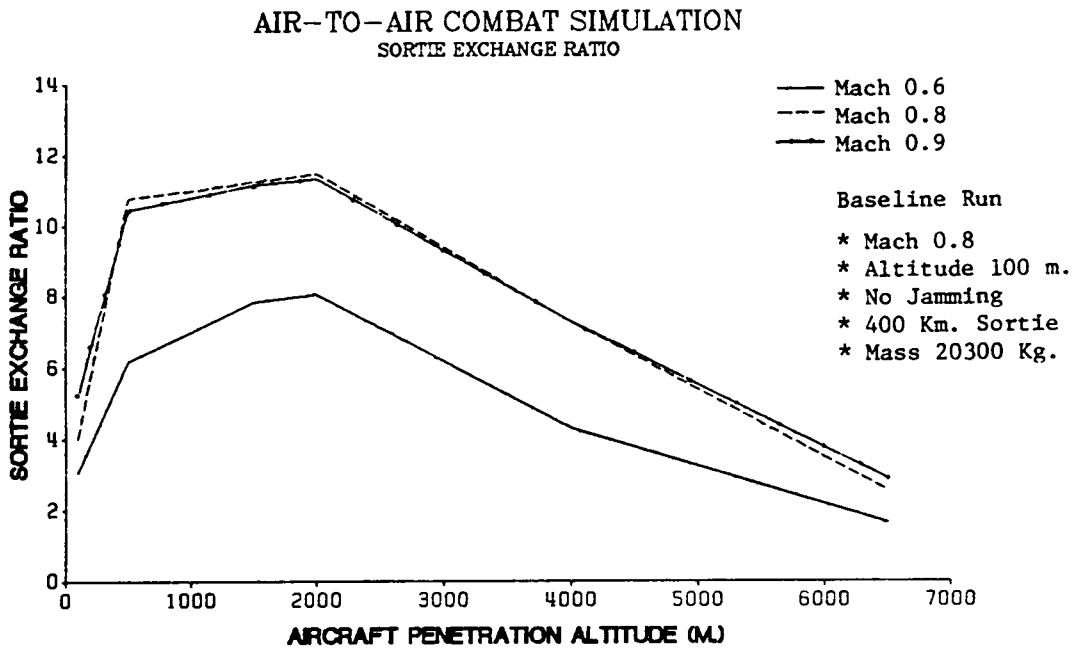


Figure 6.19 Exchange Ratio for Various Aircraft Flight Altitudes.

function is highly conditioned to the physical characteristics of the defense weapon envelopes. Note that in this case due to the limitation imposed on the missiles operational ceiling the probability of aircraft survival at high altitude is dramatically increased. In fact, above 9.0 Km. the probability of aircraft survival becomes unity. The second portion of Fig. 6.18 shows how lethality of the aircraft is described by what we might term *lethality bucket* . For very low altitudes ($< 500m.$) the lethality of the aircraft is improved with an increase in penetration altitude. This is expected since the acquisition and tracking capabilities of the aircraft improve with increases in altitude in this particular range. For the altitude range between 1000 and 2000 meters a near flat lethality region is identified. Finally, for higher altitudes the lethality of the CBF aircraft is decreased until the point where no ground target would be kill due to the inability of the weapons to accurately designate and discriminate the target. It should added that aircraft maneuverability is considerably degraded at high altitude thus reducing the potential high altitude sanctuary against new and powerful surface-to-air weapons. This poses a serious problem to aircraft designers due to the high levels of performance that can be attained within current missile technology. For example, future surface-to-air missiles will be capable to intercept targets as high as 25 Km. in altitude which is above the maximum combat ceiling of most western fighters. Nevertheless, advances in aircraft hybrid propulsion could well counter the potential operating ceiling imbalance by boosting the aircraft combat ceiling accordingly.

6.2.5 Electronic Countermeasures.

Electronic countermeasures modeled in Section 5.3.7.2 of this dissertation are employed to explore favorable tactics to be employed during simulated attacks. The two basic jamming doctrines considered in this sensitivity study are stand-off and self-screening jamming. The former one assumes that an electronic control post aircraft is deployed simultaneously with the attack about 150 Km. from the carrier force in the vicinity of the starting point of the

simulation (250 Km. from the main target area). Self-screen jamming implies that the aircraft carry their own jammers either internally or externally (in the orm of jamming pods). A second strategy for self-screen jamming would be to escort the attacking force with an electronic countermeasures aircraft such as the Grumman E-6B "prowler". In any case all this tactics can be readily modeled in ASALT II.

Fig. 6.20 depict the survivability and lethality functions found for the baseline model in three different jamming environments. It is seen immediately that the use of self-screen jammers (on-board in this particular case) yields the highest values of probability of aircraft survival (P_{ss}) across the range of speeds tested (from mach 0.6 to 0.95). It is also noted that stand-off jamming also shows very robust values for P_{ss} in the low transonic speed regime (e.g. 0.8 to 0.9 mach). The physical characteristics of the jammers employed are similar to those used for the ASALT I model and described in Section 5.2.5 of this dissertation. Fig. 6.21 summarizes the survivability and lethality functions in terms of the sortie exchange ratio (ERATIO). The striking characteristic of this plot is the high values of exchange ratio obtained in the presence of a jamming environment, either stand-off or self-screening jamming. These plots were generated under otherwise baseline conditions of an attacking force of four, 5 square meter cross section area. similar aircraft, and 400 Km. sortie as shown in both figures.

6.2.6 Thrust-to-Mass Variations

This section incorporates several changes to the baseline model at the same time in order to estimate sortie measures of effectiveness for various aircraft design concepts. The sizing sheme used for this section is exactly the same that we used in Section 6.2.1 where we performed thrust-to-mass sensitivity analyses for the air-superiority fighter aircraft and mission. This study relies on the same arguments used in Section 6.2.1 in order to explore the effects of modifying a baseline design by installing various powerplants in order to meet certain classical performance constraints such as a desired transonic acceleration,

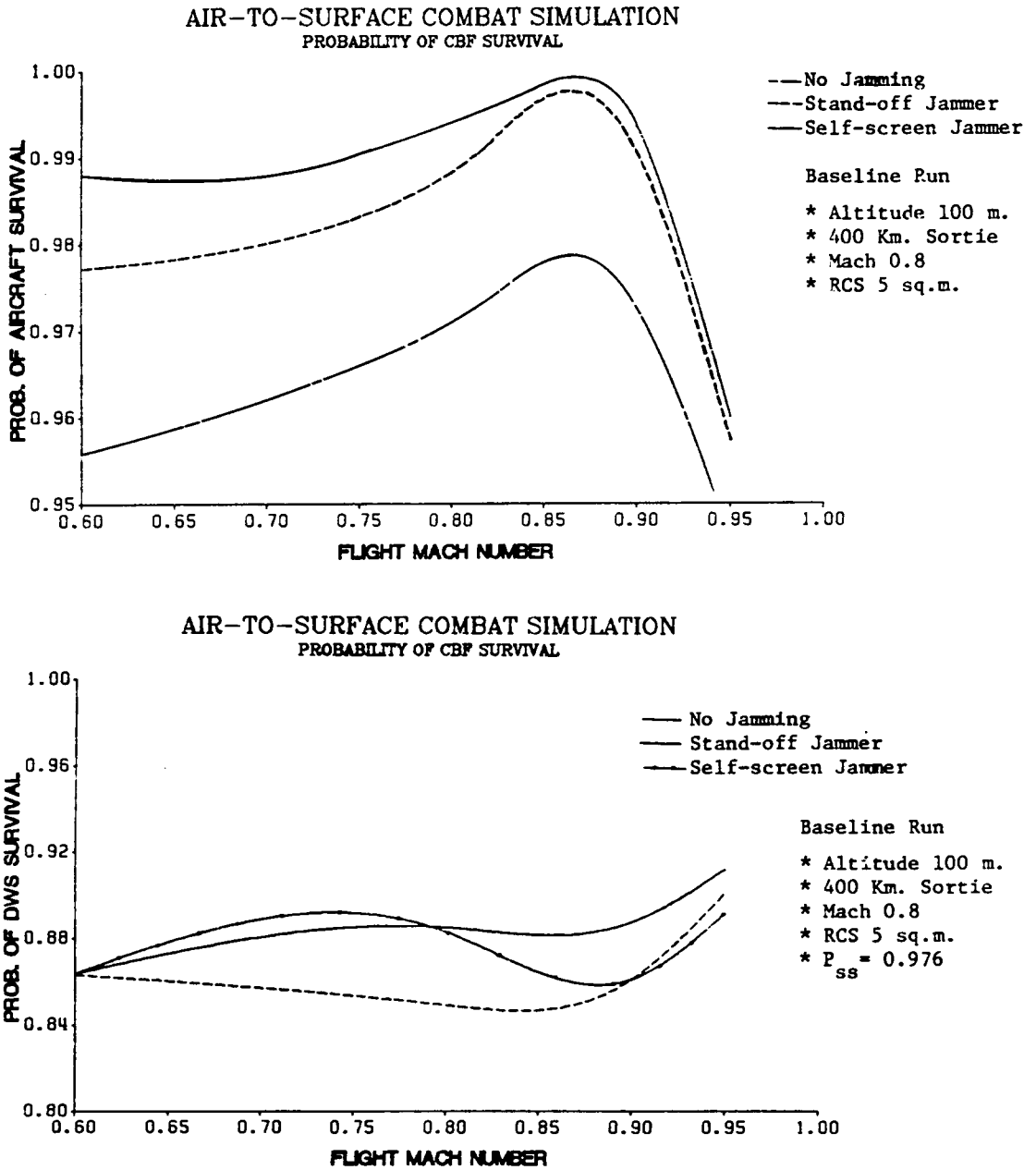


Figure 6.20 Survivability/Lethality for Various Jamming Policies.

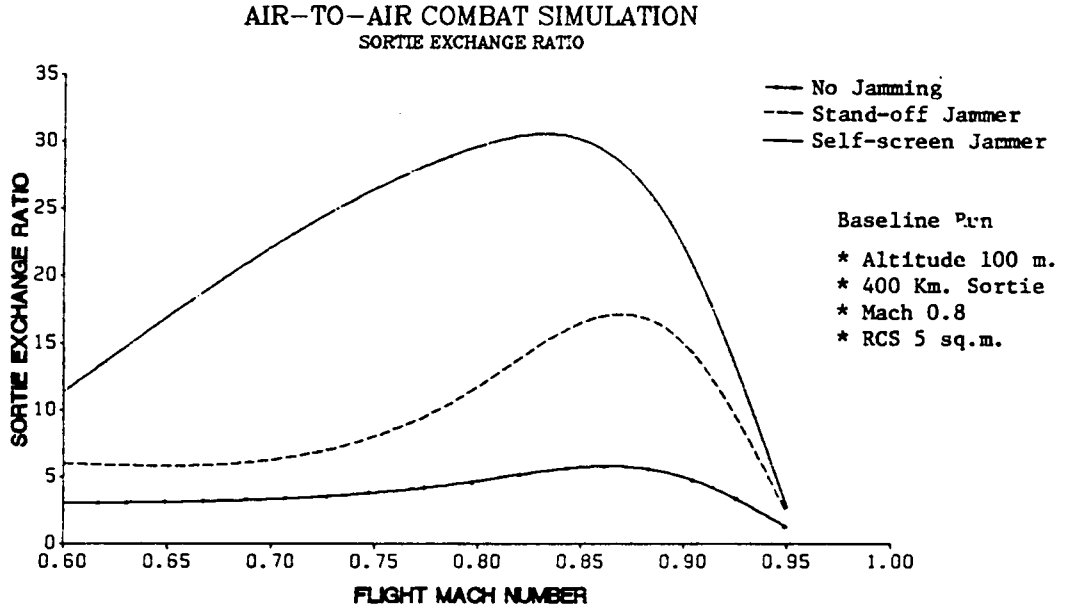


Figure 6.21 Exchange Ratio for Various Jamming Policies.

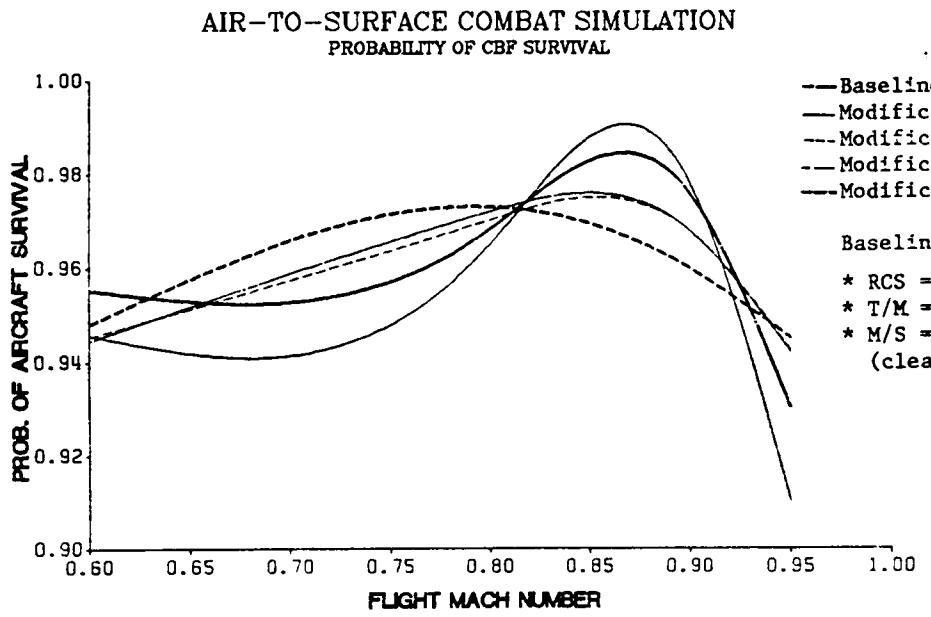
maneuvering capabilities at altitude, landing and takeoff distances, range, payload, etc. The basic goal is to compare five different configurations (including the baseline) and determine their sortie effectiveness at under various scenarios. This analysis obviously would have to be further extended into the campaign level (Level 4 shown in Table 1.3) in order to incorporate other important factors affecting survivability at the campaign level such as as availability, aircraft sortie rate, deployment rate, etc. This extension, however, has been the subject of other study by Malakhoff [1988] and thus will not be pursued here.

Using as reference Table 6.2 and modifying the aircraft masses to accommodate the heavier payload requirements of the surface attack mission it is possible to generate Table 6.6. Design variables affected in these modifications are the engine thrust, aircraft empty mass, aircraft radar cross section (RCS), and drag characteristics (C_{DO}) as shown in Table 6.6.

Table 6.6 Summary of ASALT II Modifications to Baseline Design.

	ALTERNATIVE A/C				
DESCRIPTION	BASE	MOD. 1	MOD. 2	MOD. 3	MOD. 4
1) Engine Thrust SSL (kg)	8131	5260	6840	9473	10525
2) Mission Mass (kg)	20300	18602	19473	21143	21869
3) Thrust/Weight	0.80	0.57	0.70	0.90	0.96
4) ΔC_{D0} (counts)	0.0	-30.60	-14.25	12.90	23.40
5) Engine Capture Area (sq. m)	0.363	0.472	0.567	0.653	0.723
6) Engine Diameter (m)	0.95	0.76	0.87	1.02	1.07
7) Radar Cross Section (sq. m)	5.00	3.23	4.08	5.98	6.88
8) Normalized RCS	1.00	0.646	0.816	1.196	1.376

Thrust-to-mass ratio (T/M) values ranging from 0.55 to near 1.0 were tested in ASALT II in order to estimate sortie measures of effectiveness for different designs. Fig. 6.22 depicts the results obtained for the probability of survival of the CBF aircraft and the lethality of each configuration and various mach numbers. It is observed from the top figure that modification # 2 is the best performer overall under the base scenario conditions achieving an exchange ration of nearly 7 to 1 at about mach 0.8. Similarly, modification # 4 shows good capability for the range 0.6 to 0.7 mach. This result might come to a surprise since one can argue that better performance aircraft will always dominate in the low transonic regime. However,



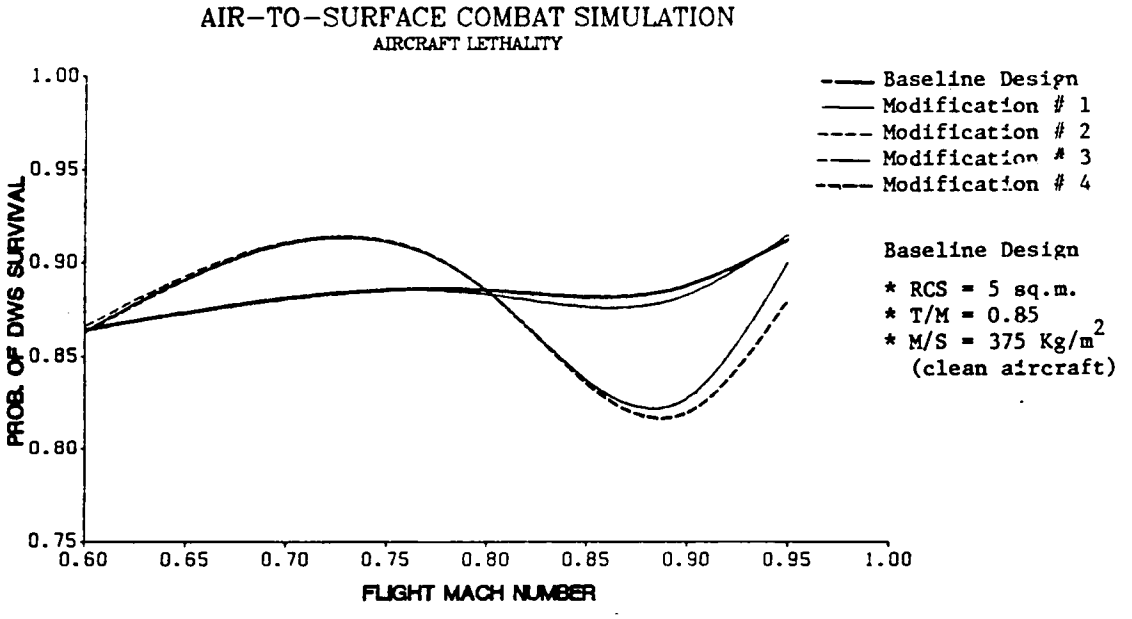


Figure 6.22 Survivability/Lethality for Aircraft Configurations.

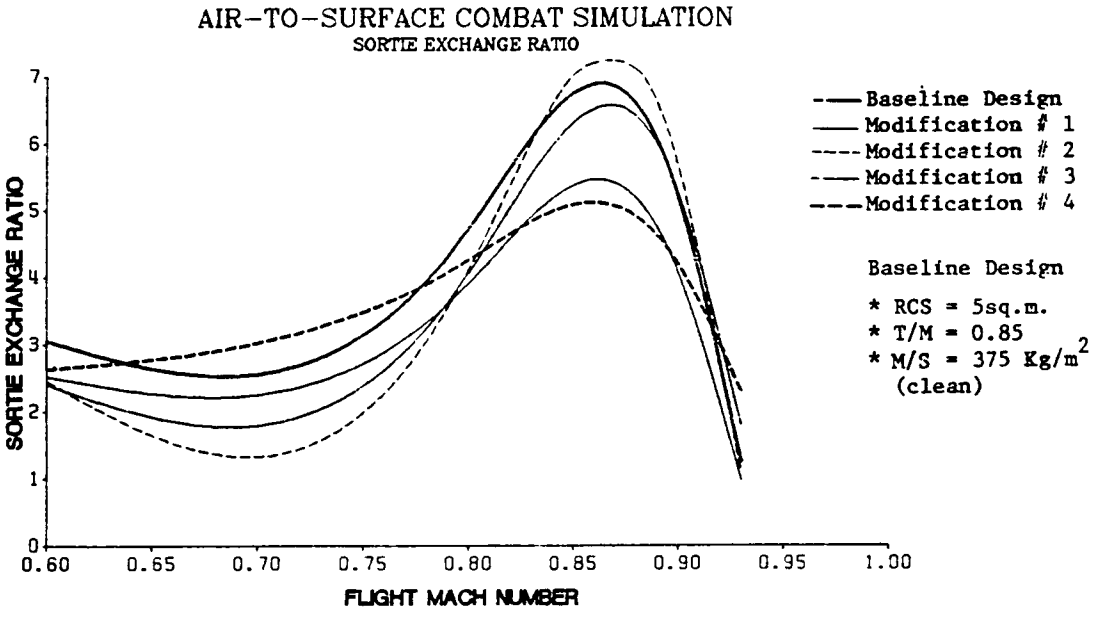
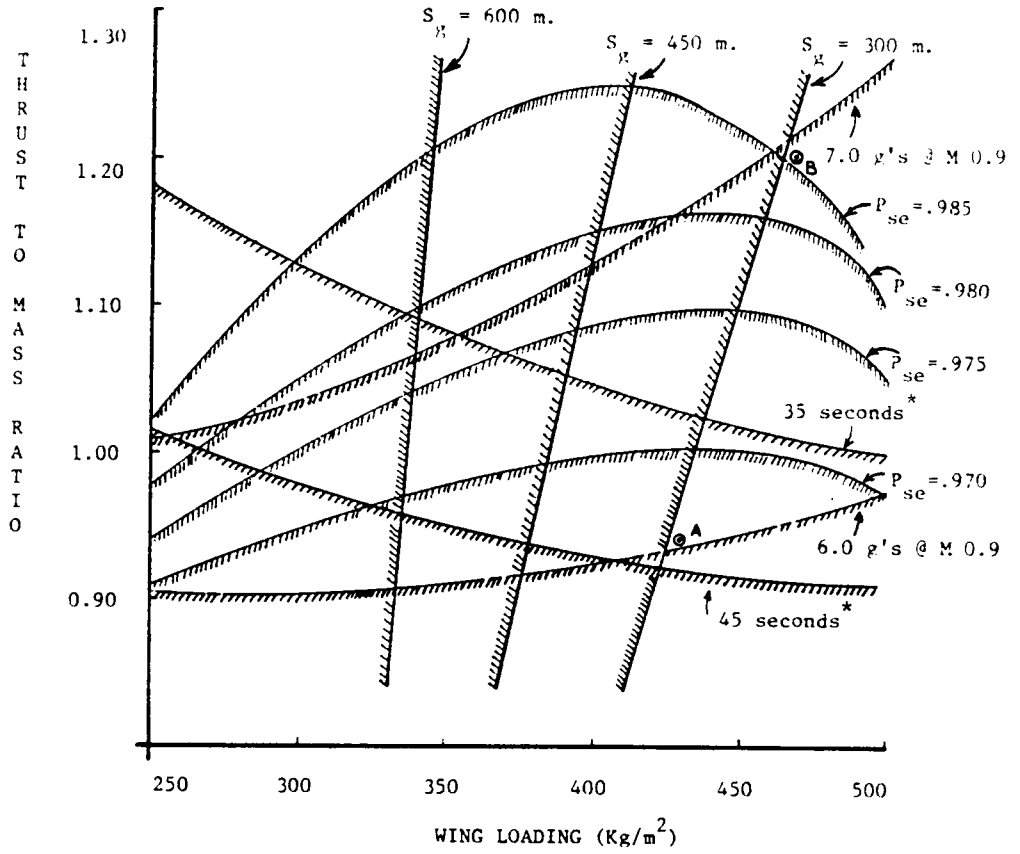


Figure 6.23 Exchange Ratio for Various Aircraft Configurations.



* Denotes Transonic Acceleration from M 0.8 to M 1.5

Figure 6.24 Typical Carpet Plot for Preliminary Design Assessment.

because the engine modification does involve other important variables such as RCS and C_{DO} it is wrong to completely rely on intuition. In this particular case the sensitivity analisys shows clearly that the best aircraft performance is heavily penalized as for RCS and C_{DO} thus reducing its effectiveness. This in part satisfies one of the fundamental objectives of this research, that is, to identify the complex interactions between aircraft preliminary design parameters in order to select a "best" configuration. Fig. 6.23 shows the sortie exchange ratio for the same five different configurations and as one can observe modifications there are speed regimes of dominance for some of the modifications. For example, the baseline configuration dominates between mach value 0.78 and 0.83, while modification 4 dominates for speeds ranging from 0.65 to 0.77 and so on. This can have important repercussions not only in the design but in the operational phases of flight as well.

Another example of the potential use of the models and the methodology proposed in this dissertation can be seen in Fig. 6.24 where a typical preliminary design carpet plot involving traditional performance parameters, such as takeoff ground run, transonic acceleration, and aircraft maneuvering requirements, are superimposed to a family of aircraft sortie survivability curves. This curve uses aircraft wing loading (in $Kg./m^2$) as the independent variable and aircraft thrust-to-mass ratio as the dependent variable. The idea pursued in this type of analysis is to select feasible values of both variables in order to comply with a determined level of performance. Notice that, although this figure only emphasizes in three performance parameters, it is possible to extend the analysis to other important parameters that could also "drive" the design of the aircraft. Cost, reliability, maintainability, and other factors can be added as extra constraints to this plot in order to have a more complete perspective of the feasible design region. In practice, the design could have hundredths of constraints requiring highly specialized non-linear programming techniques for its solution. The importance from this research point of view is the fact that the methodology and the models developed seem to offer an alternative to estimate survivability-related constraints.

7.0 Discussion and Conclusions

The main goal of this research has been to develop computer simulation models that quantify survivability/lethality tradeoffs to be used in the conceptual design of modern fighter aircraft operating in a total weapon system environment. These models address the complex mechanics of modern war scenarios using the *Systems Dynamics* methodology which permits the synthesis of many engineering-related disciplines into manageable dynamic combat simulation models that quantify the outcome of engagements between two forces at the sortie level. Parameters of interest in this research are the estimation of the probability of aircraft sortie survival ($P_{s/s}$) and the aircraft lethality ($P_{k/s}$).

Aircraft conceptual design and operational factors are considered as inputs to the models to assess the impact of aircraft modifications in $P_{s/s}$ and $P_{k/s}$. It is felt that the results at the sortie level constitute the first step in identifying areas of technological risk that could enhance the aircraft survivability in a real combat scenario. The models then are aimed to to expand our knowledge of the complex interactions taking place in modern warfare. These scenario specific models constitute the second step towards the complete implementation of a survivability analysis (the first one being vulnerability assessment) for a complex air vehicle. The outputs of these models constitute inputs to more macroscopic models developed as part of the research in aircraft survivability analysis performed at Virginia Tech for the Joint

Technical Committee for Aircraft Survivability in recent years. Thus it should be understood that their scope, although limited to a level of the survivability discipline is an essential part of the systems approach taken in this research.

The scenario specific models developed focus their attention in the susceptibility aspect of aircraft survivability. Therefore, detail consideration of threat, aircraft, and environmental factors comprise the bulk of the models. Both models consider the combat interactions between the enemy forces as part of a second order positive loop structure. This structure is mathematically modeled as an *n* th order system of differential equations which are solved numerically and parallel to the state equations describing each combat element. Two computer languages, DYNAMO III and FORTRAN 77 were used to accomplish the modeling effort and although there are many differences between them both seemed equally suited to model the combat scenarios developed in this dissertation.

As all models have limitations, it is considered that these models are by no means the end point of the objectives initially delimited for this research. They should be viewed as the skeleton to more sophisticated models in which further details can be added if deemed necessary. The models were developed with the multimission role capability in mind and can be easily adapted to represent a great variety of scenarios such as close air support, air superiority, fleet defense, etc. This makes these models suitable to analyze proposed or modified aircraft that can perform a variety of roles thus ultimately determining its overall mission effectivess.

In the past, aircraft conflicting roles (from the design point of view) have lead to highly specialized aircraft with high life-cycle cost due to low aircraft procurement. High specialization also could mean reduced useful service life due to the rapidly changing nature of threats (i.e. evolving threats progress technologically faster than the possible modifications implemented in current aircraft rendering them obsolete in few years). The designer is then faced from the beginning with the difficult task of compromising the many parameters that dictate a particular design to achieve optimal results in various combat scenarios. Traditionally, performance parameters have been the center of aircraft design requirements

and figures of merit used in the selection of baseline designs. Present studies by Herbst [1983] and Parker [1986] suggest that in modern air warfare performance gains are becoming of less importance as air-to-surface and air-to-air engagements drive towards the beyond visual range character. Thus higher lethality will be associated with more capable fire control systems and higher ordnance carrying capacity.

Due to the complexity of these events it is necessary to incorporate realistic design changes from the conception of every new design when the cost os incorporation is minimum. Simulation models are thus becoming more and more important [Kitowski, 1986; Baldwin, 1986; Fettelshob, 1987] in conceptualizing future aircraft. It is the intend of the models developed here to serve as a preliminary tool in the determination of potential aircraft survivability and lethality measures of merit that hopefully will contribute to more robust and survivable aircraft designs. The models can be easily modified to suit a large variety of scenarios and can also be quickly upgraded to improve threat and aircraft representation. This is particularly useful when identifying survivability operational requirements (see Figure 1.1) and when reassessment of the threat is done continuously.

As far as the results of the model are concerned these should be considered with caution when compared with other combat simulation models. Most combat models cannot be replicated in real life, nevertheless their results are important because they allow us to gain understanding of a complex process whose output cannot be predicted unless it is simulated. The results of both models show trends compatible with the results of Parker [1986] and Hague [1981]. However, it should be emphasized that most of the results derived from combat models are difficult to transfer to other scenarios and their comparison should be based more on qualitative analysis.

In Chapter 5 we described in detail the structures comprising the ASALT models, now some of the important highlights are given below. Aircraft Sortie Survivability increased with sortie speed as far as no severe drag divergence effects were encountered. $P_{s/s}$ was Some of ASALT II important results can be summarized as follows. Aircraft Sortie Survivability increased with sortie speed as far as no severe drag divergence effects were encountered.

$P_{s/s}$ was found to be a maximum for the baseline aircraft investigated at a sortie speed of mach 0.85 (at sea level) which incidentally is very close to the drag divergence mach number (M_{DD}) of .86. This fact strongly suggests a strong dependence of $P_{s/s}$ on performance measures such as specific excess power (which dictates aircraft acceleration and turning performance capabilities). It was also shown that an increase in sortie speed beyond M_{DD} is detrimental for aircraft survivability due to the low aircraft energy available to be traded by maneuverability in case of a threat propagator launch. Another conclusion is that aircraft lethality represented by the probability of kill of defense weapon sites peaks at about mach 0.67 for the baseline aircraft investigated. The reduction in $P_{k/s}$ at higher speeds is attributed to a reduction in the target acquisition-identification and weapon delivery accuracy present at higher speeds, while that for speeds below mach 0.75 is attributed to the large attritions on the aircraft inflicted by a larger number of surviving defense weapon sites.

In a different sensibility analysis it was shown that the effect of decreasing aircraft signatures increases significantly $P_{s/s}$. This last statement was particularly true at high sortie speeds. The effect of RCS in the attack aircraft lethality was almost insignificant. Sortie altitude and the probability of aircraft survival were characterized by several curves which represented the lethality of the aircraft system. Discontinuities in these curves were present due to the sudden end of the weapon defense kinematic envelopes.

These results show that both ASALT models are in fact able to predict $P_{s/s}$ and $P_{k/s}$ to establish a tradeoff between them. The results cannot be interpreted as ultimate values since every combat scenario coupled with specific threat and aircraft characteristics will in fact yield different values of $P_{s/s}$ and $P_{k/s}$. It should always be kept in mind that this type of model is almost impossible to validate and that further fine tunning of the computer code has to be performed once more is known about the aircraft and/or the threat.

Future expansion to these two models could include the incorporation of interactive windows for selecting modification changes from the computer terminal. Also a graphics package could be developed in order to perceive clearly the stages by which the combat develops and a third extension could be implementation of man-in-the-loop simulation where

the user is invited to participate in the systems decisions as the simulation progressess. This last model extension could be implemented in two personal computers so that every opponent can develop independent tactics.

Appendix A. ASALT I Model Code (DYNAMO III)

```
NOTE
NOTE                AIR-TO-AIR COMBAT SIMULATION MODEL
NOTE
NOTE                    MODEL NOTES
NOTE
NOTE     I          - SUBSCRIPT TO IDENTIFY FRIENDLY AIRCRAFT
NOTE     J          - SUBSCRIPT TO IDENTIFY AGGRESSOR AIRCRAFT
NOTE     K          - SUBSCRIPT TO IDENTIFY FRIENDLY AIRCRAFT WEAPONS
NOTE     L          - SUBSCRIPT IDENTIFYING AGGRESSOR AIRCRAFT WEAPONS
NOTE
NOTE                            WEAPONS SUBSCRIPTS
NOTE
NOTE                        1 - LONG RANGE AIR-TO-AIR MISSILE
NOTE                        2 - MEDIUM RANGE AIR-TO-AIR MISSILE
NOTE                        3 - SHORT RANGE AIR-TO-AIR MISSILE
NOTE                        4 - GUN SHOTS

MACRO    ARCSIN(X1,Y1,X2,Y2,HY)
A        ARCSIN=CLIP($SIN2.K,$SIN1.K,Y1.K,Y2.K)                                  5.1
A          $SIN2.K=CLIP($SIN3.K,$SINIV.K,X1.K,X2.K)                              5.2
A            $SIN3.K=CLIP($SIN1I.K,$SIN2I.k,.925,MAX(Y1.K-Y2.K,-Y1.K+Y2.K)
X              /(HY.K+1E-6))+180                                                 5.3
A            $SINIV.K=CLIP($SIN22.K,$SIN12.k,.925,MAX(Y1.K-Y2.K,-Y1.K+Y2.K)
X              /(HY.K+1E-6))+180                                                 5.4
A          $SIN1.K=CLIP($SINII.K,$SINI.K,X1.K,X2.K)                              5.5
A            $SINII.K=CLIP($SIN12.K,$SIN22.k,.925,MAX(Y2.K-Y1.K,-Y2.K+Y1.K)
X              /(HY.K+1E-6))                                                     5.6
A              $SIN12.K=TABHL(TS1II,MAX(Y2.K-Y1.K,-Y2.K+Y1.K)/(HY.K+1E-6)
X                ,.925,1.0,.00375)                                             5.7
A              $SIN22.K=TABHL(TS2II,MAX(Y2.K-Y1.K,-Y2.K+Y1.K)/(HY.K+1E-6)
X                ,0.0,.925,.025)                                               5.8
A            $SINI.K=CLIP($SIN1I.K,$SIN2I.k,.925,MAX(Y2.K-Y1.K,-Y2.K+Y1.K)
X              /(HY.K+1E-6))                                                   5.9
A              $SIN1I.K=TABHL(TSIN1I,MAX(Y2.K-Y1.K,-Y2.K+Y1.K)/(HY.K+1E-6)
X                ,0.0,.925,.025)                                             5.10
A              $SIN2I.K=TABHL(TSIN2I,MAX(Y2.K-Y1.K,-Y2.K+Y1.K)/(HY.K+1E-6)
X                ,.925,1.00,.00375)                                          5.11
MEND

T        TSIN1I=0/1.43/2.87/4.30/5.74/7.18/8.63/10.08/11.54/13.00/14.48
X         /15.96/17.46/18.97/20.49/22.02/23.58/25.15/26.74/28.36/30.31
X         /33.37/35.10/36.87/38.68/40.54/42.45/44.42/46.47/48.59/50.81
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X       /53.13/55.59/58.21/61.05/64.15/67.7                                    5.12
T       TSIN2I=67.67/68.24/68.82/69.43/70.05/70.69/71.35/72.04/72.75
X       /73.5/74.26/75.07/75.93/76.84/77.82/78.88/80.06/81.40/82.98
X       /85.04/90                                                              5.13
T       TS1II=112.3/111.76/111.2/110.6/110/109.3/108.7/108/107.3/106.5
X       /105.7/104.9/104.1/103.2/102.2/101.1/100/98.6/97/95/90                 5.14
T       TS2II=180/178.57/177.1/175.7/174.3/172.8/171.4/169.9/168.5/167
X       /164/162.5/161/159.5/158/156.4/153/154/152/150/148.3/146.6/145
X       /143.1/141/139.5/137.6/135.6/133.5/131/129/126.9/124/121.8/119
X       /115.8/112.3                                                           5.15

MACRO SSOUND(ALT)
A       SSOUND.K=CLIP(295.2,TABHL(AT,ALT.K,0,12200,1525),ALT.K,12200)          5.16
MEND
T       AT=340.5/334.5/328.4/322.34/315.85/309.8/303.0/296.6/295.2             5.17

MACRO TEM(ALT)
A       TEM.K=CLIP(216.7,T0-.0065*ALT.K,ALT.K,11000)                           5.18
MEND

MACRO SIGM(DELTA,THETA)
A       SIGM.K=DELTA.K/THETA.K                                                 5.19
MEND

MACRO PRATIO(ALT)
A       PRATIO.K=CLIP(.2234*EXP(-(ALT.K-11000)/6340.64),
X       (TEM(ALT.K)/T0)**5.2561,ALT.K,11000)                                   5.20
MEND

MACRO DIREC(HEAD,VLOS,YCOMP1,YCOMP2)
A       DIREC.K=CLIP($DIR12.K,$DIR34.K,YCOMP1.K,YCOMP2.K)                      5.21
A       $DIR34.K=CLIP(HEAD.K-VLOS.K,(HEAD.K-VLOS.K)-360,180,HEAD.K-VLOS.K)     5.22
A       $DIR12.K=CLIP(360+(HEAD.K-VLOS.K),HEAD.K-VLOS.K,-180,HEAD.K-VLOS.K)    5.23
MEND

MACRO YAW(ANGLE)
A       $NUM.K=ANGLE.K/360                                                     5.24
A       YAW.K=CLIP($YAWPO.K,$YAWNE.K,$NUM.K,0)                                 5.25.0
A       $YAWPO.K=CLIP($N1P.K,$N036.K,$NUM.K,1)                                 5.25.1
A       $N036.K=ANGLE.K                                                        5.25.2
A       $N1P.K=CLIP($N2P.K,$N3672.K,$NUM.K,2)                                  5.25.3
A       $N3672.K=ANGLE.K-360                                                   5.25.4
A       $N2P.K=CLIP($N3P.K,$N7210.K,$NUM.K,3)                                  5.25.5
A       $N7210.K=ANGLE.K-720                                                   5.25.6
A       $N3P.K=CLIP($N4P.K,$N1014.K,$NUM.K,4)                                  5.25.6
A       $N1014.K=ANGLE.K-1080                                                  5.25.7
A       $N4P.K=CLIP($N5P.K,$N1418.K,$NUM.K,5)                                  5.25.8
A       $N1418.K=ANGLE.K-1440                                                  5.25.9
A       $N5P.K=CLIP($N6P.K,$N1821.K,$NUM.K,6)                                  5.25.10
A       $N1821.K=ANGLE.K-1800                                                  5.25.11
A       $N6P.K=ANGLE.K-2160
NOTE
A       $YAWNE.K=CLIP($N1N.K,$NN036.K,-1,$NUM.K)                               5.26.0
A       $NN036.K=360+ANGLE.K                                                   5.26.1
A       $N1N.K=CLIP($N2N.K,$NN367.K,-2,$NUM.K)                                 5.26.2
A       $NN367.K=720+ANGLE.K                                                   5.26.3
A       $N2N.K=CLIP($N3N.K,$NN721.K,-3,$NUM.K)                                 5.26.4
A       $NN721.K=1080+ANGLE.K                                                  5.26.5
A       $N3N.K=CLIP($N4N.K,$NN101.K,-4,$NUM.K)                                 5.26.6
A       $NN101.K=1440+ANGLE.K                                                  5.26.7
A       $N4N.K=CLIP($N5N.K,$NN141.K,-5,$NUM.K)                                 5.26.8
A       $NN141.K=1800+ANGLE.K                                                  5.26.9
A       $N5N.K=CLIP($N6N.K,$NN181.K,-6,$NUM.K)                                 5.26.9
A       $NN181.K=2160+ANGLE.K                                                  5.26.10
A       $N6N.K=2520+ANGLE.K                                                    5.25.11
MEND

MACRO SPECTR(EGT,MUHIGH,MULOW)
A       SPECTR.K=$ENHIGH.K-$ENLOW.K                                            5.27
A       $ENHIGH.K=TABHL(ENERGY,$LTHIGH.K,1000,15000,1000)                      5.28
A       $ENLOW.K=TABHL(ENERGY,$LTLOW.K,1000,15000,1000)                        5.29
A       $LTLOW.K=MULOW*EGT.K                                                   5.30
```

```
A       $LTHIGH.K=MUHIGH*EGT.K                                          5.31
MEND

MACRO IRDET(SNOISE)
A       IRDET.K=TABHL(IRDT,SNOISE.K,2,7,.2)                             5.32
MEND
T       IRDT=0/.01/.02/.03/.04/.05/.08/.11/.21/.33/.45/.56/.65/.73
X         /.81/.87/.93/.96/.975/.983/.988/.993/.996/.998/.999/1         5.33

MACRO ALPH(ALT)
A       ALPH.K=TABHL(ALPTT,ALT.K,0/15000,3000)                          5.34
MEND
T       ALPTT=.04/.031/.0225/.0137/.005/.003                            5.35

MACRO AF(ANGLE
A       AF.K=TABHL(AFT,MAX(ATN.K,-ATN.K),0,180,20)                      5.36
MEND
T       AFT=.15/.17/.20/.25/.32/.39/.50/.62/.75/1.0                     5.37

MACRO LOS(ALTD,RLOS)
A       LOS.K=CLIP(1,0,ALTD.K,$ALOS.K)                                  5.38
A         $ALOS.K=TABLE(ALOST,RLOS.K/2,0,3E5,2E4)                       5.39
MEND
T       ALOST=0/9.63/38.5/86.55/153.90/240.45/346.3/471.31/615.95
X       /780/962/1164.1/1385.4/1626.1/1885.98/2164.6                    5.40

MACRO RCSAGM(ATN)
A       RCSAGM.K=TABHL(RCSAGT,MAX(ATN.K,-ATN.K),0,180,22.5)             5.41
MEND
MACRO RCSAAM(TAA)
A       RCSAAM.K=TABHL(RCSAAT,MAX(TAA.K,-TAA.K),0,180,22.5)             5.42
MEND
T       RCSAGT=1/.85/1.3/2.5/5.5/3.8/3.0/1.8/1.6                        5.43
T       RCSAAT=1/.88/1.5/3.3/5.7/3.9/2.3/1.8/1.5                        5.44

MACRO MRBSM(AA)
A       MRBSM.K=TABHL(MRBSMT,MAX(AA.K,-AA.K),0,180,22.5)                5.45
MEND

T       MRBSMT=1/.75/.55/.50/.45/.417/.40/.375/.375/.35                 5.46

MACRO MICF(R,RMAX,RNE,RMIN)
A       MICF.K=CLIP(0,$MICF1.K,R.K,RMAX.K)                              5.47
A       $MICF1.K=CLIP((RMAX.K-R.K)/(RMAX.K-RNE.K),$MICF2.K,R.K,RNE.K)   5.48
A       $MICF2.K=CLIP(1,0,R.K,RMIN.K)                                   5.49
MEND

MACRO BINARY(DIST,MLE)
A       BINARY.K=CLIP(0,1,DIST.K,MLE.K)                                 5.50
MEND

MACRO MABSLA(AA,THETA)
A       MABSLA.K=TABHL(DELAT,$DELAZ.K,0,60,10)                          5.51
A       $DELAZ.K=(THETA.K/2)-MAX(AA.K,-AA.K)                            5.52
T       DELAZ=1/.96/.93/.90/.85/.80/.75                                 5.53
MEND

MACRO RATINV(A)
A       RATINV.K=10*(LOGN(MAX(.001,A.K))/LOGN(10))                      5.54
MEND

MACRO DINV(A)
A       DINV.K=10**(A.K/10)                                             5.55
MEND

MACRO INTRP(E,F,H,I,J)
A       INTRP.K=E.K+((F.K-E.K)*(J.K-H.K)/(I.K-H.K)                      5.56
MEND

MACRO LOADF(Q,WEIGHT,K,THRUST,WAREA,CDO,NSTRUC)
A       LOADF.K=MIN($NTRUS.K,MIN(NSTRUC,$NCREW))                        5.57
A         $NTRUS.K=CLIP((WAREA*Q.K/(WEIGHT.K))*SQRT($THIRD.K),1
```

```
X           ,$FIRST.K-$SECON.K,0)                                          5.58
A             $THIRD.K=ABS($FIRST.K-SECON.K)                               5.59
A             $SECON.K=CDO.K/K                                             5.60
A             $FIRST.K=THRUST.K/(K*Q.K*WAREA)                              5.61
A           $NCREW.K=7.5                                                   5.62
MEND

MACRO YAWRTE(LOAD,SPEED)
A           YAWRTE.K=G*SQRT(LOAD.K**2-1)/SPEED.K                           5.64
MEND

MACRO TFLY(RLOS,MSPEED,ASPEED,ATNTAA)
A           TFLY.K=RLOS.K/(ASPEED.K*COS(ATNTAA.K/57.29)+MSPEED.K)          5.65
MEND

MACRO STAT(X,MEAN,VAR,STD)
A           STAT.K=X.K(DT)                                                 5.66
L           $CUMX.K=$CUMX.J+(DT)(X.J)                                      5.67
N           $CUMX=0                                                        5.68
A           MEAN.K=$CUMX.K/$TTIME.K                                        5.69
A           $TTIME.K=TIME.K+$ITIME+1E-15                                   5.70
N           ITIME=TIME                                                     5.71
L           $CUMX2.K=$CUMX2.J+(DT)(X.J**2)                                 5.72
N           $CUMX2=0                                                       5.73
A           VAR.K=($CUMX2.K/$TTIME.K)-MEAN.K**2                            5.73
A           STD.K=SQRT(VAR.K)                                              5.74
MEND

MACRO TIMER(RATE)
L           TIMER.K=TIMER.J+(DT)(RATE.J)                                   5.75
N           TIMER=0                                                        5.76
MEND

MACRO DTECT(DR,R0,RC,P5T,P75T,P9T,P10T,P13T,P15T,P175T,P20T,P22T,P24T)
A           DTECT.K=CLIP($PD5.K,$PDT1.K,5.0,$R0DR.K)                       5.77
A             $PD5.K=TABHL(P5T,0-$RCR0.K,2.5,9,0.5)                        5.78
A             $PDT1.K=CLIP($P575.K,$PDT2.K,7.5,$R0DR.K)                    5.79
A             $P575.K=INTRP($PD5.K,$PD75.K,5.0,7.5,$R0DR.K)                5.80
A             $PD75.K=TABHL(P75T,0-$RCR0.K,2.25,8.75,0.5)                  5.81
A             $PDT2.K=CLIP($P759.K,$PDT3.K,9.0,$R0DR.K)                    5.82
A             $P759.K=INTRP($PD75.K,$PD9.K,7.5,9,$R0DR.K)                  5.83
A             $PD9.K=TABHL(P9T,0-$RCR0.K,2,8,0.5)                          5.84
A             $PDT3.K=CLIP($P910.K,$PDT4.K,10,$R0DR.K)                     5.85
A             $P910.K=INTRP($PD9.K,$PD10.K,9,10,$R0DR.K)                   5.86
A             $PD10.K=TABHL(P10T,0-$RCR0.K,2,7,0.5)                        5.87
A             $PDT4.K=CLIP($P1013.K,$PDT5.K,13,$R0DR.K)                    5.88
A             $P1013.K=INTRP($PD10.K,$PD13.K,10,13,$R0DR.K)                5.89
A             $PD13.K=TABHL(P13T,0-$RCR0.K,1.75,5.25,0.5)                  5.90
A             $PDT5.K=CLIP($P1315.K,$PDT6.K,15,$R0DR.K)                    5.91
A             $P1315.K=INTRP($PD13.K,$PD15.K,13,15,$R0DR.K)                5.92
A             $PD15.K=TABHL(P15T,0-$RCR0.K,1.5,4.5,0.5)                    5.93
A             $PDT6.K=CLIP($P1517.K,$PDT7.K,17.5,$R0DR.K)                  5.94
A             $P1517.K=INTRP($PD15.K,$PD175.K,15,17.5,$R0DR.K)             5.95
A             $PD175.K=TABHL(P175T,0-$RCR0.K,1.25,3.75,0.5)                5.96
A             $PDT7.K=CLIP($P1720.K,$PDT8.K,20,$R0DR.K)                    5.97
A             $P1720.K=INTRP($PD175.K,$PD20.K,17.5,20,$R0DR.K)             5.98
A             $PD20.K=TABHL(P20T,0-$RCR0.K,1,3,.25)                        5.99
A             $PDT8.K=CLIP($P2022.K,$PDT9.K,22,$R0DR.K)                    5.100
A             $P2022.K=INTRP($PD20.K,$PD22.K,20,22,$R0DR.K)                5.101
A             $PD22.K=TABHL(P22T,0-$RCR0.K,.75,2.75,.25)                   5.102
A             $PDT9.K=CLIP($P2224.K,$PD24.K,24,$R0DR.K)                    5.103
A             $P2224.K=INTRP($PD22.K,$PD24.K,22,24,$R0DR.K)                5.104
A             $PD24.K=TABHL(P24T,0-$RCR0.K,.75,2.5,.25)                    5.105
A             $R0DR.K=RATINV(R0.K/DR.K)                                    5.106
A             $RCR0.K=RATINV(RC.K/R0.K)                                    5.107

T           PD5T=0/.1/.22/.33/.42/.51/.59/.65/.72/.77/.81/.85/.87/.89      5.108
T           PD75T=0/.16/.32/.46/.58/.69/.78/.85/.89/.93/.95/.97/.98/.99    5.109
T           PD9T=0/.15/.34/.5/.65/.76/.84/.90/.94/.96/.98/.99/1.0          5.110
T           PD10T=0/.22/.41/.6/.75/.86/.92/.96/.98/.99/1.0                 5.111
T           PD13T=0/.3/.54/.72/.85/.93/.98/1                               5.112
T           PD15T=0/.28/.57/.80/.95/.98/1.0                                5.113
```

```
T       PD175T=0/.3/.61/.86/.97/1                                                    5.114
T       PD20T=0/.17/.34/.50/.69/.83/.94/.98/1.0                                      5.115
T       PD22T=0/.1/.3/.5/.67/.83/.93/.99/1.0                                         5.116
T       PD24T=0/.21/.44/.66/.83/.94/.99/1.0                                          5.117

L       X.K(I)=X.J(I)+(DT)(V.J(I)*COS(SAI.J(I)/57.29)                                5.125
N       X(I)=XN(I)                                                                   5.126
T       XN(*)=0/500/1000/1500                                                        5.127
L       Y.K(I)=Y.J(I)+(DT)(V.J(I)*SIN(SAI.K(I)/57.29)                                5.128
N       Y(I)=YN(I)                                                                   5.129
T       YN(*)=0/0/0/0                                                                5.130

NOTE    X       - DOWNRANGE (METERS)
NOTE    Y       - LATERAL RANGE (METERS)
NOTE    V       - AIRCRAFT BODY/WIND AXES VELOCITY VECTOR (METERS/SEC)
NOTE    XN      - INITIAL AIRCRAFT DOWNRANGE POSITION (METERS)
NOTE    YN      - INITIAL AIRCRAFT Lateral DOWNRANGE POSITION (METERS)
NOTE    SAI     - AIRCRAFT HEADING ANGLE (DEGREES)

L       XAG.K(J)=XAG.J(J)+(DT)(VAG.J(J)*COS(SAIG.J(J)/57.29)                         5.131
N       XAG(I)=XAGN(I)                                                               5.132
T       XAGN(*)=2.5E5/2.505E5/2.51E5/2.515E5                                         5.133
L       YAG.K(J)=YAG.J(J)+(DT)(VAG.J(J)*SIN(SAIG.J(I)/57.29)                         5.134
N       YAG(I)=YAGN(I)                                                               5.135
T       YAGN(*)=0/0/0/0                                                              5.136

NOTE    XAG     - AGGRESSOR AIRCRAFT DOWNRANGE (METERS)
NOTE    YAG     - AGGRESSOR AIRCRAFT LATERAL RANGE (METERS)
NOTE    VAG     - AGG AIRCRAFT BODY/WIND AXES VELOCITY VECTOR (METERS/SEC)
NOTE    XAGN    - INITIAL AGG AIRCRAFT DOWNRANGE POSITION (METERS)
NOTE    YAGN    - INITIAL AGG AIRCRAFT Lateral DOWNRANGE POSITION (METERS)
NOTE    SAIG    - AGG AIRCRAFT HEADING ANGLE (DEGREES)

A       ALT.K(1)=TABHL(ALTT1,X.K(1)/1000,0,500,50)
T       ALTT1=6000/6000/6000/6000/6000/6000/6000/6000/6000/6000/6000
A       ALT.K(2)=TABHL(ALTT2,X.K(2)/1000,0,500,50)
T       ALTT2=6300/6300/6300/6300/6300/6300/6300/6300/6300/6300/6300
A       ALT.K(3)=TABHL(ALTT3,X.K(3)/1000,0,500,50)
T       ALTT3=6300/6300/6300/6300/6300/6300/6300/6300/6300/6300/6300
A       ALT.K(4)=TABHL(ALTT4,X.K(4)/1000,0,500,50)
T       ALTT4=6300/6300/6300/6300/6300/6300/6300/6300/6300/6300/6300
T       SIGMA(*)=.01/.01/.01/.01

A       ATN.K(I,J)=DIREC(SAI.K(I),DIRLOS.K(I,J),Y.K(I),YAG.K(J))                     5.137
A       TAA.K(I,J)=DIREC(SAIG.K(J),DIRGOS.K(I,J),YAG.K(J),Y.K(I))                    5.138

NOTE    ATN     - TARGET ASPECT ANGLE MEASURED FROM CBF VELOCTY VECTOR (DEG)
NOTE    TAA     - TARGET ASPECT ANGLE MEASURED FROM AGG VELOCTY VECTOR (DEG)

A       SAI.K(I)=YAW(SAIA.K(I))                                                      5.139
L       SAIA.K(I)=SAIA.J(I)+(DT)(RSAIA.J(I))                                         5.140
A       RSAIA.K(I)=RSAI1.JK(I)+RSAI2.JK(I)+RSAI3.JK(I)+RSAI4.JK(I)                   5.141

NOTE    SAI     - YAW ANGLE (HEADING ANGLE)
NOTE    YAW     - MACRO TO COMPUTE COMPUTE YAW ANGLES OVER 360 DEGREES AND
NOTE              BELOW ZERO DEGREES
NOTE    RSAIA   - INSTANTANEOUS YAW RATE (DEG/SEC)
NOTE    RSAI1   - YAW RATE IN THE INITIAL COMBAT PHASE (DEG/SEC)
NOTE    RSAI2   - YAW RATE IN BVR PHASE (DEG/SECOND)
NOTE    RSAI3   - YAW RATE IN ACM ENGAGEMENT (DEG/SEC)
NOTE    RSAI4   - YAW RATE IN DISENGAGEMENT/RETURN COMBAT PHASE (D/SEC)

A       SAIG.K(J)=YAW(SAIGA.K(J))                                                    5.139A
L       SAIGA.K(J)=SAIGA.J(J)+(DT)(RSAIG.JK(J))                                      5.140A
R       RSAIG.KL(J)=RSAIG1.JK(J)+RSAIG2.JK(J)+RSAIG3.JK(J)+RSAIG4.JK(J)              5.141A

NOTE    SAIG    - YAW ANGLE (HEADING ANGLE)
NOTE    YAW     - MACRO TO COMPUTE COMPUTE YAW ANGLES OVER 360 DEGREES AND
NOTE              BELOW ZERO DEGREES
NOTE    RSAIG1  - YAW RATE IN THE INITIAL COMBAT PHASE (DEG/SEC)
NOTE    RSAIG2  - YAW RATE IN BVR PHASE (DEG/SECOND)
NOTE    RSAIG3  - YAW RATE IN ACM ENGAGEMENT (DEG/SEC)
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NOTE    RSAIG4   - YAW RATE IN DISENGAGEMENT/RETURN COMBAT PHASE (D/SEC)

N       SAIA(I)=SAIAN(I)                                                    5.142
T       SAIAN(*)=45/45/46/47                                                5.143

NOTE    SAIN     - INITIAL HEADING ANGLE (DEGREES)
NOTE    SAIA     - CBF HEADING ANGLE (DEG.)

N         SAIGA(J)=SAIGN(J)                                                 5.142A
T         SAIGN(*)=130.5/130.3/130/130.7                                    5.143A
R         RSAIG1.KL(I)=0                                                    5.144

NOTE    SAIGN    - INITIAL HEADING ANGLE (DEGREES)
NOTE    SAIGA    - AGG HEADING ANGLE (DEG.)

L       V.K(I)=V.J(I)+(DT)(ACC.JK(I))                                       5.145
N       V(I)=VN(I)                                                          5.146
T       VN(*)=260/260/260/260                                               5.147
R       ACC.KL(I)=((T.K(I)*COS(ALP.K(I)+SIGMA(I))-D.K(I))/WK.K(I)           5.148

NOTE    V        - CBF AIRCRAFT VELOCITY VECTOR MAGNITUDE (M/SEC)
NOTE    VN       - INITIAL SPEED FOR CBF AIRCRAFT (M/SEC)
NOTE    ACC      - INSTANTANEOUS LODGITUDINAL ACCELERATION OF CBF AIRCRAFT
NOTE               (M/SEC-SEC)
NOTE    T        - AIRCRAFT THRUST (NEWTONS)
NOTE    ALP      - AIRCRAFT ANGLE OF ATTACK (RADIANS)
NOTE    SIGMA    - LONGITUDINAL THRUST OFFSET ANGLE (RADIANS)
NOTE    D        - AIRCRAFT TOTAL DRAG FORCE (NEWTONS)
NOTE    WK       - AIRCRAFT MASS (KGS.)

L       WK.K(I)=WK.J(I)-(DT)(FFLOW.JK(I)+SCLPRD(ATAWR.JK(I,*),1,4
X         ,ATAAWW.K(*),1))                                                  5.149
N         WK(I)=IM(I)                                                       5.150
N           IM(I)=EM(I)+PYL(I)+FUELN(I)                                     5.151
N           EM(I)=EMB(I)*MIEM(I)                                            5.152
T             EMB(*)=14000/14000/14000/14000                                5.153
T             MIEM(*)=1/1/1/1                                               5.154
N           PYL(I)=SCLPRD(ATAWN(I,*),1,KK,ATAAWW(*),1)
X           +WEECM(I)+WEXP(I)                                               5.155
N             WEECM(I)=NEECM(I)*WECMU(*)                                    5.156
T              NEECM(*)=0/0/0/0                                             5.157
T              WECMU(*)=250/250/250/250                                     5.158
T              WEXP(*)=300/300/300/300                                      5.159

NOTE    IM       - INITIAL MASS (KG.)
NOTE    EM       - EMPTY MASS (KG.)
NOTE    EMB      - BASELINE EMPTY MASS (KG.)
NOTE    MIEM     - MASS INCREASE VS. ENGINE MODIFICATION (KG.)
NOTE    PYL      - PAYLOAD (KG.)
NOTE    FUELN    - INITIAL FUEL MASS (KG.)
NOTE    CBFWN    - INITIAL NO. OF AA WEAPONS (UNITS)
NOTE    CBFAWW   - AIR-TO-AIR WEAPON MASS (KGS.)
NOTE    MEECM    - MASS OF EXTERNAL ECM EQUIPMENT (KG.)
NOTE    NEECM    - NO. OF ECM EXTERNAL PODS (UNITS)
NOTE    WECMU    - WEIGHT OF EXTERNAL ECM POD (KG.)

L         MAG.K(J)=MAG.J(J)-(DT)(FFLOWG.JK(J)+SCLPRD(AGAWR.JK(J,*),1,LL
X           ,AGAAWW(*),1))                                                  5.149A
N           MAG(J)=MAGN(J)                                                  5.150A
N           MAGN(J)=EMG(J)+PYLG(J)+FUELGN(J)                                5.151A
N           EMG(J)=EMBG(J)+MIEMG(J)                                         5.152A
T             EMBG(*)=13000/13000/13000/13000                               5.153A
T             MIEMG(*)=0/0/0/0                                              5.154A
N           PYLG(J)=SCLPRD(AGAWN(J,*),1,LL,AGAAWW(*),1)
X             +WEECMG(J)+GWEXP(J)                                           5.155A
N             WEECMG(J)=NEECMG(J)*WECMUG(*)                                 5.156A
T              NEECMG(*)=0/0/0/0                                            5.157A
T              WECMUG(*)=250/250/250/250                                    5.158A
T           AGAAWW(*)=500/170/110/.25                                       5.159A

A       T1.K(I)=TIMER(RTT1.K(I))                                            5.167
A       T2.K(I)=TIMER(RTT2.K(I))                                            5.168
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A       T3.K(I)=TIMER(RTT3.K(I))                                                5.169
R       RTT1.KL(I)=RT1.K(I)*SWITCH(1,0,RTT2.JK(I))*SWITCH(1,0,RTT3.JK(I))       5.170.1
R       RTT2.KL(I)=RT2.K(I)*SWITCH(1,0,RTT3.JK(I))                              5.171.1
R       RTT3.KL(I)=RT3.K(I)                                                     5.172
A         RT1.K(I)=CLIP(1,0,RT11.K(I)+RT12.K(I),1)                              5.170
A         RT11.K(I)=CLIP(1,0,SUMV(PGRD.K(I,*),1,JJ)/JJ,.8)                      5.171
A         RT12.K(I)=CLIP(0,RT13.K(I),FAW.K,.98)                                 5.172
C         FAW.K=SUM(AGAW.K)/(SUM(AGAWN)+1.0E-6)
A         RT13.KL(I)=CLIP(1,0,SUMV(RWRA(I,*),1,JJ)/JJ,
X         SUMV(RLOS.K(I,*),1,JJ)/JJ                                             5.173
R         RT2.KL(I)=CLIP(1,0,20000,SUMV(RLOS.K(I,*),1,JJ)/JJ)                   5.174
R         RT3.KL(I)=CLIP(1,0,RT31.K(I)+RT32.K(I),1)                             5.175
A           RT31.K(I)=CLIP(1,0,FUELAC,FUELR.K(I))                               5.176
A           RT32.K(I)=CLIP(1,0,WEAPAC,AVWEAP.K(I))                              5.177
A           AVWEAP.K(I)=SUMV(CBFW.K(I,*),1,KK)/SUMV(CBFWN(I,*),1,KK             5.178
C           FUELAC=.4                                                           5.179
C           AVWEAP=.1                                                           5.180

NOTE    TIMER    - MACRO TO INITIALIZE AND UPDATE COMBAT TIMES
NOTE    T1       - TIMER THAT TRIGGERS BVR ENGAGEMENT
NOTE    T2       - TIMER THAT TRIGGERS ACM ENGAGEMENT
NOTE    T3       - TIMER THAT TRIGGERS DISENGAGEMENT-RETURN PHASE
NOTE    RT1,..   - CHANGES IN TIMERS
NOTE    WEAPAC   - WEAPON STATUS FRACTION USED TO INITIALIZE DISENGAGEMENT
NOTE               TIMER
NOTE    FUELAC   - FUEL FRACTION USED AS CUTOFF FOR DISENGAGEMENT
NOTE    AVWEAP   - AVERAGE WEAPONS REMAINING IN AN AIRCRAFT
NOTE    FCBFWR   - FRACTION OF WEAPONS REMAINING IN A GIVEN AIRCRAFT
NOTE    FUELR    - FUEL FRACTION REMAINING ON EACH CBF AIRCRAFT

R       RSAI1.K(I)=0                                                            5.181

L       TS.K(I)=TS.J(I)+(DT)(TSR.J(I))                                          5.182
N         TS(I)=TSN(I)                                                          5.183
T         TSN(*)=.8/.8/.8/.8                                                    5.184
A       TSR.K(I)=TSR1.JK(I)+TSR2.JK(I)+TSR3.JK(I)+TSR4.JK(I)                    5.185
R         TSR1.KL(I)=TSR1C(*)                                                   5.186
T         TSR1C(*)=0/0/0/0                                                      5.187

NOTE    TS       - CBF AIRCRAFT THROTTLE SETTING (DIM)
NOTE    TSR      - CBF AIRCRAFT THROTTLE SETTING RATE OF CHANGE (DIM)
NOTE    TSN      - INITIAL CBF AIRCRAFT THROTTLE SETTING (DIM)
NOTE    TSR1     - TS RATE OF CHANGE DURING INITIAL COMBAT PHASE (DIM)
NOTE    TSR2     - TS RATE OF CHANGE DURING BVR COMBAT PHASE (DIM)
NOTE    TSR3     - TS RATE OF CHANGE DURING ACM COMBAT PHASE (DIM)
NOTE    TSR4     - TS RATE OF CHANGE DURING DISENGAGEMENT COMBAT PHASE (DIM)
NOTE    TSR1C    - NUMERICAL VALUE OF TSR1 DURING INITIAL COMBAT PHASE (DIM)

R       RSAI2.KL(I)=switch(0,RSAI2A.K(I),rtt1.jK(I))                            5.188
A         RSAI2A.K(I)=CLIP(-AVATN.K(I)/DT,RSAI2B.K(I),SAI1M.K(I)*DT
X         ,MAX(AVATN.K(I),-AVATN.K(I)))                                         5.189
A         RSAI2B.K(I)=CLIP(-SAI1M.K(I),SAI1M.K(I),AVATN.K(I),0)                 5.190
A           AVATN.K(I)=SUMV(ATN.K(I,*),1,JJ)/JJ                                 5.191

NOTE    RSAI2    - HEADING ANGLE RATE OF CHANGE IN BVR PHASE (DEG/SEC)
NOTE    RSAI2    - HEADING ANGLE RATE OF CHANGE IN BVR PHASE (DEG/SEC)
NOTE    AVATN    - AVERAGE ANTENNA TRAIN ANGLE (DEG)
NOTE    ACMT     - ACM TURNING VECTOR (DEG)
NOTE    ATNP     - MATRIX CONTAINING POSITIVE VALUES OF ATN (DEG)
NOTE    ATNN     - MATRIX CONTAINING NEGATIVE ATN VALUES (DEG)

R       TSR2.KL(I)=switch(0,TSR2A.K(I),rttT1.jK(I))                             5.194
A         TSR2A.K(I)=CLIP(TSR2B.K(I),0,0,T2.K(I))                               5.195
A           TSR2B.K(I)=CLIP(0,TSR2C(I),TS.K(I),.90)                             5.196
T             TSR2C(*)=.005/.005/.005/.005                                      5.197

NOTE    TSR2     - THROTTLE SETTING RATE OF CHANGE DURING BVR PHASE (DIM)
NOTE    T1       - TIMER TO START THE BVR COMBAT PHASE
NOTE    T2       - TIMER TO START THE ACM COMBAT PHASE
NOTE    TS       - CBF AIRCRAFT THROTTLE SETTING (DIM)
NOTE    TSR2A, TSR2B, .. ARE INTERMEDIATE DUMMY VARIABLES
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R       RSAI3.KL(I)=switch(0,RSAI3A.K(I),RTT2.JK(I))                          5.198
A        RSAI3A.K(I)=CLIP(RSAI3B.K(I),0,0,T3.K(I))                            5.199
A        RSAI3B.K(I)=CLIP(-ACMT.K(I)/DT,RSAI3C.K(I),SAI1M.K(I)*DT
X        ,MINATN.K(I))                                                        5.200
A         RSAI3C.K(I)=CLIP(-SAI1M.K(I),SAI1M.K(I),ACMT.K(I),0)                5.201
A        ATNP.K(I,J)=CLIP(ATN.K(I,J),1000,ATN.K(I,J),0)                       5.202
A         ATNN.K(I,J)=CLIP(1000,-ATN.K(I,J),ATN.K(I,J),0)                     5.203
A        MNATNP.K(I)=MIN(ATNP.K(I,1),MIN(ATNP.K(I,2),MIN(ATNP.K(I,3)
X        ,ATNP.K(I,4))))                                                      5.204
A        MNATNN.K(I)=MIN(ATNN.K(I,1),MIN(ATNN.K(I,2),MIN(ATNN.K(I,3)
X        ,ATNN.K(I,4))))                                                      5.205
A        MINATN.K(I)=MIN(MNATNP.K(I),MNATNN.K(I))                             5.206
A         ACMT.K(I)=CLIP(-MINATN.K(I),MINATN.K(I),MNATNP.K(I)                 5.207

NOTE    RSAI3     - HEADING RATE OF CHANGE IN ACM ENVIRONMENT (DEG/SEC)
NOTE    ACMT      - ANGULAR CHANGE TO PURSUIT A TARGET (DEGREES)
NOTE    SAI1M     - MAXIMUM SUSTAINED TURN RATE (DEG/SEC)
NOTE    ATN       - TARGET ASPECT ANGLE MEASURED FROM CBF VELOCITY VECTOR (DEG)
NOTE    ATNP      - MATRIX CONTAINING POSITIVE VALUES OF ATN (DEG)
NOTE    ATNN      - MATRIX CONTAINING NEGATIVE ATN VALUES (DEG)
NOTE    MNATNP    - MINIMUM POSITIVE ATN FROM I TH AIRCRAFT TO JTH AIRCRAFT
NOTE                (USED TO KEEP UP WITH THE DIRECTION TO WHICH THE AIRCRAFT
NOTE                SHOULD TURN TO MAINTAIN LOS ALIGNMENT WITH TARGET)
NOTE    MNATNN    - ABSOLUTE VALUE OF MINIMUM ELEMENT IN ATNN MATRIX FROM
NOTE                I TH TO J TH AIRCRAFT

R       TSR3.KL(I)=SWITCH(0,-TSR3A.K(I),RTT2.K(I))                            5.208
A        TSR3A.K(I)=CLIP(TSR3B.K(I),0,0,T3.K(I))                              5.209
A         TSR3B.K(I)=CLIP(TSR3C(I),0,V.K(I),VC.K(I))                          5.210
T          TSR3C(*)=.0008/.0008/.0008/.0008                                   5.211

NOTE    TSR3      - THROTTLE SETTING RATE OF CHANGE IN ACM COMBAT PHASE
NOTE    TSR3A, TSR3B, .. ARE INTERMEDIATE DUMMY VARIABLES
NOTE    T2        - TIMER TO START ACM PHASE
NOTE    T3        - TIMER TO INITIATE DISENGAGEMENT COMBAT PHASE
NOTE    V         - CBF AIRCRAFT SPEED (M/SEC)
NOTE    VC        - CBF AIRCRAFT CORNER SPEED (M/SEC)

R       RSAI4.KL(I)=SWITCH(0,RSAI4A.K(I),RTT3.K(I))                           5.212
A        RSAI4A.K(I)=CLIP(-STCBF.K(I)/DT,RSAI4B.K(I),SAI1M.K(I)*DT
X        ,ABS(STCBF.K(I)))                                                    5.213
A          RSAI4B.K(I)=CLIP(-SAI1M.K(I),SAI1M.K(I),STCBF.K(I),0)              5.214

NOTE    RSAI4     - HEADING RATE OF CHANGE IN DISENGAGEMENT PHASE (DEG/SEC)
NOTE    RSAI4A, RSAI4B,.. INTERMEDIATE RSAI4 COMPUTATION VARIABLES
NOTE    SAI1M     - MAXIMUM SUSTAINED TURN RATE (DEG/SEC)
NOTE    T3        - TIMER TO START THE DISENGAGENT PHASE
NOTE    STCBF     - ANGULAR DIFFERENCE BETWEEN SAI VECTOR AND RETURN STEERING
NOTE                VECTOR (DEGREES)

A       STVMA.K(I)=SQRT(MAX(X.K(I)-XN(I),-X.K(I)+XN(I))**2
X        +MAX(Y.K(I)-YN(I),-Y.K(I)+YN(I))**2)                                 5.215
A       STVDA.K(I)=ARCSIN(X.K(I),XN(I),Y.K(I),YN(I),STVMA.K(I))               5.216
A       STCBF.K(I)=DIREC(SAI.K(I),STVDA.K(I),Y.K(I),YN(I))                    5.217

NOTE    STVMA     - CBF STEERING VECTOR MAGNITUDE (M.)
NOTE    STVDA     - CBF STEERING VECTOR DIRECTION (DEG)
NOTE    STCBF     - ANGULAR DIFFERENCE BETWEEN SAI VECTOR AND RETURN STEERING
NOTE                VECTOR (DEGREES)

R       TSR4.KL(I)=SWITCH(0,TSR4A.K(I),RTT3.JK(I))                            5.218
A        TSR4A.K(I)=CLIP(-TSR4B(I),TSR4B(I),TS.K(I),.85)                      5.219
T        TSR4B(*)=.005/.005/.005/.005                                         5.220

NOTE    TSR4      - THROTTLE SETTING RATE OF CHANGE IN DISENGAGEMENT PHASE
NOTE    TSR4A, TSR4B,INTERMEDIATE TSR4 VARIABLES
NOTE    TS        - CBF AIRCRAFT THROTTLE SETTING (DIM)
NOTE    T3        - TIMER TO START DISENGAGEMENT COMBAT PHASE

R           RSAIG2.KL(J)=SWITCH(0,RSAG2A.K(J),RTTG1.JK(J))                    5.188A
A           RSAG2A.K(J)=CLIP(-AVTAA.K(J)/DT,RSAG2B.K(J),SAIG1M.K(J)*DT
X            ,MAX(AVTAA.K(J),-AVTAA.K(J)))                                    5.189A
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A          RSAG2B.K(J)=CLIP(-SAIG1M.K(J),SAIG1M.K(J),AVTAA.K(J),0)                5.190A
A           AVTAA.K(J)=SUMV(TAA.K(*,J),1,II)/II                                  5.191A

R         RSAIG3.KL(J)=SWITCH(0,RSAG3A.K(J),RTTG2.JK(J))                         5.198A
A          RSAG3A.K(J)=CLIP(RSAG3B.K(J),0,0,TG3.K(J))                            5.199A
A          RSAG3B.K(J)=CLIP(-ACMGT.K(J)/DT,RSAG3C.K(J),SAIG1M.K(J)*DT
X           ,MINTAA.K(J))                                                        5.200A
A           RSAG3C.K(J)=CLIP(-SAIG1M.K(J),SAIG1M.K(J),ACMGT.K(J),0)              5.201A
A           TAAP.K(I,J)=CLIP(TAA.K(I,J),1000,TAA.K(I,J),0)                       5.202A
A           TAAN.K(I,J)=CLIP(1000,-TAA.K(I,J),TAA.K(I,J),0)                      5.203A
A           MNTAAP.K(J)=MIN(TAAP.K(1,J),TAAP.K(2,J))                             5.205A
A           MNTAAN.K(J)=MIN(TAAN.K(1,J),TAAN.K(2,J))                             5.206A
A           MINTAA.K(J)=MIN(MNTAAP.K(J),MNTAAN.K(J))                             5.207A
A           ACMGT.K(J)=CLIP(-MINTAA.K(J),MINTAA.K(J),MNTAAP.K(J)
X         ,MNTAAN.K(J))                                                          5.208A

R         RSAIG4.KL(J)=SWITCH(0,RSAG4A.K(J),RTTG3.JK(J))                         2.212A
A         RSAG4A.K(J)=CLIP(-STAGG.K(J)/DT,RSAG4B.K(J),SAIG1M.K(J)*DT
X           ,MAX(STAGG.K(J),-STAGG.K(J)))                                        2.213A
A           RSAG4B.K(J)=CLIP(-SAIG1M.K(J),SAIG1M.K(J),STAGG.K(J),0)              2.213A

NOTE      AVTAA    - AVERAGE ANTENNA TRAIN ANGLE (DEG)
NOTE      ACMGT    - ACM TURNING VECTOR (DEG)
NOTE      TAAP     -  MATRIX CONTAINING POSITIVE VALUES OF TAA (DEG)
NOTE      TAAN     -  MATRIX CONTAINING NEGATIVE TAA VALUES (DEG)
NOTE      MNTAAP   -  MINIMUM POSITIVE TAA FROM I TH AIRCRAFT TO JTH AIRCRAFT
NOTE                  (USED TO KEEP UP WITH THE DIRECTION TO WHICH THE AIRCRAFT
NOTE                  SHOULD TURN TO MAINTAIN LOS ALIGNMENT WITH TARGET)
NOTE      MNTAAN   -  ABSOLUTE VALUE OF MINIMUM ELEMENT IN TAAN MATRIX FROM
NOTE                  I TH TO J TH AIRCRAFT

A          TG1.K(J)=TIMER(RTTG1.K(J))                                            5.167A
A          TG2.K(J)=TIMER(RTTG2.K(J))                                            5.168A
A          TG3.K(J)=TIMER(RTTG3.K(J))                                            5.169A
R           RTTG1.KL(J)=RTG1.K(J)*SWITCH(1,0,RTTG2.JK(J))*
X            SWITCH(1,0,RTTG3.JK(J))                                             5.170.1
R          RTTG2.KL(J)=RTG2.K(J)*SWITCH(1,0,RTTG3.JK(J))                         5.171.1
R          RTTG3.KL(J)=RTG3.K(J)                                                 5.172.1
R           RTG1.KL(J)=CLIP(1,0,RTG11.K(J)+RTG12.K(J),1)                         5.170A
A           RTG11.K(J)=CLIP(1,0,SUMV(PARD.K(*,J),1,II)/II,.8)                    5.171A
A           RTG12.K(J)=CLIP(0,RTG13.K(J),SUMV(FCBFWR.K(*,J),1,II)/II,.98)        5.172A
A           RTG13.K(J)=CLIP(1,0,SUMV(RWRG(*,J),1,II)/II
X            ,SUMV(RLOS.K(*,J),1,II)/II)                                         5.173A

R           RTG2.KL(J)=CLIP(1,0,35000,SUMV(RLOS.K(*,J),1,II)/II)                 5.174A
R           RTG3.KL(J)=CLIP(1,0,RTG31.K(J)+RTG32.K(J),1)                         5.175A
A             RTG31.K(J)=CLIP(1,0,FUELAC,FUELGR.K(J))                            5.176A
A             RTG32.K(J)=CLIP(1,0,WEAPAC,AVWEAG.K(J))                            5.177A
A             AVWEAG.K(J)=SUMV(FAGAWR.K(*,J),1,II)/II                            5.178A

NOTE      TIMER    - MACRO TO INITIALIZE AND UPDATE COMBAT TIMES
NOTE      TG1      - TIMER THAT TRIGGERS BVR ENGAGEMEN                           T
NOTE      TG2      - TIMER THAT TRIGGERS ACM ENGAGEMEN                           T
NOTE      TG3      - TIMER THAT TRIGGERS DISENGAGEMENT-RETURN PHASE
NOTE      RTG1,..  - CHANGES IN TIMERS
NOTE      ----------------------------------------
L          TSG.K(J)=TSG.J(J)+(DT)(TSGR.J(J))                                     5.182A
N           TSG(J)=TSGN(J)                                                       5.183A
T           TSGN(*)=.8/.8/.8/.8                                                  5.184A
A          TSGR.K(J)=TSGR1.JK(J)+TSGR2.JK(J)+TSGR3.JK(J)+TSGR4.JK(J)             5.185A
R           TSGR1.KL(J)=TSGR1C(*)                                               5.186A
T             TSGR1C(*)=0/0/0/0                                                 5.187A
R           TSGR2.KL(J)=CLIP(0,TSGR2A.K(J),0,TG1.K(J))                          5.194A
A             TSGR2A.K(J)=CLIP(TSGR2B.K(J),0,0,TG2.K(J))                        5.195A
A               TSGR2B.K(J)=CLIP(0,TSGR2C(J),TSG.K(J),.90)                      5.196A
T                 TSGR2C(*)=.03/.03/.03/.03                                     5.197A
R           TSGR3.KL(J)=CLIP(0,-TSGR3A.K(J),0,TG2.K(J))                         5.208A
A             TSGR3A.K(J)=CLIP(TSGR3B.K(J),0,0,TG3.K(J))                        5.209A
A               TSGR3B.K(J)=CLIP(0,TSGR3C(J),TSG.K(J),.70)                      5.210A
T                 TSGR3C(*)=.03/.03/.03/.03                                     5.211A
R           TSGR4.KL(J)=CLIP(0,TSGR4A.K(J),0,TG3.K(J))                          5.218A
A               TSGR4A.K(J)=CLIP(0,TSGR4B(J),TSG.K(J),.85)                      5.219A
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T       TSGR4B(*)=.03/.03/.03/.03                                          5.220A

A       PCBFE.K(I,J,K)=PALOS.K(I,J)*PAGGD.K(I,J)*PATWL.K(I,J,K)*
X       PATWSG.K(I,J,K)*PAWDET.K(K)                                        5.222

NOTE    PCBFE   - PROBABILITY OF CBF AIRCRAFT SYSTEMS EFFECTIVENESS (DIM)
NOTE    PALOS   - PROBABILITY OF TARGET AIRCRAFT IN LINE OF SIGHT (DIM)
NOTE    PAGGD   - PROBABILITY OF AGGRESSOR AIRCRAFT DETECTION (DIM)
NOTE    PAGGD   - PROBABILITY OF AGGRESSOR AIRCRAFT DETECTION (DIM)
NOTE    PATWL   - PROBABILITY OF CBF AIRCRAFT WEAPONS LAUNCH (DIM)
NOTE    PATWSG  - PROBABILITY OF CBF AIRCRAFT WEAPONS SUCCESSFUL GUIDANCE
NOTE    PAWDET  - PROBABILITY OF CBF AIRCRAFT WEAPONS DETONATION (DIM)

A       PAGGE.K(I,J,L)=PALOS.K(I,J)*PCBFD.K(I,J)*PAGWL.K(I,J,K)*
X       PAGWSG.K(I,J,K)*PGWDET.K(K)                                        5.223

NOTE    PAGGE   - PROBABILITY OF AGG AIRCRAFT SYSTEMS EFFECTIVENESS (DIM)
NOTE    PALOS   - PROBABILITY OF TARGET AIRCRAFT IN LINE OF SIGHT (DIM)
NOTE    PCBFD   - PROBABILITY OF CBF AIRCRAFT DETECTION (DIM)
NOTE    PAGWL   - PROBABILITY OF AGG AIRCRAFT WEAPONS LAUNCH (DIM)
NOTE    PAGWSG  - PROBABILITY OF AGG AIRCRAFT WEAPONS SUCCESSFUL GUIDANCE
NOTE    PAGDET  - PROBABILITY OF AGG AIRCRAFT WEAPONS DETONATION (DIM)

A       PALOS.K(I,J)=LOS(ALT.K(I),RLOS.K(I,J))                             5.224

A       PAGGD.K(I,J)=MAX(PDIRG.K(I,J),PGRD.K(I,J))                         5.225

A       PGRD.K(I,J)=DTECT(DRC.K(I,J),R0CBF.K(I,J),RLOS.K(I,J),PD5T,PD75T
X       ,PD9T,PD10T,PD13T,PD15T,PD175T,PD20T,PD22T,PD24T)*CLIP(0,1,
X       MAX(ATN.K(I,J),-ATN.K(I,J)),THETAA(I)/2)                           5.226
A       DRC.K(I,J)=MAX(V.K(I)*COS(ATN.K(I,J)/57.29)+VAG.K(J)*COS(TAA.K(I,J)
X       /57.29),-V.K(I)*COS(ATN.K(I,J)/57.29)-VAG.K(J)*COS(TAA.K(I,J)
X       /57.29))*TSA(I)                                                    5.227

NOTE    THERE ARE THREE SWITHCHES (SWC#) TO ACTIVATE THE DESIRED ECM
NOTE    SCHEME TO BE IMPLEMENTED.
NOTE
NOTE    SWC1 - SELECTS WHETHER OR NOT ELECTRONIC JAMMING IS TO BE USED
NOTE           SWC1=0 IMPLIES NO JAMMING AT ALL TO BE USED
NOTE           SWC1 NOT ZERO IMPLIES JAMMING IS TO BE USED
NOTE
NOTE    SWC2 - SELECTS BETWEEN JAMMING THROUGHOUT THE ENTIRE MISSION OR
NOTE         JUST JAMMING AFTER BVR PHASE.
NOTE           SWC2=0 IMPLIES JAMMING IS USED THROUGHOUT THE MISSION
NOTE           SWC2 NOT ZERO IMPLIES JAMMING IS ACTIVATED AT BVR POINT
NOTE
NOTE    SWC3 - SELECTS BETWEEN STAND-OFF AND SELF-SCREENING JAMMING
NOTE           SWC3=0 IMPLIES STAND-OFF JAMMING IS USED
NOTE           SWC3 NOT ZERO IMPLIES SELF-SCREENING JAMMING IS USED
NOTE
NOTE    THE SAME ECM SCHEME IS USED FOR THE AGGRESSOR AIRCRAF

NOTE    PGRD    - CUMMULATIVE PROBABILITY OF AGGRESSOR AIRCRAFT RADAR
NOTE              DETECTION (DIM)
NOTE    DR      - DELTA RANGE COVERED BY THE TARGET WITH RESPECT TO THE
NOTE              ENEMY AIRCRAFT IN A RADAR FRAME SCAN INTERVAL.

A       R0CBF.K(I,J)=SWITCH(R0ANJ.K(I,J),SJAMON.K(I,J),SWC1)               5.228
C       SWC1=0                                                             5.228.1
A       SJAMON.K(I,J)=SWITCH(SJAM1.K(I,J),SJAM2.K(I,J),SWC2)               5.228.2
C         SWC2=0                                                           5.228.3
A         SJAM1.K(I,J)=SWITCH(R0ASOJ.K(I,J),R0ASSJ.K(I,J),SWC3)            5.228.4
C           SWC3=0                                                         5.228.5
A       JAMTMM.K(I)=CLIP(1,0,T1.K(I),1)                                    5.229

A       R0ANJ.K(I,J)=(RLPA(I)*ERCSG.K(I,J))**.25                           5.230
N       RLPA(I)=2*PAVA(I)*ADA(I)**2*TSA(I)*NUA**2/(PI**3*BK*TNO(I)
X       *LA(I)*OMEGAA(I))                                                  5.231
T         PAVA(*)=200/200/200/200                                          5.232
T         ADA(*)=.91/.91/.91/.91                                           5.233
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T       TSA(*)=3/3/3/3                                                    5.234
T       TNO(*)=400/400/400/400                                            5.235
T       LA(*)=16/16/16/16                                                 5.236
N       OMEGAA(I)=(THETAE(I)/57.29)*(THETAA(I)/57.29)                     5.237
T         THETAA(*)=120/120/120/120                                       5.238
T         THETAE(*)=30/30/30/30                                           5.239
C       BK=1.38E-23                                                       5.240
C       NUA=.8                                                            5.241

NOTE    PAVA    - RADAR AVERAGE POWER (WATTS)
NOTE    ADA     - CBF RADAR ANTENNA DIAMETER (M)
NOTE    RCSG    - AGGRESSOR RADAR CROSS SECTIONAL AREA (SQ. METERS)
NOTE    RCSAAM  - RADAR CROSS SECTION ASPECT ANGLE MULTIPLIER (DIM)
NOTE    OMEGAA  - CBF VOLUME SEARCH AREA (DIM)
NOTE    THETAE  - SEARCH RADAR ELEVATION (RADIANS)
NOTE    THETAA  - AZIMUTH ANGLE COVERED BY RADAR IN VOLUME SCAN MODE (RAD)
NOTE    TNO     - RADAR NOISE TEMPERATURE (DEGREES KELVIN)
NOTE    LN      - SYSTEM LOSSES (DIM) CONVERTED FROM 12 DB TYPICAL
NOTE    BK      - BOLTZMANN CONSTANT (JOULES/DEG. KELVIN)
NOTE    NU      - EFFECTIVE APERTURE FACTOR FOR CBF RADAR ANTENNA (DIM)

A       R0AJ.K(I,J)=SWITCH(R0ASOJ.K(I,J),R0ASSJ.K(I,J),SWTCH)             5.242
C         SWTCH=0                                                         5.243
A         R0ASOJ.K(I,J)=((32*PAVA(I)*NUA*TSA(I)*ERCSG.K(I,J)*RJAM.K(I)**2)
X           /(PI*OMEGAA(I)*LA(I)*JDSOJ))**.25                           5.244
A         RJAM.K(I)=SQRT(DIXJ.K(I)**2+DIYJ.K(I)**2+DIZJ.K(I)**2)          5.245
A           DIXJ.K(I)=MAX(X.K(I)-XSJG,-X.K(I)+XSJG)                       5.246
A           DIYJ.K(I)=MAX(Y.K(I)-YSJG,-Y.K(I)+YSJG)                       5.247
A           DIZJ.K(I)=MAX(ALT.K(I)-ALTSJG,-ALT.K(I)+ALTSJG)               5.248
C             XSJG=250000                                                 5.249
C             YSJG=0                                                      5.250
C             ALTSJG=6000                                                 5.251
N             JDGSOJ=PGSOJ*GGSOJ/BWGSOJ                                   5.252
C               PGSOJ=150                                                 5.253
C               GGSOJ=35                                                  5.254
C               BWGSOJ=2E8                                                5.255

NOTE    SWTCH   - SWITCH FOR SPECIFYING SELF SCREENING OR STAND-OFF
NOTE              JAMMING. IF SWTCH=0 THEN STAND-OFF JAMMING IS USED
NOTE    R0AJ    - MAXIMUM RADAR DETECTION RANGE WITH JAMMER ON (METERS)
NOTE    R0ASOJ  - MAXIMUM DETECTION RANGE WITH STAND-OFF JAMMER ON (M)
NOTE    ROASSJ  - MAXIMUM DETECTION RANGE WITH SELF-SCREENING JAMMER ON (M)
NOTE    RJAM    - RANGE FROM JTH AIRCRAFT TO STANDOFF JAMMER (METERS)
NOTE    DIXJ    - DOWNRANGE DISTANCE FROM SOJ JAMMER TO JTH AIRCRAFT (M)
NOTE    DIYJ    - LATERAL DISTANCE FROM SOJ JAMMER TO JTH AIRCRAFT (M)
NOTE    DIZJ    - ALTITUDE DIFFERENTIAL FROM SOJ JAMMER TO JTH AIRCRAFT (M)
NOTE    XSJ,YSJ,ZSJ COORDINATES OF SOJ JAMMER (METERS)
NOTE    JDSOJ   - NOISE JAMMING POWER OF STAND-OFF JAMMER (W/HZ)
NOTE    PGSOJ   - AVERAGE POWER OF SOJ JAMMER(W)
NOTE    GGSOJ   - JAMMER GAIN (DIMENSIONLESS)
NOTE    BWGSOJ  - JAMMER BANDWIDTH (HZ)

A       R0ASSJ.K(I,J)=(32*PAVA(I)*NUA*TSA(I)*ERCSG.K(I,J)/(PI*OMEGAA(I)
X       *LA(I)*JDSSJ))**.5                                                5.256
N       JDSSJ=PSSJ*GSSJ/BWSSJ                                             5.257
C       PSSJ=50                                                           5.258
C       GSSJ=35                                                           5.259
C       BWSSJ=2E8                                                         5.260

NOTE    JDSSJ   - NOISE JAMMING POWER OF SELF-SCREENING JAMMER (W/HZ)
NOTE    PSSJ    - AVERAGE POWER OF SSJ JAMMER(W)
NOTE    GSSJ    - JAMMER GAIN (DIMENSIONLESS)
NOTE    BWSSJ   - JAMMER BANDWIDTH (HZ)

N       RWRA(I,J)=SQRT(9*PAVG(J)*ADG(J)**2*NUG*RGAIN(I)/((4*PI)**2*LARWR(I)
X       *BK*TNO(I)*BN(I)*FR(I)))                                          5.261
T         BN(*)=2E8/2E8/2E8/2E8                                           5.262
T         RGAIN(*)=10/10/10/10                                            5.263
T         LARWR(*)=20/20/20/20                                            5.264
T         FR(*)=20/20/20/20                                               5.265

NOTE    RWRA    - RADAR WARNING RECEIVER RANGE FOR CBF AIRCRAFT (METERS)
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NOTE    RGAIN    - RADAR WARNING RECEIVER ANTENNA GAIN
NOTE    BN       - RWR RECEIVER BANDWIDTH (HERTZ)
NOTE    LARWR    - RECEIVER LOSSES (DIM)
NOTE    PAVG     - AGGRESSOR AVERAGE POWER (WATTS)
NOTE    BK       - BOLTZMANN CONSTANT (JOU/DEG KELVIN)
NOTE    FR       - NOISE FIGURE OF RWR RECEIVER
L       RCSG.K(J)=RCSG.J(J)-(DT)(RCSRWG.JK(J))                                  5.266
N       RCSG(J)=RCSGN(J)+SCLPRD(AGAWN(J,*),1,4,DRCSWG(*),1)                     5.267
T         RCSGN(*)=5/5/5/5                                                      5.268
R         RCSRWG.KL(J)=SCLPRD(AGAWR.JK(J,*),1,4,DRCSWG(*),1)                    5.269
T           DRCSWG(*)=.4/.3/.2/0                                                5.270
A       ERCSG.K(I,J)=RCSG.K(J)*RCSAGM(ATN.K(I,J))                               5.271

NOTE    RCSG     - AGGRESSOR AIRCRAFT RADAR CROSS SECTION (SQ.M.)
NOTE    RCSRWG   - AGGRESSOR RCS RATE OF CHANGE (SQ.M/SEC)
NOTE    RCSGN    - CLEAN AGGRESSOR AIRCRAFT RCS (SQ.M.)
NOTE    AGAWR    - AGGRESSOR AIRCRAFT WEAPONS (UNITS)
NOTE    DRSCWG   - DELTA RCS DUE TO AGGRESSOR AIRCRAFT WEAPONS CARRIAGE (SQ.M.)
NOTE    ERCSG    - EFFECTIVE AGGRESSOR AIRCRAFT RCS (SQ.M.)
NOTE    RCSAGM   - AGGRESSOR RCS ASPECT ANGLE MULTIPLIER (DIM.)

A       PDIRG.K(I,J)=IRDET(SNOISG.K(I,J))                                       5.272
A       SNOISG.K(I,J)=HTG.K(I,J)/NEI.K(I)                                       5.273
A         NEI.K(I)=NEIB(I)*NEINAM.K(I)                                          5.274
T         NEIB(*)=2E-10/2E-10/2E-10/2E-10                                       5.275
A         NEINAM.K(I)=TABHL(NEIMT(*),SUM(AGG.K),1,6,1)                          5.276
T           NEIMT(*)=1/.98/.95/.91/.88/.84                                      5.277
A         HTG.K(I,J)=JAG.K(I,J)*TAUG.K(I,J)/(RLOS.K(I,J)*100)**2                5.278
A           TAUG.K(I,J)=EXP(-ALPH(ALTG.K(J))*RLOS.K(I,J)/1000)                  5.279
A           JAG.K(I,J)=JTOTEG.K(J)*AF(TAA.K(I,J))                               5.280

NOTE    AF       - MACRO CORRECTING TARGET RADIANCE FOR ASPECT ANGLE
NOTE    JAG      - INFRARED RADIANCE CORRECTED BY ASPECT ANGLE
NOTE    HTG      - IRRADIANCE (W/SQ. CM.)
NOTE    TAUG     - RATIO OF TRANSMITTED RADIANT FLUX
NOTE    NEI      - NOISE EQUIVALENT IRRADIANCE OF SENSOR (W/SQ.CM.)
NOTE    NEIB     - BASELINE NEI (W/SQ. CM.)
NOTE    NEINAM   - NEI VS. NUMBER OF AGGRESSORS MULTIPLIER (DIM)

A       JTOTEG.K(J)=JEFFG.K(J)+JPEFFG.K(J)+JSEFFG.K(J)                          5.281
A       JEFFG.K(J)=SPECTR(EGTG.K(J),MUHIG1,MULOW1)*JEG.K(J)                     5.282
A       JEG.K(J)=EMM*SIG*EGTG.K(J)**4*AEG.K(J)/(4*PI)                           5.283
A         EGTG.K(J)=EGTGB(J)*TSEGTG.K(J)                                        5.284
T           EGTGB(*)=980/980/980/980                                            5.285
A         TSEGTG.K(J)=TABHL(TSEGGT(*),TSG.K(J),.5,1,.1)                         5.286
T           TSEGGT(*)=.6/.78/.86/.94/1/2                                        5.287
A         AEG.K(J)=AEGB(J)*TSAEMG.K(J)*NEG(J)                                   5.288
T           AEGB(*)=6030/6030/6030/6030                                         5.289
A           TSAEMG.K(J)=TABHL(TSAEGT(*),TSG.K(J),.5,1,.1)                       5.290
T           TSAEGT(*)=.9/.94/.97/.98/1/.96                                      5.291
T           NEG(*)=2/2/2/2                                                      5.292

NOTE    JTOTEG   - TOTAL EFFECTIVE RADIANCE (W/SR)
NOTE    JEFFG    - EFFECTIVE ENGINE RADIANCE (W/SR)
NOTE    JEG      - ENGINE RADIANCE (W/SR)
NOTE    EMM      - EMMISSITIVITY FACTOR (I.E. GRAY BODY=.9)
NOTE    EGTG     - ENGINE EXHAUST TEMPERATURE (DEGREES ABSOLUTE)
NOTE    EGTGB    - BASELINE EGT (DEGREES ABSOLUTE)
NOTE    TSEGTG   - THROTTLE SETTING EGT MULTIPLIER (DIM)
NOTE    AEG      - ENGINE EXHAUST AREA (SQ. CM.)
NOTE    AEGB     - BASELINE ENGINE EXHAUST AREA (SQ. CM)
NOTE    TSAEMG   - THROTTLE SETTING EXHAUST AREA MULTIPLIER (DIM)
NOTE    NEG      - NUMBER OF ENGINES (UNITS)

A       JPEFFG.K(J)=SPECTR(EGTG.K(J),MUHIG2,MULOW2)
X       *JPG.K(J)                                                               5.293
A       JPG.K(J)=.5*SIG*(0.85*EGTG.K(J))**4*APG.K(J)/(4*PI)                     5.294
A         APG.K(J)=APGB(J)*TSAPMG.K(J)                                          5.295
T           APGB(*)=2.54E4/2.54E4/2.54E4/2.54E4                                 5.296
A           TSAPMG.K(J)=TABHL(TSAPGM(*),TSG.K(J),.5,1,.1)                       5.297
T             TSAPGM(*)=.9/.94/.96/.99/1/25                                     5.298
C         MUHIG2=4.55                                                           5.299
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C         MULOW2=4.30                                                    5.300

NOTE      JPG       - PLUME RADIANCE (W/SR)
NOTE      JPEFFG    - EFFECTIVE PLUME RADIANCE (W/SR)
NOTE      APG       - EQUIVALENT EXHAUST TEMPERATURE SURFACE (SQ. CM)
NOTE      APGB      - BASELINE EXHAUST TEMP. SURFACE (SQ. CM)
NOTE      TSAPMG    - THROTTLE SETTING EXHAUST TEMP. SURFACE MULTIPLIER (DIM)
NOTE      MUHIG2    - UPPER LIMIT OF IR EMISSION BOUNDARY (MICRONS)
NOTE      MULOW2    - LOWER LIMIT OF IR EMISSION BOUNDARY (MICRONS)

A         JSEFFG.K(J)=SPECTR(TSTGG.K(J),MUHIG1,MULOW1)
X         *JSG.K(J)                                                      5.303
A           JSG.K(J)=EMM*SIG*(TSTGG.K(J)+273)**4*0.25*ASG.K(J)/(4*PI)    5.304
A             TSTGG.K(J)=TEMPG.K(J)*(1+R*(GAMA-1)*MACHG.K(J)**2/2)       5.305
N               ASG(J)=10**(C+LOGN(MAGN(J)**D)*(10000/10.7584)           5.306
C                 C=-0.1289                                              5.307
C                 D=0.7506                                               5.308

NOTE      JSEFF     - EFFECTIVE SKIN FRICTION RADIANCE (W/SR)
NOTE      JS        - SKIN FRICTION RADIANCE (W/SR)
NOTE      TSTAG     - STAGNATION TEMPERATURE (DEG ABSOLUTE)
NOTE      R         - FLOW RECOVERY FACTOR (.85 ASSUMED FOR MIXED FLOW)
NOTE      ASG       - AGGRESSOR AIRCRAFT SKIN WETTED AREA (SQ. CM.)

A          PATWL.K(I,J,K)=PAGGFE.K(I,J,K)*PAGTR.K(I,J)*AMICF.K(I,J,K)
X           *PCBFLA.K(I)                                                 5.309
A          PAGWL.K(I,J,L)=PCBFFE.K(I,J,L)*PATTR.K(I,J)*GMICF.K(I,J,L)
X             *PAGGLA.K(J)                                              5.309A
A           PAGGFE.K(I,J,K)=BINARY(RLOS.K(I,J),MAAMLE.K(I,J,K))         5.310
A           PCBFFE.K(I,J,L)=BINARY(RLOS.K(I,J),MIGMLE.K(I,J,L))         5.310A

NOTE      PATWL     - PROB. CBF WEAPONS LAUNCH (DIM)
NOTE      PCBFLA- PROB. OF CBF IN LAUNCH ATTITUDE (DIM)
NOTE      PAGGFE    - PROB. OF AGGRESSOR IN FIRING ENVELOPE OF WEAPON K
NOTE      PCBFT     - PROB. OF CBF IN LAUNCH ATTITUDE (DIM)
NOTE      PAGWL     - PROB. OF AGGRESSOR WEAPONS LAUNCH (DIM)
NOTE      PCBFFE    - PROB. OF CBF IN FIRING ENVELOPE OF WEAPON L
NOTE      PAGAT     - PROB. OF AGGRESSOR IN LAUNCH ATTITUDE (DIM)

A          PAGTR.K(I,J)=CLIP(1,0,PGRD.K(I,J),0.8)*CLIP(1,0,THETAA(I)/2
X          ,MAX(ATN.K(I,J),-ATN.K(I,J)))*ABSLAM.K(I,J)                  5.311
A          ABSLAM.K(I,J)=MABSLA(ATN.K(I,J),THETAA(I))
A          PATTR.K(I,J)=CLIP(1,0,PARD.K(I,J),0.8)*CLIP(1,0,THETGA(J)/2
X           ,MAX(TAA.K(I,J),-TAA.K(I,J)))*ABSLGM.K(I,J)                 5.311A
A          ABSLGM.K(I,J)=MABSLA(TAA.K(I,J),THETGA(J))

A            PCBFE.K(I,J,K)=PALOS.K(I,J)*PAGGD.K(I,J)*PATWL.K(I,J,K)*
X            PCBWSG.K(I,J,K)*PCBWDE.K(I,J,K)
A            PAGGE.K(I,J,L)=PALOS.K(I,J)*PCBFD.K(I,J)*PAGWL.K(I,J,L)*
X            PAGWSG.K(I,J,L)*PAGWDE.K(I,J,L)

NOTE      PALOS     - PROBABILITY OF AGGRESSOR AIRCRAFT IN LINE OF SIGHT (DIM)
NOTE      PAGGD     - PROBABILITY OF AGGRESOR DETECTION (DIM)
NOTE      PATWL     - PROBABILITY OF CBF WEAPONS LAUNCH (DIM)
NOTE      PCBWSG    - PROBABILITY OF CBF WEAPON SUCCESSFUL GUIDANCE (DIM)
NOTE      PCBWDE    - PROBABILITY OF CBF WEAPON DETONATION (DIM)
NOTE      PGLOS     - PROBABILITY OF CBF IN LINE OF SIGHT (DIM)
NOTE      PCBFD     - PROBABILITY OF CBF DETECTION (DIM)
NOTE      PAGWL     - PROBABILITY OF AGGRESSOR WEAPONS LAUNCH (DIM)
NOTE      PAGWSG    - PROBABILITY OF AGGRESSOR WEAPON SUCCESSFUL GUIDANCE (DIM)
NOTE      PAGWDE    - PROBABILITY OF AGGRESSOR WEAPON DETONATION (DIM)

A            PALOS.K(I,J)=LOS(ALT.K(I),RLOS.K(I,J))
A            PASSK.K(L)=PASSKB(L)                                        5.386
T            PASSKB(*)=0.3/.25/.2/.001                                   5.387
A            PGSSK.K(K)=PGSSKB(K)                                        5.386A
T            PGSSKB(*)=.3/.25/.2/.001                                    5.387A

NOTE      PALOS     - PROBABILITY OF LINE OF SIGHT (DIM)
NOTE      PASSK     - PROBABILITY OF SINGLE SHOT KILL OF CBF (DIM)
NOTE      PGSSK     - PROBABILITY OF SINGLE SHOT KILL OF AGGRESSOR (DIM)
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A       PAGGD.K(I,J)=MAX(PDIRG.K(I,J),PGRD.K(I,J))
A       PCBFD.K(I,J)=MAX(PDIR.K(I,J),PARD.K(I,J))

NOTE    PAGGD   - PROB. OF AGGRESSOR BEING DETECTED (DIM)
NOTE    PCBFD   - PROB. OF CBF BEING DETECTED (DIM)

A       PCBWSG.K(I,J,K)=(1-CAIME.K(I,J))*AGAC.K(I,J,K)*(1-AGCM.K(J,K))
X       *PCLOH.K(I,J,K)                                                    5.343
A       CAIME.K(J,K)=AIMEK(K)*(1-NCOMG.K(J)**Z)                            5.344
T       AIMEK(*)=.016/-.0116/-.0116/-.020
C       Z=1.5                                                              5.346

NOTE    CAIME   - CBF AIRCRAFT WEAPON AIMING ERROR (DIM)
NOTE    AIMEK   - AIMING ERROR CONSTANT
NOTE    NCOMG   - AGGRESSOR COMMANDED LOAD FACTOR (G)
NOTE    Z       - AIMING ERROR GROWTH FACTOR CONSTANT

A       AGAC.K(I,J,K)=AGMC.K(J,K)*AGWC.K(I,J,K)                            5.348
A       AGMC.K(J,K)=TABHL(AGMCT(*,K),SAIG1M.K(J)/SAIWEA(K),0,2,.2)         5.348
T       AGMCT(*,1)=1/.99/.97/.93/.86/.5/.22/.11/.06/.03/0                  5.349
T       AGMCT(*,2)=1/.99/.97/.93/.86/.5/.22/.11/.06/.03/0                  5.350
T       AGMCT(*,3)=1/.99/.97/.93/.86/.5/.22/.11/.06/.03/0                  5.351
T       AGMCT(*,4)=1/1/1/1/1/1/1/1/1/1/1                                   5.352
N       SAIWEA(K)=YAWRTE(ANMIS(K),AMAS(K))*57.29                           5.353
T       ANMIS(*)=30/25/25/100                                              5.354
A       AGWC.K(I,J,K)=SAWE(MTOFA.K(I,J,K),AGIJRT(K))                       5.355
T       AGIJRT(*)=5/5/3/1.5                                                5.356

NOTE    AGAC    - AGGRESSOR AIRCRAFT AVOIDANCE CAPABILITY (DIM)
NOTE    AGMC    - AGGRESSOR AIRCRAFT MANEUVERING CAPABILITY (DIM)
NOTE    AGWC    - AGGRESSOR AIRCRAFT WARNING CAPABILITY (DIM)
NOTE    SAIG1M- AGGRESSOR AIRCRAFT MAXIMUM SUSTAINED LOAD FACTOR (G)
NOTE    SAIWEA- WEAPON MAXIMUM LOAD FACTOR (G)
NOTE    ANMIS   - MAXIMUM CBF WEAPON NORMAL LOAD FACTOR (G)
NOTE    AMAS    - AVERAGE CBF WEAPON SPEED (M/SEC.)
NOTE    AGIJRT- AGGRESSOR AIRCRAFT CREW PERCEPTION-IDENTIFICATION-
NOTE        RESCTION TIME (SEC.)

A       AGCM.K(J,K)=TABHL(AGCMT(*,K),NEXLG.K(J,K),0.0,4.0,0.5)             5.359
T       AGCMT(*,1)=0/.02/.05/.07/.1/.13/.15/.16/.17                        5.360
T       AGCMT(*,2)=0/.02/.05/.07/.1/.13/.15/.16/.17                        5.361
T       AGCMT(*,3)=0/.018/.035/.045/.06/.075/.088/.095/.10                 5.362
T       AGCMT(*,4)=0/0/0/0/0/0/0/0/0                                       5.363
L     NEXPG.K(J,K)=NEXPG.J(J,K)-(DT)(DEXPG.JK(J,K))                        5.364
N     NEXPG(J,K)=NEXPGN(J,*)                                               5.365
T       NEXPGN(*,1)=50/50/50/50                                            5.366
T       NEXPGN(*,2)=50/50/50/50                                            5.367
T       NEXPGN(*,3)=100/100/100/100                                        5.368
T       NEXPGN(*,4)=0/0/0/0                                                5.369
R     DEXPG.KL(J,K)=MIN(NEXPG.K(J,K)/DT,MNEXRG(J,K)*SUMV(PATWL.K(*,J,K)
X       ,1,II))*CLIP(0,1,0.90,SUMV(PATWL.K(*,J,K),1,II)/II)                5.370
T       MNEXRG(*,1)=.5/.5/.5/.5                                            5.371
T       MNEXRG(*,2)=.5/.5/.5/.5                                            5.372
T       MNEXRG(*,3)=.5/.5/.5/.5                                            5.373
T       MNEXRG(*,4)=0/0/0/0                                                5.374
L     GWEXP.K(J)=GWEXP.J(J)-(DT)(GWEXPR.JK(J))                             5.375
N     GWEXP(J)=SCLPRD(NEXPGN(J,*),1,KK,UWEXPG(*),1)                        5.376
T       UWEXPG(*)=1/1/1/0                                                  5.377
R     GWEXPR.KL(J)=SCLPRD(DEXPG.JK(J,*),1,KK,UWEXPG(*),1)                  5.378
A     NEXLG.K(J,K)=DEXPG.JK(J,K)                                           5.379

NOTE    NEXPC   - NUMBER OF CBF EXPENDABLES (CARTRIDGES)
NOTE    NEXPCN  - INITIAL NUMBER OF EXPENDABLES (CARTRIDGES)
NOTE    DEXPC   - RATE OF CHANGE OF EXPENDABLES (CARTRIDGES/SEC.)
NOTE    CWEXP   - CBF TOTAL EXPENDABLE MASS (KG.)
NOTE    UWEXPC  - CBF EXPENDABLE CARTRIDGE MASS (KG/CARTRIDGE)
NOTE    CWEXPR  - CBF EXPENDABLE MASS RATE OF CHANGE (KG./SEC)
NOTE    MNEXRC  - DESIRED EXPENDABLE LAUNCH RATE (CARTRIDGES PER SECOND)
NOTE    NEXLC   - NUMBER OF EXPENDABLES LAUNCHED PER SIMULATION INTERVAL
NOTE        (CARTRIDGES/DT)

A       PCLOH.K(I,J,K)=1-LOCK(K)*ATN.K(I,J)/57.29                          5.381
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T       LOCK(*)=.25/.25/.31/0                                                    5.382

NOTE    PCLOH   - CBF WEAPON LOCK-ON AND HOMING CAPABILITY (DIM)
NOTE    LOCK    - CBF WEAPON LOCK-ON AND HOMING CONSTANT (DIM)
NOTE    ATN     - TARGET ASPECT ANGLE (DEG.)

A       PCBWDE.K(I,J,K)=1-KDETC(K)*(ATN.K(I,J)/57.29)*(ATN.K(I,J)/57.29)         5.384
T       KDETC(*)=.09/.09/.10/0                                                   5.385

NOTE    PCBWDE  - PROBABILITY OF CBF WEAPON DETONATION (DIM)
NOTE    KDETC   - CBF WEAPON DETONATION CONSTANT (DIM)
NOTE    ATN     - TARGET ASPECT ANGLE MEASURED FROM CBF AIRCRAFT (DEG.)

A       PAGWSG.K(I,J,L)=(1-GAIME.K(I,J))*CBAC.K(I,J,L)*(1-CBCM.K(I,L))
X       *PGLOH.K(I,J,L)                                                          5.343A
A       GAIME.K(I,L)=GIMEK(L)*(1-NCOM.K(I)**ZG)                                  5.344A
T       GIMEK(*)=-.08/-.08/-.08/-.085                                            5.345A
C       ZG=1.5                                                                   5.346A

NOTE    GAIME   - AGG AIRCRAFT WEAPON AIMING ERROR (DIM)
NOTE    GIMEK   - AGG AIRCRAFT AIMING ERROR CONSTANT
NOTE    NCOM    - CBF COMMANDED LOAD FACTOR (G)
NOTE    ZG      - AIMING ERROR GROWTH FACTOR CONSTANT

A       CBAC.K(I,J,L)=CBMC.K(I,L)*CBWC.K(I,J,L)                                  5.348A
A       CBMC.K(I,L)=TABHL(CBMCT(*,L),SAI1M.K(I)/SAIWEC(L),0,2,.2)                5.349A
T       CBMCT(*,1)=1/.99/.97/.93/.86/.5/.22/.11/.06/.03/0                        5.350A
T       CBMCT(*,2)=1/.99/.97/.93/.86/.5/.22/.11/.06/.03/0                        5.351A
T       CBMCT(*,3)=1/.99/.97/.93/.86/.5/.22/.11/.06/.03/0                        5.352A
T       CBMCT(*,4)=1/1/1/1/1/1/1/1/1/1/1                                         5.353A
N       SAIWEC(L)=YAWRTE(GNMIS(L),GMAS(L))*57.29                                 5.354A
T       GNMIS(*)=30/25/25/100                                                    5.355A
A       CBWC.K(I,J,L)=SAWE(MTOFG.K(I,J,L),CBIJRT(L))                             5.357A
T       CBIJRT(*)=5/5/3/1.5                                                      5.358A

NOTE    CBAC    - CBF AIRCRAFT AVOIDANCE CAPABILITY (DIM)
NOTE    CBMC    - CBF AIRCRAFT MANEUVERING CAPABILITY (DIM)
NOTE    CBWC    - CBF AIRCRAFT WARNING CAPABILITY (DIM)
NOTE    SAI1M   - CBF AIRCRAFT MAXIMUM SUSTAINED LOAD FACTOR (G)
NOTE    SAIWEC- CBF AIRCRAFT WEAPON MAXIMUM LOAD FACTOR (G)
NOTE    GNMIS   - MAXIMUM AGG WEAPON NORMAL LOAD FACTOR (G)
NOTE    GMAS    - AVERAGE AGG WEAPON SPEED (M/SEC.)
NOTE    CBIJRT- CBF CREW PERCEPTION-IDENTIFICATION-JUDGMENT-
NOTE        REACTION TIME (SEC.)

A       CBCM.K(I,L)=TABHL(CBCMT(*,L),NEXLC.K(I,L),0.0,4.0,0.5)                   5.359A
T       CBCMT(*,1)=0/.02/.05/.07/.1/.13/.15/.16/.17                              5.360A
T       CBCMT(*,2)=0/.02/.05/.07/.1/.13/.15/.16/.17                              5.361A
T       CBCMT(*,3)=0/.018/.035/.045/.06/.075/.088/.095/.10                       5.362A
T       CBCMT(*,4)=0/0/0/0/0/0/0/0/0                                             5.363A
L   NEXPC.K(I,L)=NEXPC.J(I,L)-(DT)(DEXPC.JK(I,L))                               5.364A
N   NEXPC(I,L)=NEXPCN(I,*)                                                      5.365A
T       NEXPCN(*,1)=50/50/50/50                                                  5.366A
T       NEXPCN(*,2)=50/50/50/50                                                  5.367A
T       NEXPCN(*,3)=100/100/100/100                                              5.368A
T       NEXPCN(*,4)=0/0/0/0                                                      5.369A
R       DEXPC.KL(I,L)=MIN(NEXPC.K(I,L)/DT,MNEXRC(I,L)*SUMV(PAGWL.K(I,*,L)
X       ,1,JJ))*CLIP(0,1,0.90,SUMV(PAGWL.K(I,*,L),1,JJ)/JJ)                      5.370A
T       MNEXRC(*,1)=.5/.5/.5/.5                                                  5.371A
T       MNEXRC(*,2)=.5/.5/.5/.5                                                  5.372A
T       MNEXRC(*,3)=.5/.5/.5/.5                                                  5.373A
T       MNEXRC(*,4)=0/0/0/0                                                      5.374A
L   CWEXP.K(I)=CWEXP.J(I)-(DT)(CWEXPR.JK(I))                                    5.375A
N   CWEXP(I)=SCLPRD(NEXPCN(I,*),1,LL,UWEXPC(*),1)                              5.376A
T       UWEXPC(*)=1/1/1/0                                                        5.377A
R       CWEXPR.KL(I)=SCLPRD(DEXPC.JK(I,*),1,LL,UWEXPC(*),1)                      5.378A
A   NEXLC.K(I,L)=DEXPC.JK(I,L)                                                  5.379A

NOTE    NEXPC   - NUMBER OF CBF EXPENDABLES (CARTRIDGES)
NOTE    NEXPCN  - INITIAL NUMBER OF EXPENDABLES (CARTRIDGES)
NOTE    DEXPC   - RATE OF CHANGE OF EXPENDABLES (CARTRIDGES/SEC.)
NOTE    CWEXP   - CBF TOTAL EXPENDABLE MASS (KG.)
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NOTE    UWEXPC  -  CBF EXPENDABLE CARTRIDGE MASS (KG/CARTRIDGE)
NOTE    CWEXPR  -  CBF EXPENDABLE MASS RATE OF CHANGE (KG./SEC)
NOTE    MNEXRC  -  DESIRED EXPENDABLE LAUNCH RATE (CARTRIDGES PER SECOND)
NOTE    NEXLC   -  NUMBER OF EXPENDABLES LAUNCHED PER SIMULATION INTERVAL
NOTE               (CARTRIDGES/DT)

A        PGLOH.K(I,J,L)=1-LOCKG(L)*TAA.K(I,J)/57.29                          5.381A
T        LOCKG(*)=.25/.25/.31/0                                              5.382A

NOTE    PGLOH   -  AGG WEAPON LOCK-ON AND HOMING CAPABILITY (DIM)
NOTE    LOCKG   -  AGG WEAPON LOCK-ON AND HOMING CONSTANT (DIM)
NOTE    TAA     -  TARGET ASPECT ANGLE (DEG.)
A          PAGWDE.K(I,J,L)=1-KDETG(L)*(TAA.K(I,J)/57.29)*(TAA.K(I,J)/57.29) 5.384A
T          KDETG(*)=1.52E-2/1.52E-2/2.53E-2/0                               5.385A

NOTE    PAGWDE  -  PROBABILITY OF AGG WEAPON DETONATION (DIM)
NOTE    KDETG   -  AGG WEAPON DETONATION CONSTANT (DIM)
NOTE    TAA     -  TARGET ASPECT ANGLE MEASURED FROM AGG AIRCRAFT (DEG.)
NOTE    ZDETG   -  AGG WEAPON GROWTH FACTOR (DIM)

C        G=9.81
C        TMULT=1.0
A        T.K(I)=TS.K(I)*THRUST.K(I)*G*NE(I)                                  5.414
A        THRUST.K(I)=CLIP(THAB.K(I),THNAB.K(I),TS.K(I),.9)*TMULT             5.415
A        THNAB.K(I)=TABHL(THNABT(*),MACH.K(I),0,2,.2)*DELTA.K(I)**1.23496    5.416
T        THNABT(*)=5320/5177/5242/5465/5795/6183/6578/6930/7190/7307/7231    5.417
A        THAB.K(I)=TABHL(THABT(*),MACH.K(I),0,2,.2)*DELTA.K(I)**1.23496      5.418
T        THABT(*)=8131/7793/7851/8248/8876/9625/10388/11056/11523/11678/11415 5.419

NOTE    T       -  ENGINE THRUST (NEWTONS)
NOTE    THRUST  -  ENGINE THRUST (KG.) CORRECTED BY DENSITY EFFECTS
NOTE    THNAB   -  NON-AFTERBURNING ENGINE THRUST (KG.) CORRECTED BY SPEED
NOTE    THAB    -  FULL AFTERBURNING ENGINE THRUST (KG.) CORRECTED BY SPEED

R           FFLOW.KL(I)=T.K(I)*SFC.K(I)/G                                    5.420
A             SFC.K(I)=CLIP(SAB.K(I),SNAB.K(I),TS.K(I),.9)/3600              5.421
A             SAB.K(I)=TABHL(SABT(*),MACH.K(I),0,2.0,.2)*SABM.K(I)           5.422
T             SABT(*)=1.6/1.67/1.70/1.72/1.70/1.73/1.75/1.79/1.84/1.89/1.96  5.423
A             SABM.K(I)=TABHL(SABMT(*),ALT.K(I),0,18000,3000)                5.424
T             SABMT(*)=1/.95/.94/.97/1.02/1.13/1.34                          5.425
A             SNAB.K(I)=TABHL(SNABT(*),MACH.K(I),0,2.0,.2)*SNABM.K(I)        5.426
T             SNABT(*)=.90/.91/.92/.94/.96/.98/1.03/1.08/1.14/1.20/1.30      5.427
A             SNABM.K(I)=TABHL(SNABMT(*),ALT.K(I),0,18000,3000)              5.428
T             SNABMT(*)=1/.94/.89/.87/.89/.99/1.09                           5.429

NOTE    SFC     -  ENGINE THRUST SPECIFIC FUEL CONSUMPTION (KG/KG/HR)
NOTE    SAB     -  AFTERBURNING TSFC CORRECTED BY MACH NO. AND ALTITUDE
NOTE    SNAB    -  NON-AFTERBURNING TSFC CORRECTED BY MACH NO. AND ALTITUDE
NOTE    SABM    -  AFTERBURNING TSFC ALTITUDE CORRECTION MULTIPLIER (DIM)
NOTE    SNABM   -  NON-AFTERBURNING TSFC ALTITUDE CORRECTION FACTOR MULT.(DIM)

L        FUEL.K(I)=FUEL.J(I)-(DT)(FFLOW.JK(I))                               5.430
N          FUEL(I)=FUELN(I)                                                  5.431
T          FUELN(*)=7000/7000/7000/7000                                      5.432
A          FUELR.K(I)=FUEL.K(I)/FUELN(I)                                     5.433

A       NAMAX.K(I)=LOADF(Q.K(I),WK.K(I),WINGK(I),TH.K(I),S(I),CDO.K(I)
X       ,NSTRUC(I))                                                          5.446
A       NTMAX.K(I)=LOADF(Q.K(I),WK.K(I),WINGK(I),TH.K(I),S(I),CDO.K(I)
X       ,NSTRUC(I))                                                          5.446.1
T          NSTRUC(*)=7/7/7/7                                                 5.447
A       CLNAX.K(I)=2*NAMAX.K(I)*WK.K(I)*G/(Q.K(I)*S(I))                      5.448
A       CL1.K(I)=MIN(CLMAX.K(I),CLNAX.K(I))                                  5.449
A          CLMAX.K(I)=CLMAXA(I)                                              5.450
T           CLMAXA(*)=1.5/1.5/1.5/1.5                                        5.451
A       N1.K(I)=Q.K(I)*S(I)*CL1.K(I)/(WK.K(I)*G)                             5.452
A       SAI1M.K(I)=YAWRTE(N1.K(I),V.K(I))*57.29                              5.453
A       SAICO.K(I)=MIN(SAI1M.K(I),ABS(RSAIA.JK(I)))                          5.454
A       NCOM.K(I)=SQRT(1+(SAICO.K(I)*V.K(I)/(G*57.29))**2)                   5.455
A       CL.K(I)=NCOM.K(I)*WK.K(I)*G/(Q.K(I)*S(I))                            5.456
A       VC.K(I)=SQRT(2*NSTRUC(*)*G*WK.K(I)/(RHO*SGMA.K(I)*S(*)
X         *CLMAX.K(*)))                                                      5.457
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A       SAIMM.K(I)=YAWRTE(NTMAX.K(I),V.K(I))*57.29                          5.457.1

NOTE    NAMAX   - MAXIMUM LOAD FACTOR
NOTE     NTMAX - MAXIMUM POTENTIALLY AVAILABLE LOAD FACTOR IF MAX THRUST
NOTE          IS APPLIED INSTANTANEOUSLY
NOTE    CLNAX   - MAXIMUM LIFT COEFFICIENT AVAILABLE FOR TURNING AT NAMAX
NOTE    CL1     - MAXIMUM LIFT COEFFICIENT CONSTRAINED DUE TO TURN OR
NOTE              MAXIMUM FLOW SEPARATION CHARACTERISTICS
NOTE    N1      - LOAD FACTOR CONSTRAINED BY THIS LIFT COEFFICIENT
NOTE    SAI1M   - MAXIMUM USABLE TURN RATE CAPABILITY CONSTRAINED BY N1
NOTE    SAICO   - DESIRED TURN RATE (CONSTRAINED BY NAVIGATION SCHEME)
NOTE    NCOM    - LOAD FACTOR CORRESPONDING THE DESIRED TURN RATE
NOTE    CL      - CL AT DESIRED LOAD FACTOR
NOTE    VC      - CBF CORNER SPEED (M/S)

A        D.K(I)=Q.K(I)*S(I)*CD.K(I)
T          S(*)=40/40/40/40                                                 5.434
A          Q.K(I)=.5*P0*GAMA*DELTA.K(I)*MACH.K(I)**2                        5.444
C            P0=1.013E5                                                     5.405
C            RHO=1.125                                                      5.406
C            GAMA=1.4                                                       5.407
C            T0=288.2                                                       5.408
A            MACH.K(I)=V.K(I)/SSOUND(ALT.K(I))                              5.413

NOTE    M       - AIRCRAFT MASS (KGS)
NOTE    MN      - INITIAL AIRCRAFT MASS (KGS)
NOTE    FFLOW   - ENGINE FUEL FLOW (KGS/SEC)
NOTE    SFC     - ENGINE SPEFICIC FUEL CONSUMPTION (N/N/SEC)
NOTE    D       - AIRCRAFT TOTAL DRAG (NEWTONS)
NOTE    Q       - DYNAMIC PRESSURE TERM (PA)
NOTE    P0      - SEA LEVEL STANDARD PRESSURE (PA)
NOTE    GAMMA   - RATIO OF SPECIFIC HEATS (DIM)
NOTE    DELTA   - ATMOSPHERIC PRESSURE RATIO (DIM)
NOTE    T0      - SEA LEVEL STANDARD TEMPERATURE (DEG KELVIN)

A        TEMP.K(I)=TEM(ALT.K(I))                                            5.401
A          THE.K(I)=TEMP.K(I)/T0                                            5.402
A          DELTA.K(I)=PRATIO(ALT.K(I))                                      5.403
A        SGMA.K(I)=SIGM(DELTA.K(I),THE.K(I))                                5.404

A        CD.K(I)=CDLI.K(I)+CDI.K(I)                                         5.437
A        CDLI.K(I)=CDO.K(I)+CDC(I)+CDW(I)+SCLPRD(CBFW.K(I,*),1,4,CDWEAP,1)  5.438
A        CDI.K(I)=CL.K(I)**2/(PI*AR(I)*EFF(I))                              5.439
A        CDO.K(I)=TABHL(CDOT(*),MACH.K(1),0,2,.1)+MULT                      5.440
T        CDOT(*)=.011/.011/.011/.011/.011/.011/.011/.011/.011/.012/.02/.023
X        /.024/.023/.022/.021/.0205/.0203/.02/.0205/.022                    5.441
T        CDWEAP(*)=.002/.0015/.001/0                                        5.442

NOTE    NA      - CBF MAXIMUM AVAILABLE LOAD FACTOR FOR MANEUVERING
NOTE    TEMP    - ATMOSPHERIC TEMPERATURE (DEG. KELVIN)
NOTE    T       - ENGINE THRUST (NEWTONS)
NOTE    THE     - TEMPERATURE RATIO AT FLIGHT ALTITUDE (DIM)
NOTE    SIGM    - DENSITY RATIO (DIM)
NOTE    CD      - TOTAL DRAG COEFFICIENT (DIM)
NOTE    CD0     - ZERO LIFT DRAG COEFFICIENT (DIM)
NOTE    CDI     - INDUCED DRAG COEFFICIENT (DIM)

C        PI=3.14159
T        AR(*)=3.5/3.5/3.5/3.5                                              5.435
T        EFF(*)=.79/.79/.79/.79                                             5.436
N        WINGK(I)=1/(PI*EFF(I)*AR(I))
NOTE

NOTE    TEMP    - ATMOSPHERIC TEMPERATURE (DEGREES ABSOLUTE)
NOTE    CD      - TOTAL DRAG COEFFICIENT (DIM)
NOTE    CDI     - INDUCED DRAG COEFFICIENT (DIM)
NOTE    CDO     - ZERO LIFT DRAG COEFFICIENT (DIM)
NOTE    CDC     - COMPRESSIBILITY DRAG COEFFICIENT (DIM)
NOTE    CDW     - WAVE DRAG COEFFICIENT (DIM)

A        CLALP.K(I)=TABHL(CLALT,MACH.K(I),0,2,.4)                           5.457
T        CLALT=4.2/3.5/4.8/3.7/3.1/2.4                                      5.458
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T       ALPO(*)=.015/.015/.15/.15                                          5.459
A       ALP.K(I)=(CL.K(I)/CLALP.K(I))+ALPO(I)                              5.460

NOTE    CLALP   - COMPLETE CBF AIRCRAFT WING LIFT CURVE SLOPE (1/RAD)
NOTE    CLALT   - NUMERICAL VALUES FOR CLALP (1/RAD)
NOTE    ALPO    - ZERO LIFT ANGLE OF ATTACK (RAD)
NOTE    ALP     CBF AIRCRAFT ANGLE OF ATTACK (RAD)

A       PDIR.K(I,J)=IRDET(SNOISE.K(I,J))                                   5.272A
A       SNOISE.K(I,J)=HT.K(I,J)/NEIG.K(J)                                  5.273A
A         NEIG.K(J)=NEIGB(J)*NEINAG.K(J)                                   5.274A
T         NEIGB(*)=2E-10/2E-10/2E-10/2E-10                                 5.275A
A         NEINAG.K(J)=TABHL(NEIGMT(*),SUM(CBF.K),1,6,1)                    5.276A
T         NEIGMT(*)=1/.98/.95/.91/.88/.84                                  5.277A
A       HT.K(I,J)=JA.K(I,J)*TAU.K(I,J)/(RLOS.K(I,J)*100)**2                5.278A
A       TAU.K(I,J)=EXP(-ALPH(ALT.K(I))*RLOS.K(I,J)/1000)                   5.279A
A       JA.K(I,J)=JTOTE.K(I)*AF(ATN.K(I,J))                                5.280A

NOTE    AF      - MACRO CORRECTING TARGET RADIANCE FOR ASPECT ANGLE
NOTE    JA      - INFRARED RADIANCE CORRECTED BY ASPECT ANGLE
NOTE    HT      - IRRADIANCE (W/SQ. CM.)
NOTE    TAU     - RATIO OF TRANSMITTED RADIANT FLUX
NOTE    NEIG    - NOISE EQUIVALENT IRRADIANCE OF AGG IR SENSOR (W/SQ.CM.)
NOTE    NEIGB   - BASELINE NEI (W/SQ. CM.)
NOTE    NEINAG  - NEI VS. NUMBER OF AGGRESSORS MULTIPLIER (DIM)

A       JTOTE.K(I)=JEFF.K(I)+JPEFF.K(I)+JSEFF.K(I)                         5.281A
A       JEFF.K(I)=SPECTR(EGT.K(I),MUHIG1,MULOW1)*JE.K(I)                   5.282A
C         MUHIG1=5
C         MULOW1=3
A       JE.K(I)=EMM*SIG*EGT.K(I)**4*AE.K(I)/(4*PI)                         2.83A
A         EGT.K(I)=EGTB(I)*TSEGTM.K(I)                                     5.284A
T           EGTB(*)=980/980/980/980                                        5.285A
C           SIG=5.67E-12                                                   5.286A
C           EMM=0.9                                                        5.287A
A         TSEGTM.K(I)=TABHL(TSEGTT(*),TS.K(I),.5,1,.1)                     5.288A
T           TSEGTT(*)=.6/.78/.86/.94/1/2                                   5.289A
A         AE.K(I)=AEB(I)*TSAEM.K(I)*NE(I)                                  5.290A
T           AEB(*)=5030/5030/5030/5030                                     5.291A
A           TSAEM.K(I)=TABHL(TSAEMT(*),TS.K(I),.5,1,.1)                    5.292A
T           TSAEMT(*)=.9/.94/.97/.98/1/.96                                 5.293A
T           NE(*)=2/2/2/2                                                  5.294A

NOTE    JTOTE   - TOTAL EFFECTIVE RADIANCE (W/SR)
NOTE    JEFF    - EFFECTIVE ENGINE RADIANCE (W/SR)
NOTE    JE      - ENGINE RADIANCE (W/SR)
NOTE    EMM     - EMMISSITIVITY FACTOR (I.E. GRAY BODY=.9)
NOTE    EGT     - ENGINE EXHAUST TEMPERATURE (DEGREES ABSOLUTE)
NOTE    EGTB    - BASELINE EGT (DEGREES ABSOLUTE)
NOTE    TSEGT   - THROTTLE SETTING EGT MULTIPLIER (DIM)
NOTE    AE      - ENGINE EXHAUST AREA (SQ. CM.)
NOTE    AEB     - BASELINE ENGINE EXHAUST AREA (SQ. CM)
NOTE    TSAEM   - THROTTLE SETTING EXHAUST AREA MULTIPLIER (DIM)
NOTE    NE      - NUMBER OF ENGINES (UNITS)

A         JPEFF.K(I)=SPECTR(EGT.K(I),MUHIG2,MULOW2)*JP.K(I)                5.293A
A         JP.K(I)=.5*SIG*(0.85*EGT.K(I))**4*AP.K(I)/(4*PI)                 5.294A
A           AP.K(I)=APB(I)*TSAPM.K(I)                                      5.295A
T             APB(*)=2.04E4/2.04E4/2.04E4/2.04E4                           5.296A
A             TSAPM.K(I)=TABHL(TSAPMT(*),TS.K(I),.5,1,.1)                  5.297A
T               TSAPMT(*)=.9/.94/.96/.98/1/25                              5.298A

NOTE    JP      - PLUME RADIANCE (W/SR)
NOTE    JPEFF   - EFFECTIVE PLUME RADIANCE (W/SR)
NOTE    AP      - EQUIVALENT EXHAUST TEMPERATURE SURFACE (SQ. CM)
NOTE    APB     - BASELINE EXHAUST TEMP. SURFACE (SQ. CM)
NOTE    TSAPM   - THROTTLE SETTING EXHAUST TEMP. SURFACE MULTIPLIER (DIM)

A         JSEFF.K(I)=SPECTR(TSTAG.K(I),MUHIG1,MULOW1)*JS.K(I)              5.303A
A         JS.K(I)=EMM*SIG*(TSTAG.K(I)+273)**4*0.25*AS(I)/(4*PI)            5.304A
A           TSTAG.K(I)=TEMP.K(I)*(1+R*(GAMA-1)*MACH.K(I)**2/2)             5.305A
C             R=.85                                                        5.306A
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N       AS(I)=10**(C+LOGN(IM(I)**D1))*(10000/10.7584)                    5.307A
C       C=-.1289                                                         5.308A
C       D1=.7506                                                         5.309A

NOTE    JSEFF   - EFFECTIVE SKIN FRICTION RADIANCE (W/SR)
NOTE    JS      - SKIN FRICTION RADIANCE (W/SR)
NOTE    TSTAG   - STAGNATION TEMPERATURE (DEG ABSOLUTE)
NOTE    R       - FLOW RECOVERY FACTOR (.85 ASSUMED FOR MIXED FLOW)
NOTE    AS      - AIRCRAFT SKIN WETTED AREA (SQ. CM.)
NOTE    C AND D- REGRESSION COEFFICIENTS OF MTOW VS. WETTED AREA CURVE

A       ALTG.K(J)=TABHL(ALTTG,XAG.K(J)/1000,0,500,50)
T       ALTTG=6000/6000/6000/6000/6000/6000/6000/6000/6000/6000/6000
L       VAG.K(J)=VAG.J(J)+(DT)(ACCAG.JK(J))
N       VAG(J)=VAGN(J)
T       VAGN(*)=230/230/230/230
R       ACCAG.KL(J)=(TG.K(J)*COS(ALPG.K(J)+SIGMAG(J))-DAG.K(J))/MAG.K(J)
T       SIGMAG(*)=.01/.01/.01/.01

NOTE    X       - DOWNRANGE (METERS)
NOTE    Y       - LATERAL RANGE (METERS)
NOTE    V       - AIRCRAFT BODY/WIND AXES VELOCITY VECTOR (METERS/SEC)
NOTE    VN      - INITIAL AIRCRAFT SPEED (M/SEC)

NOTE    SAI     - HEADING ANGLE (DEGREES)
NOTE    SAIN    - INITIAL HEADING ANGLE (DEGREES)
NOTE    TS      - THROTTLE SETTING (DIM)

R       FFLOWG.KL(J)=TG.K(J)*SFCG.K(J)/G                                 5.420A
A       SFCG.K(J)=CLIP(SABG.K(J),SNABG.K(J),TSG.K(J),.9)/3600            5.421A
A       SABG.K(J)=TABHL(SABGT(*),MACHG.K(J),0,2,.2)*SABGM.K(J)           5.422A
T       SABGT(*)=1.8/1.87/1.90/1.92/1.90/1.93/1.95/1.99/2.04/2.08/2.12   5.423A
A       SABGM.K(J)=TABHL(SABGMT(*),ALTG.K(J),0,18000,3000)               5.424A
T       SABGMT(*)=1/.95/.94/.97/1.02/1.13/1.34                           5.425A
A       SNABG.K(J)=TABHL(SNABGT(*),MACHG.K(J),0,2,.2)*SNABGM.K(J)        5.426A
T       SNABGT(*)=1.05/1.06/1.07/1.09/1.11/1.14/1.19/1.25/1.32/1.40/1.50 5.427A
A       SNABGM.K(J)=TABHL(SNBGMT(*),ALTG.K(J),0,18000,3000)              5.428A
T       SNBGMT(*)=1/.94/.89/.87/.89/.99/1.09                             5.429A

NOTE    SFCG    - AGG. ENGINE THRUST SPECIFIC FUEL CONSUMPTION (KG/KG/HR)
NOTE    SABG    - ENGINE TSFC AT FULL AFTERBURNER AND CORRECTED FOR SPEED
NOTE    SNABG   - ENGINE TSFC IN NON-AFTERBURNING CONDITION (KG/KG/HR)
NOTE    SABGM   - ENGINE TSFC (AFTERBURNING) ALTITUDE CORRECTION MULTIPLIER
NOTE    SNABGM  - ENGINE TSFC (NON-AFTERBURNING) ALTITUDE CORRECTION MULT.

A       TG.K(J)=TSG.K(J)*THRUSG.K(J)*G*NEG(J)                            5.414A
A       THRUSG.K(J)=CLIP(THGAB.K(J),THGNAB.K(J),TSG.K(J),.9)             5.415A
A       THGAB.K(J)=TABHL(THGABT(*),MACHG.K(J),0,2,.2)*DELTAG.K(J)**1.23496 5.416A
T       THGABT(*)=8320/7602/7505/7886/8600/9504/10454/11307/11921/
X       12150/11052                                                      5.417A
A       THGNAB.K(J)=TABHL(THNABT(*),MACHG.K(J),0,2,.2)*DELTAG.K(J)**1.23496 5.418A
T       THGNABT(*)=5113/5025/5132/5386/5740/6145/6556/6923/7200/7338/7291 5.419A

NOTE    THRUSG  - AGGRESSOR AIRCRAFT ENGINE THRUST CORRECTED BY DENSITY
NOTE    TG      - AGGRESSOR AIRCRAFT ENGINE THRUST (NEWTONS)
NOTE    THGAB   - AGGRESSOR AIRCRAFT FULL AFTERBURNING ENGINE THRUST (KG)
NOTE    THGNAB  - AGGRESSOR AIRCRAFT NON-AFTERBURNING ENGINE THRUST (KG)

L       FUELG.K(J)=FUELG.J(J)-(DT)(FFLOWG.JK(J))                         5.430A
N         FUELG(J)=FUELGN(J)                                             5.431A
T         FUELGN(*)=7000/7000/7000/7000                                  5.432A
A       FUELGR.K(J)=FUELG.K(J)/FUELGN(J)                                 5.433A

A       DAG.K(J)=QAG.K(J)*SG(J)*CDG.K(J)
A         QAG.K(J)=.5*P0*GAMA*DELTAG.K(J)*MACHG.K(J)**2                  5.444A
T         SG(*)=40/40/40/40                                              5.434A
A         MACHG.K(J)=VAG.K(J)/SSOUND(ALTG.K(J))                          5.413A

NOTE    MAG     - AIRCRAFT MASS (KGS)
NOTE    MAGN    - INITIAL AIRCRAFT MASS (KGS)
NOTE    FFLOWG- ENGINE FUEL FLOW (KGS/SEC)
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NOTE    SFC      -  ENGINE SPEFICIC FUEL CONSUMPTION (N/N/SEC)
NOTE    D        -  AIRCRAFT TOTAL DRAG (NEWTONS)
NOTE    Q        -  DYNAMIC PRESSURE TERM (PA)
NOTE    P0       -  SEA LEVEL STANDARD PRESSURE (PA)
NOTE    DELTA    -  ATMOSPHERIC PRESSURE RATIO (DIM)
NOTE    T0       -  SEA LEVEL STANDARD TEMPERATURE (DEG KELVIN)

A        TEMPG.K(J)=TEM(ALTG.K(J))                                          5.401A
A          THEG.K(J)=TEMPG.K(J)/T0                                          5.402A
A        DELTAG.K(J)=PRATIO(ALTG.K(J))                                      5.403A
A        SIGG.K(J)=SIGM(DELTAG.K(J),THEG.K(J))                              5.404A

A        CDG.K(J)=CDLIG.K(J)+CDIG.K(J)                                      5.437A
A        CDLIG.K(J)=CDOG.K(J)+CDCG(J)+CDWG(J)+SCLPRD(AGAW.K(J,*),1,4,CDWEAG
X        ,1)                                                                5.438A
A        CDIG.K(J)=CLG.K(J)**2*WINGGK(J)                                    5.439A
A        CDOG.K(J)=TABHL(CDOTG(*),MACHG.K(J),0,2,.1)                        5.440A
T        CDOTG(*)=.014/.014/.014/.014/.014/.014/.014/.014/.014/.015/.027
X        /.028/.029/.030/.0294/.0286/.028/.0275/.027/.028/.030              5.441A
T        CDWEAG(*)=.003/.002/.001/0                                         5.442A
N        WINGGK(J)=1/(PI*ARG(J)*EFFG(J))

NOTE    TEMP     -  ATMOSPHERIC TEMPERATURE (DEGREES ABSOLUTE)
NOTE    CD       -  TOTAL DRAG COEFFICIENT (DIM)
NOTE    CDI      -  INDUCED DRAG COEFFICIENT (DIM)
NOTE    CDO      -  ZERO LIFT DRAG COEFFICIENT (DIM)
NOTE    CDC      -  COMPRESSIBILITY DRAG COEFFICIENT (DIM)
NOTE    CDW      -  WAVE DRAG COEFFICIENT (DIM)

A        CLALPG.K(J)=TABHL(CLALTG,MACHG.K(J),0,2,.4)                        5.457A
T        CLALTG=4.2/3.5/4.8/3.7/3.1/2.4                                     5.458A
T        ALPOG(*)=.015/.015/.015/.015                                       5.459A
A        ALPG.K(J)=(CLG.K(J)/CLALPG.K(J))+ALPOG(J)                          5.460A
T        ARG(*)=3.5/3.5/3.5/3.5                                             5.435A
T        EFFG(*)=.79/.79/.79/.79                                            5.436A

NOTE    TEMP     -  ATMOSPHERIC TEMPERATURE (DEG. KELVIN)
NOTE    T        -  ENGINE THRUST (NEWTONS)
NOTE    CD       -  TOTAL DRAG COEFFICIENT (DIM)
NOTE    CD0      -  ZERO LIFT DRAG COEFFICIENT (DIM)
NOTE    CDI      -  INDUCED DRAG COEFFICIENT (DIM)
NOTE    G        -  GRAVITY CONSTANT (M/SEC-SEC)

A        CL1G.K(J)=MIN(CLMAG.K(J),CLNAXG.K(J))                              5.445A
A        NGMAX.K(J)=LOADF(QAG.K(J),MAG.K(J),WINGGK(J),THRUSG.K(J),SG(J)
X        ,CDOG.K(J),NSTRUG(J))                                              5.446A
T            NSTRUG(*)=7/7/7/7                                              5.447A
A        CLNAXG.K(J)=2*NGMAX.K(J)*MAG.K(J)*G/(QAG.K(J)*SG(J))               5.448A
A           CLMAG.K(J)=CLMAXG(J)                                            5.449A
T             CLMAXG(*)=1.5/1.5/1.5/1.5                                     5.450A
A        N1G.K(J)=QAG.K(J)*SG(J)*CL1G.K(J)/(MAG.K(J)*G)                     5.451A
A        SAIG1M.K(J)=YAWRTE(N1G.K(J),VAG.K(J))*57.29                        5.452A
A        SAICOG.K(J)=MIN(SAIG1M.K(J),ABS(RSAIG.JK(J)))                      5.453A
A        NCOMG.K(J)=SQRT(1+(SAICOG.K(J)*VAG.K(J)/(G*57.29))**2)             5.454A
A        CLG.K(J)=NCOMG.K(J)*MAG.K(J)*G/(QAG.K(J)*SG(J))                    5.455A
A        VCG.K(J)=SQRT(2*NSTRUG(*)*G*MAG.K(J)/(RHO*SIGG.K(J)*SG(*)
X         *CLMAXG(*)))                                                      5.456A

NOTE    NAMAXG   -  MAXIMUM POTENTIALLY AVAILABLE LOAD FACTOR IF MAX THRUST
NOTE                   IS APPLIED INSTANTANEOUSLY
NOTE    CLNAXG   -  MAXIMUM LIFT COEFFICIENT AVAILABLE FOR TURNING AT NAMAX
NOTE    CL1G     -  MAXIMUM LIFT COEFFICIENT CONSTRAINED DUE TO TURN OR
NOTE                   MAXIMUM FLOW SEPARATION CHARACTERISTICS
NOTE    N1G      -  LOAD FACTOR CONSTRAINED BY THIS LIFT COEFFICIENT
NOTE    SAIG1M   -  MAXIMUM USABLE TURN RATE CAPABILITY CONSTRAINED BY N1
NOTE    SAICOG   -  DESIRED TURN RATE (CONSTRAINED BY NAVIGATION SCHEME)
NOTE    NCOMG    -  LOAD FACTOR CORRESPONDING THE DESIRED TURN RATE
NOTE    CLG      -  CL AT DESIRED LOAD FACTOR
NOTE    VCG      -  CORNER VELOCITY (M/SEC)
NOTE    NG       -  AGGRESSOR MAXIMUM AVAILABLE INSTANTANEOUS LOAD FACTOR
NOTE    YAWRTG   -  AGGRESSOR MAXIMUM SUSTAINED YAW RATE (RAD/SEC)
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A       DISTX.K(I,J)=MAX(XAG.K(J)-X.K(I),-XAG.K(J)+X.K(I))
A       DISTY.K(I,J)=MAX(YAG.K(J)-Y.K(I),-YAG.K(J)+Y.K(I))
A       DISTZ.K(I,J)=MAX(ALT.K(I)-ALTG.K(J),-ALT.K(I)+ALTG.K(J))
A       RLOS.K(I,J)=SQRT(DISTX.K(I,J)**2+DISTY.K(I,J)**2+DISTZ.K(I,J)**2)
A       DIRLOS.K(I,J)=ARCSIN(X.K(I),XAG.K(J),Y.K(I),YAG.K(J),RLOS.K(I,J))

A       DIRGOS.K(I,J)=CLIP(DIRG2.K(I,J),DIRG1.K(I,J),DIRLOS.K(I,J),180)
A         DIRG1.K(I,J)=180+DIRLOS.K(I,J)
A         DIRG2.K(I,J)=DIRLOS.K(I,J)-180
A       ATN.K(I,J)=DIREC(SAI.K(I),DIRLOS.K(I,J),Y.K(I),YAG.K(J))
A       TAA.K(I,J)=DIREC(SAIG.K(J),DIRGOS.K(I,J),YAG.K(J),Y.K(I))

NOTE    DISTX    - DELTA DOWNRANGE FROM JTH AIRCRAFT TO ITH AIRCRAFT (M)
NOTE    DISTY    - DELTA LATERAL RANGE FROM JTH AIRCRAFT TO ITH AIRCRAFT (M)
NOTE    RLOS     - LINE OF SIGHT RADIAL DISTANCE FROM ITH TO JTH AIRCRAFT
NOTE    DIRLOS   - DIRECTION OF LINE OF SIGHT VECTOR (DEGREES) FROM "ATN"
NOTE    DIRGOS   - LINE OF SIGHT VECTOR FROM AGGRESSOR (DEGREES)
NOTE    ATN      - CBF ANTENNA TRAIN ANGLE (DEGREES)
NOTE    TAA      - TARGET ASPECT ANGLE (DEGREES)

A       STVMA.K(I)=SQRT(MAX(X.K(I)-XN(I),-X.K(I)+XN(I))**2
X       +MAX(Y.K(I)-YN(I),-Y.K(I)+YN(I))**2)
A       STVDA.K(I)=ARCSIN(X.K(I),XN(I),Y.K(I),YN(I),STVMA.K(I))
A         STCBF.K(I)=DIREC(SAI.K(I),STVDA.K(I),Y.K(I),YN(I))
A       STVDG.K(J)=ARCSIN(XAG.K(J),XAGN(J),YAG.K(J),YAGN(J),STVMG.K(J))
A         STAGG.K(J)=DIREC(SAIG.K(J),STVDG.K(J),YAG.K(J),YAGN(J))
A       STVMG.K(J)=SQRT(MAX(XAGN(J)-XAG.K(J),-XAGN(J)+XAG.K(J))**2
X        +MAX(YAGN(J)-YAG.K(J),YAG.K(J)-YAGN(J))**2)

NOTE    STVMA    - RETURN STEERING VECTOR MAGNITUDE (METERS)
NOTE    STVDA    - RETURN STEERING VECTOR DIRECTION (DEGREES)

A       AMICF.K(I,J,K)=MICF(RLOS.K(I,J),MAAMLE.K(I,J,K),ANEMLE.K(I,J,K)
X       ,MINMLE.K(I,J,K))                                                    5.313
A       MAAMLE.K(I,J,K)=MRBASE(K)*MRBSM(ATN.K(I,J))*MRASM.K(I)*MRALM.K(I)    5.314
T         MRBASE(*)=130000/47000/7500/2500                                   5.315
A       MRASM.K(I)=TABHL(MRASMT(*),MACH.K(I),0.6,1.6,.2)                     5.316
T         MRASMT(*)=.75/.84/1/1.16/1.25/1.3                                  5.317
A       MRALM.K(I)=TABHL(MRALMT(*),ALT.K(I),0,18000,3000)                    5.318
T         MRALMT(*)=.6/.72/.87/1/1.13/1.28/1.4                               5.319
A       MINMLE.K(I,J,K)=PMLEC(K)*MAAMLE.K(I,J,K)                             5.320
T         PMLEC(*)=.04/.05/.10/.20                                           5.321
A       ANEMLE.K(I,J,K)=NEMLEC.K(I)*MAAMLE.K(I,J,K)                          5.322
A         NEMLEC.K(I)=TABHL(NEMLCT(*),NCOM.K(I),0,8.0,1.0)                   5.323
T           NEMLCT(*)=0.8/0.69/0.60/0.51/0.44/0.39/0.35/0.32/0.30            5.324

NOTE    MAAMLE   - MAXIMUM AIR-TO-AIR KTH WEAPON RANGE FROM ITH TO JTH
NOTE               AIRCRAFT (METERS)
NOTE    MRBASE   - BASELINE MAXIMUM MISSILE/GUN RANGE IN METERS (FRONTAL
NOTE               ATTACK)
NOTE    MRBSM    - MISSILE/GUN RANGE VS. BORESIGHT ANGLE MULTIPLIER (DIM)
NOTE    MRALM    - MISSILE/GUN RANGE VS. ALTITUDE MULTIPLIER (DIM)
NOTE    MRASM    - MISSILE/GUN RANGE VS. AIRCRAFT SPEED MULTIPLIER (DIM)
NOTE    MINMLE   - MINIMUM MISSILE/GUN LAUNCH ENVELOPE (M)
NOTE    ANEMLE   - CBF WEAPONS NEVER SCAPE LAUNCH ENVELOPE (M)
NOTE    AMICF    - CBF MISSILE INTERCEPT CONFIDENCE FACTOR (DIM)
NOTE    PMLEC    - PERCENT MAAMLE ALLOCATED AS MINMLE (DIM)
NOTE    NEMLEM   - NEVER EXCEED MLE MULTIPLIER (DIM)

A       GMICF.K(I,J,L)=MICF(RLOS.K(I,J),MIGMLE.K(I,J,L),GNEMLE.K(I,J,L)
X       ,MGMMLE.K(I,J,L))                                                    5.313A
A       MIGMLE.K(I,J,L)=MGBASE(L)*MRBSM(TAA.K(I,J))*MGASM.K(J)*MGALM.K(J)    5.314A
T         MGBASE(*)=67000/35000/6500/2500                                    5.315A
A       MGASM.K(J)=TABHL(MGASMT(*),MACHG.K(J),0.6,1.6,.2)                    5.316A
T         MGASMT(*)=.75/.84/1/1.16/1.25/1.3                                  5.317A
A       MGALM.K(J)=TABHL(MGALMT(*),ALTG.K(J),0,18000,3000)                   5.318A
T         MGALMT(*)=.6/.72/.87/1/1.13/1.28/1.4                               5.319A
A       MGMMLE.K(I,J,L)=PMLEG(L)*MIGMLE.K(I,J,L)                             5.320A
T         PMLEG(*)=.04/.05/.10/.20                                           5.321A
A       GNEMLE.K(I,J,L)=NEMLEG.K(J)*MIGMLE.K(I,J,L)                          5.322A
A         NEMLEG.K(J)=TABHL(NEMLGT(*),NCOMG.K(J),0,8.0,1.0)                  5.323A
T           NEMLGT(*)=0.8/0.69/0.60/0.51/0.44/0.39/0.35/0.32/0.30            5.324A
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NOTE    MIGMLE  - MAXIMUM AIR-TO-AIR KTH WEAPON RANGE FROM JTH TO ITH
NOTE            AIRCRAFT (METERS)
NOTE    MGBASE  - AGG BASELINE MAXIMUM MISSILE/GUN RANGE IN METERS (FRONTAL
NOTE            ATTACK)
NOTE    MGBSM   - MISSILE/GUN RANGE VS. BORESIGHT ANGLE MULTIPLIER (DIM)
NOTE    MGALM   - MISSILE/GUN RANGE VS. ALTITUDE MULTIPLIER (DIM)
NOTE    MGASM   - MISSILE/GUN RANGE VS. AIRCRAFT SPEED MULTIPLIER (DIM)
NOTE    MGMMLE  - AGGRESSOR MINIMUM MISSILE/GUN LAUNCH ENVELOPE (M)
NOTE    GNEMLE  - AGGRESSOR WEAPONS NEVER SCAPE LAUNCH ENVELOPE (M)
NOTE    GMICF   - AGGRESSOR MISSILE INTERCEPT CONFIDENCE FACTOR (DIM)
NOTE    PMLEG   - PERCENT MAAMLE ALLOCATED AS MINMLE (DIM)
NOTE    NEMLEG  - NEVER EXCEED MLE MULTIPLIER FOR AGGRESSOR AIRCRAFT (DIM)

A       PCBFLA.K(I)=CLIP(0,1,NCOM.K(I),MELAC(I))                        5.325
T         MELAC(*)=6/6/6/6                                              5.336
A       PAGGLA.K(J)=CLIP(0,1,NCOMG.K(J),MELAG(J))                       5.325A
T         MELAG(*)=6/6/6/6                                              5.326A

NOTE    PATWL   - PROB. CBF WEAPONS LAUNCH (DIM)
NOTE    PCBFLA- PROB. OF CBF IN LAUNCH ATTITUDE (DIM)
NOTE    MELAC   - MAXIMUM WEAPONS LAUNCH LOAD FACTOR (G)
NOTE    PAGFE   - PROB. OF AGGRESSOR IN FIRING ENVELOPE OF WEAPON K
NOTE    PCBFT   - PROB. OF CBF IN LAUNCH ATTITUDE (DIM)
NOTE    PASTF   - PROB. OF CBF HAVING SUFFICIENT TIME TO FIRE (DIM)
NOTE    PAGWL   - PROB. OF AGGRESSOR WEAPONS LAUNCH (DIM)
NOTE    PATFE   - PROB. OF CBF IN FIRING ENVELOPE OF WEAPON L
NOTE    PAGAT   - PROB. OF AGGRESSOR IN LAUNCH ATTITUDE (DIM)
NOTE    PGSTF   - PROB. OF AGGRESSOR HAVING SUFFICIENT TIME TO FIRE (DIM)


S       AVCBF.K=SUM(CBF.K)/SUM(CBFI)                                    5.399
L       CBF.K(I)=CBF.J(I)-(DT)(SUM(CBFKR.J(I,*)))                       5.395
N       CBF(I)=CBFI(I)                                                  5.396
T       CBFI(*)=1/1/1/1                                                 5.397
S       AVAGG.K=SUM(AGG.K)/SUM(AGGI)                                    5.400
L       AGG.K(J)=AGG.J(J)-(DT)(SUM(AGGKR.J(J,*)))                       5.395A
N       AGG(J)=AGGI(J)                                                  5.396A
T       AGGI(*)=1/1/1/1                                                 5.397A
S       ERATIO.K=(1-AVCBF.K)/(1-AVAGG.K+1E-6)                           5.398
A       CBFKR.K(I,L)=CLIP(CBF.K(I)/DT,SUM(CBFKR3.JK(I,*,L))
X       ,SUM(CBFKR3.JK(I,*,L))*DT,CBF.K(I))*CLIP(1,0,SUM(CBFKR3.JK(I,*,L))
X       ,0)                                                             5.391
R       CBFKR3.KL(I,J,L)=DELAY3(PKCBF.K(I,J,L)*CBF.K(I),CBFDEL.K(I,J,L))5.392
T         GMAS(*)=1400/1300/1200/600
A         CBFDEL.K(I,J,L)=CLIP(MTOFG.K(I,J,L),5*DT,MTOFG.K(I,J,L),5*DT) 5.393
A         MTOFG.K(I,J,L)=TFLY(RLOS.K(I,J),GMAS(L),V.K(I),ATN.K(I,J))    5.394
A       AGGKR.K(J,K)=CLIP(AGG.K(J)/DT,SUM(AGGKR3.JK(*,J,K))
X       ,SUM(AGGKR3.JK(*,J,K))*DT,AGG.K(J))*CLIP(1,0,SUM(AGGKR3.JK(*,J,K))
X       ,0)                                                             5.391A
R         AGGKR3.KL(I,J,K)=DELAY3(PKAGG.K(I,J,K)*AGG.K(J),AGGDEL.K(I,J,K))5.392A
T         AMAS(*)=1400/1300/1200/600
A         AGGDEL.K(I,J,K)=CLIP(MTOFA.K(I,J,K),5*DT,MTOFA.K(I,J,K),5*DT) 5.393A
A         MTOFA.K(I,J,K)=TFLY(RLOS.K(I,J),AMAS(K),VAG.K(J),TAA.K(I,J))  5.394A

NOTE    CBF     - NUMBER OF ADVANCED TACTICAL FIGHTERS (AIRCRAFT)
NOTE    CBFI    - INITIAL NUMBER OF CBF (AIRCRAFT)
NOTE    AGG     - NUMBER OF AGGRESSOR AIRCRAFT (AIRCRAFT)
NOTE    AGGI    - INITIAL NUMBER OF AGGRESSOR AIRCRAFT (AIRCRAFT)
NOTE    PSCBF   - PROBABILITY OF SURVIVAL OF CBF (DIM) AGAINST L WEAPONS
NOTE    AGGKR   - AGGRESSOR AIRCRAFT KILL RATE (AIRCRAFT/UNIT TIME)
NOTE    PSAGG   - PROBABILITY OF SURVIVAL FOR AGGRESSOR AIRCRAFT (DIM)
NOTE    CBFKR   - CBF KILL RATE (AIRCRAFT/UNIT TIME)

A       PKAGG.K(I,J,K)=PCBFE.K(I,J,K)-PCBFE.K(I,J,K)*(1-PGSSK.K(K))**
X       AAAWL.K(I,J,K)                                                  5.390
A       PKCBF.K(I,J,L)=PAGGE.K(I,J,L)-PAGGE.K(I,J,L)*(1-PASSK.K(L))**
X       GAAWL.K(I,J,L)                                                  5.390A

NOTE    PSCBF   - PROBABILITY OF CBF SURVIVAL PER ENCOUNTER (DIM)
NOTE    PSAGG   - AGGRESSOR PROBABILITY OF SURVIVAL PER ENCOUNTER (DIM)
NOTE    PCBFE   - PROBABILITY OF CBF EFFECTIVENESS (DIM)
NOTE    PAGGE   - PROBABILITY OF AGGRESSOR EFFECTIVENESS (DIM)
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NOTE     PASSK    -  CBF WEAPON SINGLE SHOT KILL PROBABILITY (DIM)
NOTE     PGSSK    -  AGGRESSOR WEAPON SINGLE SHOT KILL PROBABILITY (DIM)
NOTE     AAAWL    -  CBF AIR-TO-AIR WEAPONS LAUNCHED (UNITS)
NOTE     GAAWL    -  AGGRESSOR AIRCRAFT AIR-TO-AIR WEAPONS LAUNCHED (UNITS)

T          CBFAWW(*)=450/160/90/.25                                    5.228
L         CBFW.K(I,K)=CBFW.J(I,K)-(DT)(CBFWR.JK(I,K))                  5.329
N          CBFW(I,K)=CBFWN(*,K)                                        5.330
T          CBFWN(*,1)=4/4/4/4                                          5.331
T          CBFWN(*,2)=2/2/2/2                                          5.332
T          CBFWN(*,3)=2/2/2/2                                          5.333
T          CBFWN(*,4)=1000/1000/1000/1000                              5.334

R         CBFWR.KL(I,K)=MIN(CBFWRA.K(I,K),AAWLR(I,K)*SUMV(PATWL.K(I,*,K),1,JJ
X         )/60)      5.335
A         CBFWRA.K(I,K)=CLIP(0,CBFW.K(I,K)/DT,0,CBFW.K(I,K))           5.336
A         FCBFWR.K(I,K)=CBFW.K(I,K)/(CBFWN(I,K)+1E-6)                  5.337
T          AAWLR(*,1)=2/2/2/2                                          5.338
T          AAWLR(*,2)=2/2/2/2                                          5.339
T          AAWLR(*,3)=2/2/2/2                                          5.340
T          AAWLR(*,4)=4000/4000/4000/4000                              5.341
A         AAAWL.K(I,J,K)=CBFWR.JK(I,K)*CBF.K(I)/MAX(1,AGG.K(J))        5.342

NOTE     CBFAWW   -  CBF AIR WEAPONS WEIGHT (LBS/MISSILE)
NOTE     CBFW     -  CBF AIR WEAPONS (MISSILE UNITS)
NOTE     CBFWR    -  CBF AIR WEAPONS LAUNCHING RATE
NOTE     CBFWN    -  INITIAL NUMBER OF CBF AIR WEAPONS (MISSILE UNITS)
NOTE     AAAWL    -  CBF AIR-TO-AIR WARHEADS LAUNCHED

L         AGAW.K(J,L)=AGAW.J(J,L)-(DT)(AGAWR.JK(J,L))                  5.328A
N          AGAW(J,L)=AGAWN(*,L)                                        5.329A
T          AGAWN(*,1)=4/4/4/4                                          5.330A
T          AGAWN(*,2)=2/2/2/2                                          5.331A
T          AGAWN(*,3)=2/2/2/2                                          5.332A
T          AGAWN(*,4)=1000/1000/1000/1000                              5.333A

R         AGAWR.KL(J,L)=MIN(AGAWRA.K(J,L),GAWLR(J,L)*SUMV(PAGWL.K(*,J,L),1,II
X         )/60)                                                        5.335A
A         AGAWRA.K(J,L)=CLIP(0,AGAW.K(J,L)/DT,0,AGAW.K(J,L))           5.336A
A         FAGAWR.K(J,L)=AGAW.K(J,L)/(AGAWN(J,L)+1E-6)                  5.337A
T          GAWLR(*,1)=3/3/3/3                                          5.338A
T          GAWLR(*,2)=3/3/3/3                                          5.339A
T          GAWLR(*,3)=2/2/2/2                                          5.340A
T          GAWLR(*,4)=4000/4000/4000/4000                              5.341A
A         GAAWL.K(I,J,L)=AGAWR.JK(J,L)*AGG.K(J)/MAX(1,CBF.K(I))        5.342A

NOTE     AGAAWW   -  CBF AIR WEAPONS WEIGHT (LBS/MISSILE)
NOTE     AGAW     -  CBF AIR WEAPONS (MISSILE UNITS)
NOTE     AGAWR    -  CBF AIR WEAPONS LAUNCHING RATE
NOTE     AGAWN    -  INITIAL NUMBER OF CBF AIR WEAPONS (MISSILE UNITS)

A        PARD.K(I,J)=DTECT(DRG.K(I,J),R0G.K(I,J),RLOS.K(I,J),PD5T,PD75T,PD9T
X        ,PD10T,PD13T,PD15T,PD175T,PD20T,PD22T,PD24T)*CLIP(0,1,MAX(TAA.K(I,J)
X          ,-TAA.K(I,J)),THETGA(J))                                   5.226A
A        DRG.K(I,J)=MAX(V.K(I)*COS(ATN.K(I,J)/57.29)+VAG.K(J)*COS(TAA.K(I,J)
X         /57.29),-V.K(I)*COS(ATN.K(I,J)/57.29)-VAG.K(J)*COS(TAA.K(I,J)/57.29))
X         *TSGG(I)                                                    5.227A
A         R0G.K(I,J)=SWITCH(R0GNJ.K(I,J),SJMONG.K(I,J),SWG1)          5.228A
C         SWG1=0                                                      5.228A.1
A         SJMONG.K(I,J)=SWITCH(SJAMG1.K(I,J),SJAMG2.K(I,J),SWG2)      5.228A.2
C           SWG2=0                                                    5.228A.3
A           SJAMG1.K(I,J)=SWITCH(R0GSOJ.K(I,J),R0GSSJ.K(I,J),SWG3)  5.228A.4
C             SWG3=0                                                  5.228A.5
A           R0GNJ.K(I,J)=(RLPG(J)*ERCSA.K(I,J))**.25                  5.229A
N           RLPG(J)=2*PAVG(J)*ADG(J)**2*TSGG(J)*NUG**2/(PI**3*BK*TNG(J)
X            *LGG(J)*OMEGAG(J))                                       5.330A
T             PAVG(*)=100/100/100/100                                 5.331A
T             ADG(*)=.75/.75/.75/.75                                  5.332A
T             TSGG(*)=3/3/3/3                                         5.333A
T             TNG(*)=500/500/500/500                                  5.334A
T             LGG(*)=20/20/20/20                                      5.335A
N             OMEGAG(J)=(THETGE(J)/57.29)*(THETGA(J)/57.29)           5.336A
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T           THETGA(*)=100/100/100/100                                    5.337A
T           THETGE(*)=25/25/25/25                                        5.338A
C         NUG=.7                                                         5.339A
A       JAMTGG.K(I)=CLIP(1,0,TG1.K(I),1)                                 5.340A

NOTE    PARD     - CUMMULATIVE PROBABILITY OF CBF AIRCRAFT RADAR DETECTION
NOTE    DR       - DELTA RANGE COVERED BY THE TARGET WITH RESPECT TO THE
NOTE               ENEMY AIRCRAFT IN A RADAR FRAME SCAN INTERVAL
NOTE    PAVG     - RADAR AVERAGE POWER (WATTS)
NOTE    AEGG     - RADAR EFFECTIVE APERTURE AREA (SQ. METERS)
NOTE    TSGG     - RADAR SCANNING TIME (SEC)
NOTE    RCSA     - AGGRESSOR RADAR CROSS SECTIONAL AREA (SQ. METERS)
NOTE    RCSAGM   - RADAR CROSS SECTION ASPECT ANGLE MULTIPLIER (DIM)
NOTE    ERCSA    - EFFECTIVE RCS AS 'SEEN' FROM JTH TO ITH AIRCRAFT
NOTE    OMEGAG   - AGGRESSOR VOLUME SEARCH AREA (DIM)
NOTE    THETGE   - SEARCH RADAR ELEVATION (RADIANS)
NOTE    THETG    A - AZIMUTH ANGLE COVERED BY RADAR IN VOLUME SCAN MODE (RAD)
NOTE    TNG      - RADAR NOISE TEMPERATURE (DEGREES KELVIN)
NOTE    ADG      - AGGRESSOR ANTENNA DIAMETER (M)
NOTE    LGG      - AGGRESSOR RADAR SYSTEM LOSSES (DIM) FROM DB CONVERSION


A       R0GJ.K(I,J)=SWITCH(R0GSOJ.K(I,J),R0GSSJ.K(I,J),SWTCHG)          5.242A
C         SWTCHG=0                                                       5.243A
A       R0GSOJ.K(I,J)=((32*PAVG(J)*NUG*TSGG(J)*ERCSA.K(I,J)*RJAMG.K(J)**2)
X        /(PI*OMEGAG(J)*LGG(J)*JDGSOJ))**.25                            5.244A
A         RJAMG.K(J)=SQRT(DIXJG.K(J)**2+DIYJG.K(J)**2+DIZJG.K(J)**2)    5.245A
A           DIXJG.K(J)=MAX(XAG.K(J)-XSJ,-XAG.K(J)+XSJ)                  5.246A
A           DIYJG.K(J)=MAX(YAG.K(J)-YSJ,-YAG.K(J)+YSJ)                  5.247A
A           DIZJG.K(J)=MAX(ALTG.K(J)-ALTSJ,-ALTG.K(J)+ALTSJ)            5.248A
C             XSJ=0                                                     5.249A
C             YSJ=0                                                     5.250A
C             ALTSJ=6000                                                5.251A
N           JDSOJ=PSOJ*GSOJ/BWSOJ                                       5.252A
C             PSOJ=150                                                  5.253A
C             GSOJ=35                                                   5.254A
C             BWSOJ=2E8                                                 5.255A

NOTE    SWTCHG   - SWITCH FOR SPECIFYING SELF SCREENING OR STAND-OFF
NOTE               JAMMING. IF SWTCH=0 THEN STAND-OFF JAMMING IS USED
NOTE    R0GJ     - MAXIMUM RADAR DETECTION RANGE WITH JAMMER ON (METERS)
NOTE    R0GSOJ   - MAXIMUM DETECTION RANGE WITH STAND-OFF JAMMER ON (M)
NOTE    ROGSSJ   - MAXIMUM DETECTION RANGE WITH SELF-SCREENING JAMMER ON (M)
NOTE    RJAMG    - RANGE FROM ITH AIRCRAFT TO STANDOFF JAMMER (METERS)
NOTE    DIXJ     - DOWNRANGE DISTANCE FROM SOJ JAMMER TO ITH AIRCRAFT (M)
NOTE    DIYJ     - LATERAL DISTANCE FROM SOJ JAMMER TO ITH AIRCRAFT (M)
NOTE    DIZJ     - ALTITUDE DIFFERENTIAL FROM SOJ JAMMER TO ITH AIRCRAFT (M)
NOTE    XSJ,YSJ,ZSJ COORDINATES OF SOJ JAMMER (METERS)
NOTE    JDGSOJ   - CBF NOISE JAMMING POWER OF STAND-OFF JAMMER (W/HZ)
NOTE    PS0J     - AVERAGE POWER OF SOJ JAMMER(W)
NOTE    GSOJ     - JAMMER GAIN (DIMENSIONLESS)
NOTE    BWSOJ    - JAMMER BANDWIDTH (HZ)

A         R0GSSJ.K(I,J)=(32*PAVG(J)*NUG*TSGG(J)*ERCSA.K(I,J)/(PI*OMEGAG(J)
X        *LGG(J)*JDGSSJ))**.5                                           5.256A
N           JDGSSJ=PGSSJ*GGSSJ/BWGSSJ                                   5.257A
C             PGSSJ=50                                                  5.258A
C             GGSSJ=35                                                  5.259A
C             BWGSSJ=2E8                                                5.260A

NOTE    JDGSSJ   - NOISE JAMMING POWER OF SELF-SCREENING JAMMER (W/HZ)
NOTE    PGSSJ    - AVERAGE POWER OF SSJ JAMMER(W)
NOTE    GGSSJ    - JAMMER GAIN (DIMENSIONLESS)
NOTE    BWGSSJ   - JAMMER BANDWIDTH (HZ)

N         RWRG(I,J)=SQRT(9*PAVA(I)*ADA(I)**2*NUA*RGGAIN(J)/((4*PI)**2
X        *LARGWR(J)*BK*TNG(J)*BNG(J)*FRG(J)))                           5.261A
T           BNG(*)=2E8/2E8/2E8/2E8                                      5.262A
T           RGGAIN(*)=10/10/10/10                                       5.263A
T           LARGWR(*)=20/20/20/20                                       5.264A
T           FRG(*)=20/20/20/20                                          5.265A
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NOTE      RWRG    - RADAR WARNING RECEIVER RANGE FOR AGG AIRCRAFT (METERS)
NOTE      RGGAIN  - RADAR WARNING RECEIVER ANTENNA GAIN
NOTE      BNG     - RWR RECEIVER BANDWIDTH (HERTZ)
NOTE      LARGWR  - RECEIVER LOSSES (DIM)
NOTE      PAVA    - CBF AVERAGE POWER (WATTS)
NOTE      BK      - BOLTZMANN CONSTANT (JOU/DEG KELVIN)
NOTE      FRG     - NOISE FIGURE OF RWR RECEIVER

L         RCSA.K(I)=RCSA.J(I)-(DT)(RCSRWA.JK(I))                          5.266A
N         RCSA(I)=RCSAN(I)*MULT2+SCLPRD(CBFWN(I,*),1,2,DRCSWA(*),1)       5.267A
T           RCSAN(*)=5/5/5/5                                              5.268A
R         RCSRWA.KL(I)=SCLPRD(CBFWR.JK(I,*),1,2,DRCSWA(*),1)              5.269A
T           DRCSWA(*)=.3/.2/.1/0                                          5.270A
A         ERCSA.K(I,J)=RCSA.K(I)*RCSAAM(TAA.K(I,J))                       5.271A
A         ERCST2.K(I,J)=RCSAAM(TAA.K(I,J))                                5.272A
SPEC DT=5/LENGTH=1200/PRTPER=50/PLTPER=50                                 5.273A
PRINT ERATIO,AGG,CBF                                                      5.274A
RUN BASE                                                                  5.275A
QUIT
```

Appendix B. ASALT I Glossary

A

AAAWL	CBF Aircraft Air-to-Air Weapons Launched (Weapons)
AAWLR	CBF Aircraft Air-to-Air Weapons Launch Rate (Weapons/Minute)
ABS	Absolute Value Macro
ACM	Close-in and Short Range Air Combat Maneuvering
ADA	CBF Aircraft Radar Antenna Diameter (meters)
ADG	AGG Aircraft Radar Antenna Diameter (meters)
AE	CBF Aircraft Engine Exhaust Area (sq. meters)
AEB	CBF Aircraft Baseline Engine Exhaust Area (sq. meters)
AEG	AGG Aircraft Engine Exhaust Area (sq. meters)
AEGB	AAG Aircraft Baseline Engine Exhaust Area (sq. meters)
AF	RCS vs. Azimuth Angle Correction Factor (dim)
AGAWN	Initial Number of AGG Aircraft Weapons (units)
AGAWR	AGG Aircraft Weapons Launching Rate (units/sec)
AGCM	Aggressor Aircraft Guidance Countermeasure Capability (dim)
AGCMT	AGCM Table Values (dim)
AGG	Number of Aggressor Aircraft (aircraft)
AGGDEL	Aggressor Aircraft Weapons Delay Time (sec)
AGGI	Initial Number of Aggressor Aircraft (aircraft)
AGGKR	Aggressor Aircraft Kill Rate (aircrftA/sec)
AGKR3	Delayed Aggressor Aircraft Kill Rate (aircraft/sec)
AGGMLE	Aggressor Aircraft Missile Launch Envelope
AGIJRT	Aggressor Aircraft Identification-Judgement-Reaction Time (sec)
AGMC	Aggressor Aircraft Maneuvering Capability (dim)
AGMCT	AGMCT Tabular Values (dim)
AGWC	Aggressor Aircraft Warning Capability (dim)
AGWCT	Aggressor Aircraft Warning Capability Tabular Values (dim)
AIMEK	CBF Aiming Error Constant (dim)
ALOS	Macro Parameter to Estimate Minimum Over the Horizont Line of Sight (meters)
ALOST	Tabular Values for ALOS (meters)
ALPH	Macro to Estimate Atmospheric Transmittance Coefficient (dim)
ALPO	Wing Body Zero Lift Angle of Attack (rad)
ALPTT	Tabular Values for ALPHA Parameter used to Estimate Transmittance
ALT	CBF Aircraft Flight Altitude (meters)
ALTD	Dummy Variable Used in the Computation of LOS Macro
ALTG	AGG Aircraft Fligth Altitude (meters)
ALTSJG	Z-coordinate Component of Stand-off Jammer Platform (meters)
AMAS	CBF Aircraft Weapon Average Speed (m/sec)
AMICF	CBF Aircraft Missile Intercept Confidence Factor (dim)
ANEMLE	CBF Aircraft Weapons Never Escape Weapons Envelope (meters)
ANMIS	Maximum CBF Weapon Mnuevering Load Factor (g's)
AR	CBF Aircraft Aspect Ratio (dim)
ARCSIN	Macro to Estimate Arcsin Function
ASALT	Aircraft Survivability and Lethality Tradeoffs Model
ASPEED	Dummy Variable to Compute the Missile Time of Flight

ATAAWW	CBF Aircraft Weapons Mass (kg.)
ATAWN	Number of CBF Aircraft Weapons (units)
ATAWR	CBF Aircraft Weapons Launch Rate (units/sec)
ATN	Target Aspect Angle Measured from CBF to AGG Aircraft (deg.)
ATNN	Negative ATN Matrix Values (deg.)
ATNP	Positive ATN Matrix Values (deg.)
AVAGG	Average Number of Aggressor Aircraft (aircraft)
AVATN	Average ATN Angle in BVR Combat Phase (deg.)
AVCBF	Average Number of CBF Aircraft (aircraft)
AVWEAP	Average Number of Weapons (units)
AWACS	Airborne Early Warning System

B

BK	Stephan-Boltzman Constant (W $cm^2deg.K^4$)
BVR	Beyond Visual Range
BWGSOJ	Stand-off Jammer Bandwidth (Hz.)
BWSSJ	Self-screening Jammer Bandwidth (Hz.)

C

CAIME	Aiming Error Constant (dim)
CBCM	CBF Countermeasure Capability (Dim)
CBF	Number of CBF Aircraft (aircraft)
CBFAWW	CBF Aircraft Weapons Mass (kg.)
CBFDEL	CBF Aircraft Weapon Time Delay (sec.)
CBFI	Initial Number of CBF Aircraft (units)
CBFKR	CBF Aircraft Kill Rate (aircraft/sec.)
CBFKR3	CBF Aircraft Delayed Kill Rate (aircraft/sec.)
CBFMLE	CBF Aircraft Missile Launch Envelope (meters)
CBFW	CBF Aircraft Weapons (units)
CBFWN	Initial Number of CBF Aircraft Weapons (units)
CBFWR	CBF Aircraft Weapons Launch Rate (units/sec.)
CBFWRA	Intermediate Dunny Variable to Find CBF Weapons Rate of Change
CBG	Carrier Based Group
CBMC	CBF Aircraft Maneuverability Multiplier (dim)
CBWC	CBF Aircraft Warning Capability (dim)
CD	Complete CBF Aircraft Drag Coefficient (dim)
CD0	Aircraft Zero Lift Drag Coefficient (Dim)
CDI	Induced Drag Coefficient
CL	Aircraft Lift Coefficient (Dim)
CLALP	Wing-Body Curve Lift Slope (1/rad)
CLMAX	CBF Aircraft Stall Lift Coefficient (dim)

D

DB	Decibels
DBINV	Macro to Convert a Ratio to Decibels
DEG	Degrees
DELAT	Tabular Values of Radar Azimuth Antenna Beam Shape Loss (dim.)
DELAY3	DYNAMO Third Order Delay Structure
DELAZ	Dummy Variable of MABSLA Macro to Find Azimuth Loss Shape
DET	Detonation
DEXPC	CBF Aircraft Rate of Change of Expendables (cartridges/sec.)
DEXPG	AGG Aircraft Rate of Change of Expendables (cartridges/sec.)
DINV	Macro to Convert Decibels to a Ratio
DIREC	Macro to Find a Heading in a Four Quadrant System
DIRGOS	Direction of Line of Sight Vector from a AGG Aircraft (deg.)
DIRLOS	Direction of Line of Sight Vector from a CBF Aircraft (deg.)
DIR12	Direction of Line of Sight in First and Second Quadrants (deg.)
DIR34	Direction of Line of Sight in Second and Third Quadrants (deg.)
DIST	Dummy Variable to Represent Distance in Macro BYNARY
DIXJ	X-Component of Jammer Location (meters.)
DIYJ	Y-Component of Jammer Location (meters.)

DIZJ	Z-Component of Jammer Location (meters.)
DRC	Delta Range from CBF Aircraft (m/sec.)
DRG	Delta Range from AGG Aircraft (m/sec.)
DRCSWG	Aggressor Delta RCS due to Weapons Carriage (sq. meters)
DR0DR	Ratio of Delta Range to that of Radar Nominal Range
DT	Simulation Step Size (sec.)
DTECT	Macro to Find the Probability of Detection

E

ECM	Electronic Countermeasures
EFF	CBF Aircraft Wing Efficiency Factor (Oswald's Factor)
EGT	CBF Aircraft Exhaust Gas Temperature (deg. absolute)
EGTBG	Aggressor Aircraft Baseline EGT (deg. absolute)
EMB	CBNF Aircraft Basilane Empty Mass (kg.)
EMM	Gray Body Emmisitivity Constant (dim.)
ER	Exchange Ratio (dim.)
ERCSG	Effective j th Aircraft Radar Cross Section (sq. meters)
ESM	Electronic Suppression Measures

F

FACP	Forward Air Control Post
FAGAWR	Fraction of Aggressor Aircraft Weapons Remaining (dim)
FAW	Total Fraction of CBF Aircraft Weapons Remaining (dim.)
FAWG	Total Fraction of AGG Aircraft Weapons Remaining (dim.)
FCBFWR	Fraction of CBF Aircraft Weapons Remaining (dim)
FFLOW	CBF Fuel Flow (kg/m.)
FUELAC	Aircraft Fuel Fraction Allocated for Disengagement (dim)
FUELGR	Aggreaaor Aircraft Fuel Fraction (dim.)
FUELN	Initial CBF Aircraft Fuel (kg.)
FUELR	CBF Aircraft Fuel Fraction (dim.)

G

GAAWL	Aggressor Aircraft Air-to-Air Weapons Launched (units)
GAMA	Ratio of Specific Heats (dim)
GCI	Ground Control Intercept
GGSOJ	Aggressor Aircraft Stand-off Jammer Gain (dim)
GMAS	Aggressor Aircraft Average Weapon Speed (m/sec.)
GMICF	Aggressor Aircraft Missile Intercept Confidence Factor (dim)
GSSJ	Aggressor Aircraft Self Screening Jammer Gain (dim)
GWEXP	Aggressor Aircraft Expendables Mass (kg.)
GWEXPR	Aggressor Aircraft Expendable Mass Rate Of Change (kg/sec.)

H

HT	CBF Aircraft Infrared Radiance (w./sq. cm.)
HTG	AGG Aircraft Infrared Radiance (w./sq. cm.)
HUD	Head-up Display
HY	Hypotenuse

I

ICAO	International Civil Aviation Organization
IR	Infrared
IRDET	Macro to Estimate the probability of Infrared Detection
IRDT	Tabular Values for the probability of Infrared Detection
ISA	International Standard Atmosphere
ITIME	Initial Time Used in Statistical Macro

J

JAMTMM	Jammer Activation Logic Switch
JDGSOJ	Aggressor Aircraft Stand-off Noise Jamming Power (watts)
JDSOJ	CBF Aircraft Stand-off Noise Jamming Power (watts)
JDSSJ	CBF Aircraft Self Screening Noise Jamming Power (watts)
JEFFG	Aggresor Aircraft Engine Effective Infrared Radiance (w/sr.)
JEG	AGG Aircraft Engine IR Radiance (w./sq. cm.)
JPEFFG	AGG Aircraft Engine Plume Effective IR Radiance (w./sq. cm.)
JPG	Aggressor Aircraft Plume IR Radiance (w./sq. cm.)
JS	CBF Aircraft Skin IR Radiance (w./sq. cm.)
JTOTEG	Aggressor Aircraft Total Effective Infrared Radiance (w./sq. cm.)

K

KDET	CBF Aircraft Weapons Detonation Constant (dim)
KDETC	Numerical Values for KDET Constants (dim)

L

LARWR	Aggressor Aircraft Radar Receiver Losses (dim.)
LOADF	Macro to Estimate the Load Factor Pulled at Any Point in Time
LRAAM	Long Range Air-to-Air Missile
LTHIGH	Dummy Var. Used in Macro SPECTR as Upper Limit Wavelentgh (microns)
LTLOW	Dummy Var. Used in Macro SPECTR as Lower Limit Wavelentgh (microns)

M

MAAMLE	CBF Aircraft Air-to-Air Missile Launch Envelope (km.)
MABSLA	Weapons Range Off-boresight Capability Multiplier (dim)
MACH	CBF Aircraft Flight Mach Number (dim)
MACHG	AGG Aircraft Flight Mach Number (dim)
MAGN	Initial Aggressor Aircraft Mass (kg.)
MEECM	Mass of Electronic Countermeasures Equipment (kg.)
MELAC	Maximum CBF Aircraft Weapons Launch Load Factor (g's)
MELAG	Maximum AGG Aircraft Weapons Launch Load Factor (g's)
MICF	Missile Intercept Confidence Factor (dim.)
MICF1	Dummy Variable Used to Estimate MICF Factor (dim.)
MICF2	Dummy Variable Used to Estimate MICF Factor (dim.)
MIEM	CBF Aircraft Increase vs. Engine Modification Multiplier (dim.)
MIGMLE	Maximum Aggressor Aircraft Missile Launching Envelope (meters)
MIN	DYNAMO Minimum Built-in Macro
MINATN	Minimum Target Aspect Angle Used in ACM Phase (degrees)
MINMLE	Minimum Aggressor Aircraft Missile Launching Envelope (meters)
MISVAL	Misssile Evaluation Program
MNATNN	Minimum Negative Target Aspect Angle (degrees)
MNATNP	Minimum Positive Target Aspect Angle (degrees)
MRAAM	Medium Range Air-to_air Missile
MRALM	Weapon Range vs. Launching Platform Altitude Multiplier (dim.)
MRALMT	Numerical Values of MRALM Multiplier (dim.)
MRASM	Weapon Range vs. Luanching Platform Flight Speed Multiplier (dim.)
MRASMT	Numerical Values of MRASM Multiplier (dim.)
MRBASE	Baseline Weapons Maximum Range (meters)
MRBSM	Weapon Range vs. Boresight Capability Multiplier (dim.)
MRBSMT	Numerical Values of MRBSM Multiplier (dim.)
MSPEED	Average Missile Speed (m/sec.)
MTOFA	Average CBF Aircraft Missile Time of Flight (sec.)
MTOFG	Average Aggressor Aircraft Missile Time of Fligth (sec.)
MUHIGH	Highest Infrared Spectrum Wavelength Value (microns)
MUHIG1	Highest Engine Infrared Spectrum Wavelength Value (microns)

MUHIG2	Highest Plume Infrared Spectrum Wavelength Value (microns)
MULOW	Lowest Infrared Spectrum Wavelength Value (microns)
MULOW1	Low Infrared Spectrum Value Used in IR Engine Contribution (microns)
MULOW2	High Infrared Spectrum Value Used in IR Engine Contribution (microns)

N

NAERO	Maximum Available Load Factor Constrained by Thrust (g's)
NCOM	CBF Commanded Load Factor (g's)
NCOMG	Aggressor Aircraft Commanded Load Factor (g's)
NCREW	Physiological Limit on Human Tolerance to Normal Load Factor (g's)
NE	CBF Aircraft Number of Engines (units)
NEECM	Number of ECM Pods (units)
NEG	Aggressor Aircraft Number of Engines (units)
NEI	Noise Equivalent Infrared Radiance (w/sr.-sq.m.)
NEIB	Baseline Noise Equivalent Infrared Radiance (w/sr.-sq.m.)
NEIMT	Tabular Values for Noise Equivalent Infrared Radiance vs. Number of Aircraft (dim.)
NEINAM	Multiplier of Noise Equivalent Radiance (NER) vs. Number of CBF Aircraft (dim.)
NEMLCT	Tabular Values of Never Escape Envelope vs. Commanded Load Factor
NEMLEC	Never Escape Envelope vs. Commanded Load Factor Multiplier (dim.)
NEMLEM	Never Escape Envelope MLE Multiplier (dim.)
NEXLC	Number of CBF Aircraft Expendables Launched (cartridges)
NEXLG	Number of AGG Aircraft Expendables Launched (cartridges)
NEXPC	CBF Aircraft Number of Expendables (cartridges)
NEXPCN	Initial Number of CBF Aircraft Expendables (cartridges)
NEXPGN	Initial Number of AGG Aircraft (cartridges)
NSTRUC	Maximum Structural Load Factor (g's)
NTRUS	Dummy Variable Used in LOADF Macro
NTRUST	Maximum Load Factor Limited by Thrust (g's)
NUA	CBF Aircraft Antenna Effective Aperture Factor (dim.)
NUG	Aggressor Aircraft Effective Aperture Factor (dim.)
N1	CBF Aircraft Maximum Available Load Factor (g's)
N1G	AGG Aircraft Maximum Available Load Factor (g's)

O

OMEGAA	CBF Aircraft Radar Azimuthal Coverage (degrees)

P

PAGAT	Probability of Aggressor Tracking (dim.)
PAGGFE	Probability of Aggressor in CBF Weapons Firing Envelope (dim.)
PAGGD	Probability of Aggressor Detection (dim.)
PAGGE	Probability of Aggressor Aircraft System Effectiveness (dim.)
PAGGLA	probability of Aggressor Aircraft in Launch Attitude (dim.)
PAGGWL	Probability of Aggressor Aircraft Weapons Launch (dim.)
PAGTR	Probability of Aggressor Aircraft Tracking (dim.)
PAGWDE	Probability of Aggressor Aircraft Weapons Detonation (dim.)
PAGWSG	Probability of Aggressor Aircraft Weapons Guidance (dim.)
PALOS	Probability of Target Aircraft in Line of Sight (dim.)
PASSK	Probability of CBF Aircraft Single Shot Kill (dim.)
PASSKB	Baseline Porbability of Single Shot Kill (dim.)
PATAE	Probability of CBF Aircraft System Effectiveness (dim.)
PATFE	Probability of CBF Aircraft in Firing Envelope (dim.)
PATTR	Probability of CBF Aircraft Tracking (dim.)
PATWL	Probability of CBF Aircraft Weapons Launch (dim.)
PATWSG	Probability of Weapons Successful Guidance (dim.)
PAVA	Average Radar Power for CBF Aircraft (watts)
PAVG	Aggressor Aircraft Average Power (watts)

PAWDET	Probability of CBF Aircraft Weapons Detonation (dim.)
PCBFD	Probability of CBF Aircraft Detection (dim.)
PCBFE	Probability of CBF Aircraft System Effectiveness (dim.)
PCBFFE	Probability of CBF Aircraft in Firing Envelope (dim.)
PCBFLA	Probability of CBF Aircraft in Launch Attitude (dim.)
PCBFT	Probability of CBF Aircraft Tracking (dim.)
PCBWDE	Probability of CBF Aircraft Weapons Detonation (dim.)
PCBWSG	Probability of CBF Aircraft Weapons Guidance (dim.)
PCLOH	Probability of CBF Aircraft Weapons Lock-on and Homing Capability (dim.)
PDT1, PDT2, etc.	Dummy Variables in Macro DTECT to Branch Between Probability of Detection Curves
PD5, PD75, etc.	Dummy Variables in Macro DTECT to Compute the Numerical Values of Universal Probability of Detection Curves
P5T, P75T, etc.	Tables Containing Numerical Values of the Universal Probability of Detection Curves
PDIRG	Probability of Aggressor Aircraft Infrared Detection (dim.)
PDRF	Probability of CBF Aircraft Radar Detection (dim.)
PGAC	Probability of Aggressor Aircraft Combat Capability (dim.)
PGRD	Probability of Aggressor Aircraft Radar Detection (dim.)
PGSOJ	CBF Fleet Stand-off Jammer Power (watts)
PGSSK	Aggressor Aircraft Weapon Single Shot Kill Probability (dim.)
PGSSKB	Baseline Aggressor Aircraft Weapon Single Shot Kill Probability (dim.)
PGWDET	Probability of Aggressor Aircraft Weapons Detonation (dim.)
PKAGG	Probability of Aggressor Aircraft Kill (dim.)
PKCBF	Probability of CBF Aircraft Kill (dim.)
PMLEC	Percent Maximum Weapons Allocated as MINMLE
PRATIO	Macro to Compute Atmospheric Pressure Ratio
PSAGG	Probability of Aggressor Aircraft Survival (dim.)
PSCBF	Probability of CBF Aircraft Survival (dim.)
PYL	CBF Aircraft Payload Mass (kg.)

R

RAD	Radians
RATINV	Macro to Invert a Ratio to Decibels
RC	Dummy Variable Used in Macro DTECT to Representing Line of Sight Range (meters)
RCDR0	Ratio of Line of Sight Range to Delta Range (dim.)
RCR0	Ratio of Line of Sight Range to Detection Range (dim.)
RCS	CBF Aircraft Radar Cross section Area (sq. meters)
RCSAAM	CBF Aircraft Radar Radar Cross Section Azimuth Multiplier (dim.)
RCSAGM	AGG Aircraft Radar Radar Cross Section Azimuth Multiplier (dim.)
RCSAGT	AGG Aircraft RCSAGM Multiplier Tabular Values (dim.)
RCSG	Aggressor Aircraft Cross Section Area (sq. meters)
RCSGN	Initial Nominal Aggressor Aircraft Cross Section Area (sq. meters)
RCSRWG	CBF Aircraft RCS Reduction Rate due to Weapons Delivery (sq. meters)
RGAIN	CBF Aircraft Radar Antenna Gain (dim.)
RJAM	Range from J th Aircraft to Stand-off Jammer (meters)
RJAMG	Range from I th Aircraft to Stand-off Jammer (meters)
RLOS	Range in Line of Sight (meters)
RLPA	Nominal CBF Range Parameter (meters)
RMAX	CBF Aircraft Maximum Weapon Range (meters)
RMIN	CBF Aircraft Minimum Weapon Range (meters)
RNE	Never Escape Envelope (meters)
ROASSJ	Nominal Aggressor Aircraft Radar Detection with Self Screening
RSAIA	CBF Aircraft Maximum Sustained Turn Rate Capability (deg/sec.)
RSAI1	CBF Aircraft Turn Rate Guidance in First Combat Phase (deg/sec.)
RSAI2	CBF Aircraft Turn Rate Guidance in Second Combat Phase (deg/sec.)
RSAI3	CBF Aircraft Turn Rate Guidance in Third Combat Phase (deg/sec.)
RSAI4	CBF Aircraft Turn Rate Guidance in Fourth Combat Phase (deg/sec.)
RT1	CBF Aircraft First Combat Phase Timer Auxiliary Variable (dim.)

RT2	CBF Aircraft Second Combat Phase Timer Auxiliary Variable (dim.)
RT3	CBF Aircraft Third Combat Phase Timer Auxiliary Variable (dim.)
RTG1	AGG Aircraft First Combat Phase Timer Auxiliary Variable (dim.)
RTG2	AGG Aircraft Second Combat Phase Timer Auxiliary Variable (dim.)
RTG3	AGG Aircraft Third Combat Phase Timer Auxiliary Variable (dim.)
RTt1	CBF Aircraft First Combat Phase Timer Rate Variable (dim.)
RTT2	CBF Aircraft Second Combat Phase Timer Rate Variable (dim.)
RTT3	CBF Aircraft Third Combat Phase Timer Rate Variable (dim.)
RTtG1	AGG Aircraft First Combat Phase Timer Rate Variable (dim.)
RTTG2	AGG Aircraft Second Combat Phase Timer Rate Variable (dim.)
RTTG3	AGG Aircraft Third Combat Phase Timer Rate Variable (dim.)
RWR	CBF Aircraft Radar Warning Receiver Range (meters)
R0	Dummy Variable Used in Macro DTECT to Represent the Line of Sight Range
ROAJ	CBF Aircraft Nominal Radar Detection Range Capability in a Jamming Environment (meters)
ROANJ	CBF Aircraft Nominal Radar Detection Range with no Jamming (meters)
R0ASSJ	CBF Aircraft Radar Detection Range Using Self Screening Jammer (meters)
ROGJ	AGG Aircraft Nominal Radar Detection Range in a Jamming Environment (meters)
ROGNJ	AGG Aircraft Nominal Radar Detection Range with no Jamming (meters)
R0GSSJ	AGG Aircraft Radar Detection Range Using Self Screening Jammer (meters)
R0DR	Ratio of the Radar Detection Range to the Delta Range (dim.)

S

SAB	Corrected Afterburning Thrust Specific Fuel Consumption (kg/kg/hr)
SABM	Afterburning TSFC vs. Altitude Correction Multiplier (dim.)
SABMT	Table Values of SABM Multiplier (dim.)
SAI	Corrected CBF Aircraft Heading Angle (deg.)
SAIA	CBF Aircraft (Level) Heading Angle (deg.)
SAIN	Initial CBF Aircraft Heading Angle (deg.)
SAIG	Corrected Aggressor Aircraft Heading Angle (deg.)
SAIG1M	AGG Maximum Useful SustainedTurn Rate Capability (deg./sec.)
SAIWEA	CBF Aircraft Weapon Maximum Turn Rate Capability (deg/sec.)
SAI1M	CBF Maximum Useful SustainedTurn Rate Capability (deg./sec.)
SAWE	Macro to Estimate The Situational Awareness of a Crew
SCLPR	DYNAMO Scalar Product Built-in Macro
SFC	Specific Fuel Consumption (kg/kg/hr)
SGMA	Atmospheric Density Ratio Associated with CBF Aircraft (dim.)
SINI	Dummy Variable to Estimate ARCSIN in First Quadrant
SINII	Dummy Variable to estimate ARCSIN in Second Quadrant
SINIV	Dummy Variable to Estimate ARCSIN in Fourth Quadrant
SIN3	Dummy Variable to estimate ARCSIN in Third Second Quadrant
SL	Sea Level Standard Conditions
SNAB	Non Afterburning Thrust Specific Fuel Consumption (kg/kg/hr)
SNABM	Non Afterburning TSFC vs. Altitude Correction Multiplier (dim.)
SNABT	Non Afterburning TSFC vs. Mach Number Multiplier (dim.)
SNABMT	Non-Afterburning TSFC vs. Altitude Numerical Values (dim.)
SNOISE	CBF Aircraft Infrared Signal-to-Noise Ratio (dim.)
SNOISG	AGG Aircraft Infrared Signal-to-Noise Ratio (dim.)
SOJ	Stand-off Jammer
SPECTR	Macro to Find the Relative Infrared Energy Radiance of a Black Body
SQRT	DYNAMO Square Root Function
SRAAM	Short Range Air-to-Air Missile
SSOUND	Macro to compute the Speed of Sound .
STAT	Macro to Estimate Statistics of a Given variable
STCBF	CBF Aircraft Corrected Return Steering Vector
STD	Standard Deviation (dim.)
STVDA	CBF Return Steering Vector Direction (deg.)
STVDG	AGG Return Steering Vector Direction (deg.)
STVMA	CBF Aircraft Return Steering Vector Magnitude (meters)

STVMG	AGG Aircraft Return Steering Vector Magnitude (meters)
SUMV	DYNAMO Vector Summing Built-in Macro
SWTCH	Swith to Branch to the Use of Noise Jamming

T

TAA	Target Aspect Angle (deg.)
TABHL	DYNAMO Linear Interpolation, Hi-Low Table Function Macro
TAUG	Atmospheric Transmittance Term Associated with AGG Aircraft (dim.)
TEM	Macro to Estimate the Atmospheric Temperature (deg. absolute)
TEMP	Atmospheric Temperature Associated with CBF Aircraft (deg. absolute)
TEMPG	Atmospheric Temperature Associated with AGG Aircraft (deg. absolute)
TFLY	Macro to Estimate a Weapon Time of Fly
THAB	Full Afterburner CBF Aircraft Engine Thrust (kg.)
THABT	Full Afterburner CBF Aircraft Engine Thrust Numerical Values (kg.)
THETAA	CBF Aircraft Radar Azimuth Scanning Limits (deg.)
THETAE	AGG Aircraft Radar Azimuth Scanning Limits (deg.)
THNAB	Non-Afterburner CBF Aircraft Engine Thrust (kg.)
THNABT	Non-Afterburner CBF Aircraft Engine Thrust Numerical Values (kg.)
TNO	CBF Aircraft Radar Noise Temperature (deg. absolute)
TOF	Time of Flight (sec.)
TS	CBF Aircraft Throttle Setting (dim.)
TSA	CBF Aircraft Radar Scanning Time (sec.)
TSAEGT	CBF Throttle Setting vs. Exhaust Area Multiplier (dim.)
TSAEMG	AGG Throttle Setting vs. Exhaust Area Multiplier (dim.)
TSAPGM	Throttle Setting vs. Exhaust Area Multiplier (dim.)
TSEGGT	Tabular AGG Aircraft Throttle Setting vs. EGT Mutiplier
TSEGTG	Throttle Setting vs. EGT Parameter
TSFC	Thrust Specific Fuel Consumption (kg/kg/hr)
TSG	AGG Aircraft Throttle Setting (dim.)
TSIN1I	Dummy Variable Containing Numerical Values of ARCSIN Macro
TSIN2I	Dummy Variable Containing Numerical Values of ARCSIN Macro
TSN	Initial Value of CBF Aircraft Throttle Setting (dim.)
TSR	Throttle Setting Rate of Change (1/sec)
TSR1	Throttle Setting Rate of Change During Initial Combat Phase (1/sec)
TSR2	Throttle Setting Rate of Change During BVR Combat Phase (1/sec)
TSR3	Throttle Setting Rate of Change During ACM Combat Phase (1/sec)
TSR4	Throttle Setting Rate of Change During Disengamement Phase (1/sec)
TSTAG	CBF Aircraft Skin Stagnation Temperature (deg. absolute)
TSTGG	Aggressor Aircraft Skin Stagnation Temperature (deg. absolute)
TTIME	Total Time Dummy Variable Used in STAT Macro (sec.)
T0	Sea Level Static Temperature (deg. absolute)
T1	Timer Used to Start BVR Phase (sec.)
T2	Timer Used to Start ACM Phase (sec.)
T3	Timer Used to Start Disengagement Phase (sec.)

U

UWEXPC	CBF Aircraft Expendable Cartridge Mass (kg./cartridge)
UWEXPG	AGG Aircraft Expendable Cartridge Mass (kg./cartridge)

V

VAG	Aggressor Aircraft Speed (m/sec.)
VC	CBF Aircraft Corner Speed (m/sec.)
VCG	Aggressor Aircraft Corner Speed (m/sec.)
VLOS	Vector Line of Sight (m/sec.)
VN	Initial CBF Aircraft Velocity (m/sec.)

W

WAREA	Dummy Variable for Wing Area in macro LOADF (dim.)
WEAPAC	Disengagement Weapons Status Parameter (dim.)
WINGK	CBF Aircraft Wing Efficiency Factor (dim.)
WK	CBF Aircraft Mass (kg.)

X

X	CBF Aircraft Downrange Position (meters)
XAG	AGG Aircraft Downrange Position (meters)
XAGN	Initial AGG Aircraft Downrange Position (meters)
XN	Initial CBF Aircraft Downrange Position (meters)
XSJ	CBF Fleet Stand-off Jammer Position (meters)
XSJG	AGG Fleet Stand-off Jammer Position (meters)
X1	Dummy Position Used to Determine Quadrant Location in ARCSIN Macro
X2	Dummy Position Used to Determine Quadrant Location in ARCSIN Macro

Y

Y	CBF Aircraft Lateral Downrange Position (meters)
YAG	AGG Aircraft lateral Downrange Position (meters)
YAG	Initial AGG Aircraft lateral Downrange Position (meters)
YAWRTE	Macro to Estimate the Aircraft Maximum Sustained Yaw Rate
YAW1	Dummy Variable Used in Macro YAWRTE
YAW2	Dummy Variable Used in Macro YAWRTE
YN	Initial CBF Aircraft Lateral Downrange Position (meters)
YSJ	CBF Fleet Stand-off Jammer Lateral Downrange Position (meters)
YSJG	AGG Fleet Stand-off Jammer Lateral Downrange Position (meters)
Y1	Dummy Position Used to Determine Quadrant Location in ARCSIN Macro
Y2	Dummy Position Used to Determine Quadrant Location in ARCSIN Macro

Z

ZDET	CBF Aircraft Weapon Detonation Constant (dim.)
ZSJ	CBF Aircraft Stand-off Jammer Elevation Position (meters)
ZSJG	Aggressor Aircraft Stand-off Jammer Elevation Position (meters)

Appendix C. ASALT II Model Code

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C$JOB
C     ************************************************************
C     *  PROGRAM  : ASALT I
C     *
C     *  USE      : TO PERFORM TRADEOFF STUDIES BETWEEN AIRCRAFT
C     *             AIRCRAFT SURVIVABILITY AND LETHALITY METRICS.
C     *
C     *  LANGUAGE : WATFIV
C     *
C     ************************************************************
C
C              DEFINITION OF VARIABLES USED IN THE PROGRAM
C     ------------------------------------------------------------
C
      INTEGER I, J, TIME, ITIME, FTIME, DT, T, M, N, W, L, K, KK, LL
      INTEGER DTPRT, NSTEP, NPSTP, TIMER(2), RTIMER(2), NW
      INTEGER ENTIME(2), RTIM(2), NRADPO
      REAL EMASS(2), MASS(2), FUELW(2), PAYLD(2), DMASS(2)
      DIMENSION XS(2), YS(2), ALTS(2), VS(2), TSS(2), TSSR(2), ACCS(2)
      DIMENSION THRUST(2), HEADS(2), DRAG(2), ALTR(2), SAID(2)
      DIMENSION CBFS(2), CBFKR(2,5,3), CBFKRD(2,5,3), CBFQUE(2,5,3,10)
      REAL S1CBKR(2), S2CBKR(2,5), S1CBKD(2), S2CBKD(2,5)
      REAL XDWS(5), YDWS(5), ARTT(2,5), ARTTX(2,5), ARTTY(2,5)
      REAL XWIN(2,6), YWIN(2,6), ATN(2,5), VTIN(2,6), VTOUT(2,6)
      REAL XWOUT(2,6), YWOUT(2,6), DELTAV(2)
      REAL AR(2), EFF(2), S(2), ALPO(2), CLALPT(2,11), CL(2), B(2)
      REAL CLALP(2), ALP(2), CDI(2), CD(2), CDO(2)
      REAL ASWU(2,2), ASWUW(2), DWS(5,3), DASWU(2,2), NDWS(5)
      REAL MACH(2), DELTA(2), SIGMA(2), THETA(2), Q(2)
      REAL PO, TO, RHO, GAMMA, G, PI
      REAL CDOM(2,11),  MACHD(2,11), CDOB(2), ASCDO(2), CDOWE(2)
      REAL THNAB(2,11), THAB(2,11), TRUST(2), NE(2)
      REAL SABT(2,11), SNABT(2,11)
      REAL ARTWI(2,6), ARTWIX(2,6), ARTWIY(2,6), LOSAWI(2,6)
      REAL LOSATT(2,5), ARTWO(2,6), ARTWOX(2,6), ARTWOY(2,6)
      REAL LOSAWO(2,6), ABAIN(2,6), FFLOW(2), SFCU(2), TSFC(2)
      REAL ABAOUT(2,6), ATND(2,5), TAAD(2,5)
      REAL ECMCDO(2), NEECM(2), WEECM(2), ECMM(2), DECMCD(2)
      REAL WLOAD(2), WINGK(2), NFAC(2), YAWR(2), PSA(2), PTRUST(2)
      REAL NCREW(2), NSTRUC(2), NAMAX(2), CLNAX(2), CLMAX(2)
      REAL SAIRUS(2), SAICO(2), CLUS(2), NCOM(2), NUS(2)
      REAL STVDA(2), DTR, SAIR(2), HEAD(2), GAIN
      REAL ASMRB(2,2), ASMRAT(2,9), ASMRST(2,5), MACAL(2,9), MACAS(2,5)
      REAL ASMR(2,2), ASMRA(2), ASMRS(2), TIM(2), ASMRO(2,5)
      REAL EASMRT(2,6), ANMR(2,6), EASMR(2,5,2), ASWS(2,2), ASFOT(2,5,2)
      REAL SRL(2,5), RCS(2), RCSAMT(2,5), LOSTAA(2,5), RCSW(2)
      REAL DRCSW(2), RCSC(2), ERCS(2,5), RCSRW(2), RCSAM(2,5)
      REAL RCSEMT(2,5), RCSEM(2,5), ELEV(2,5), ATNT(2,5), ELEVT(2,5)
      REAL THETAA(5), THETAE(5), OMEGA(5), PAVE(5), RAREA(5), TS(5)
      REAL TE(5), KB, LOSS(5), SNR(5), RRPNJ(5), DRO(2,5)
      REAL RRPSOJ(5), RRPSSJ(5), DROSSJ(2,5), DROSOJ(2,5)
      REAL DWFET(3,10), ADWFE(3,10), RDWFE(2,3), VAPPR(2,5), VAPPT(2,5)
      REAL RLOST(8), ZLOST(8), LOS(2,5), PALOS(2,5)
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      REAL DRODR(2,5), RCDRO(2,5), DR(2,5)
      REAL PRDTT(5,7), RCROTT(5,7), PRAD(2,5)
      REAL TAIE(2,5,3), DEDWFE(2,5,3), APS(3), ARFOT(2,5,3)
      REAL ATFOT(2,5,3), AATT(2,5,3), TEAFT(11), PSTFT(11)
      REAL LTEMT(15), BLACKT(15), STGTEM(2), MUSKIN(2), PADIR(2,5), R
      REAL JSEFF(2), JPEFF(2), JEFF(2), MUPLUM(2), MUENG(2), APB(2)
      REAL TSAPT(2,6), TSTAP(2,6), TSAPM(2), EGT(2), EGTB(2), AP(2)
      REAL TSEGTT(2,6), TSTEGT(2,6), TSEGTM(2), JP(2), AEB(2), AE(2)
      REAL TSAEM(2), TSAET(2,6), TSTAE(2,6), EMM, AS(2), K1, K2, SIG
      REAL JS(2), JE(2), JTOTE(2), IRSAMT(2,7), IRSEMT(2,7)
      REAL IRATNT(2,7), IELEVT(2,7), TAU(2,5)
      REAL IRSAM(2,5), IRSEM(2,5), ALPHT(6), ALTALP(6), ALF(2)
      REAL JA(2,5), HT(2,5), NEI(2), SNOISE(2,5)
      REAL IRNOIT(12), IRPDT(12), PDIR(2,5), VISPDT(11), TSIZET(11)
      REAL PVDET(2,5), TSIZE(2,5), AMCT(3,11)
      REAL PDWL(2,5,3), PT(2,5,3), PSTF(2,5,3), PAIM(2,3), PAIMN(3), ER
      REAL PSG(2,5,3), NMISS(3), PAWC(2,5,3), PAMC(2,3), PAWCT(3,11)
      REAL PDET(2,5,3), PTHAC(2,5,3), PGCMC(2,3), PLOHC(2,3)
      REAL PAFE(2,5,3), PAD(2,5), PDWID(2,5)
      REAL SAIWEA(3), DWSKR(2,5,2), S1DWKR(5), DWSQUE(2,5,2,10)
      REAL S1DWKD(5), S2DWKD(5,2), PKDWS(2,5,2), PKCBF(2,5,3)
      REAL DWSKRD(2,5,2), S2DWKR(5,2), MDWLR(3), PTSE(2,5,3)
      REAL DWPL(2,5,3), TDI(2,5,2), ASWE(2,5,2), BBC, ASWCF(2,5,2)
      REAL ASWL(2,5,2), PASG(2,5,2), PAWDET(2,5,2), PASE(2,5,2)
      REAL ASULA(2,5,2), S2SULA(2,2), S1SULA(2), ASWLR(2)
      REAL PSSDWS(2), PSSCBF(3), XSOJ, YSOJ, ZSOJ, PSOJ, GSOJ, BWSOJ
      REAL JDSOJ, PSSJ, BWSSJ, GSSJ, JDSSJ, RJSOJ(2), DXSOJ(2)
      REAL DYSOJ(2), DZSOJ(2), FUELR(2), ADWS(5,3), DWPL1(5)
      REAL DWPL2(5,3)
      REAL DWPL2(5,3), EFUEL(2), MASSZF(2), DELTAF(2)
      REAL DISFX, DISFY, DISFSE, DISTS(2,11), VSEG(2), TCRS(2)
      REAL ALTSEG, TSEG(2), MFUEL(2), RFUEL(2,11), FUELS(2), FUELCR(2)
      REAL ALTCRS(2), DISTC(2), VCRS(2), MASSTO(2), MASSEG(2)
C     ------------------------------------------------------
C                  1. INITIALIZATION OF VARIABLES
C     ------------------------------------------------------
C     1.1.0 INITIALIZE INTEGER SUBSCRIPTS USED IN THE CODE
C
C       M   - NUMBER OF SURFACE ATTACK AIRCRAFT
C       N   - NUMBER OF DEFENSIVE WEAPON SITES ENGAGED
C       W   - NUMBER OF WAYPOINTS USED TO DESCRIBE THE AIRCRAFT PATH
C       LL  - TYPES OF SURFACE-TO-AIR WEAPONS MODELED
C       KK  - TYPES OF AIR-TO-SURFACE WEAPONS MODELED
C
      DATA M,N,W,KK,LL/2,5,6,2,3/
      DATA G, PI, R, EMM, K1, K2, SIG,ER,BBC/ 9.81, 3.14159, 0.85, 0.9,
     +     -.1289, 0.7506, 5.67E-12,1.5,0.15/
      DATA (TIMER(I),I=1,2)/0,0/
      DATA (ENTIME(I),I=1,2)/0,0/
      DATA NRADPO/1/
C
C       G      - GRAVITY FORCE (M/SEC-SEC.)
C       R      - AIRFLOW RECOVERY FACTOR (DIM.)
C       GAMMA  - RATIO OF SPECIFIC HEATS (DIM.)
C       ER     - CONSTANT FOR AIMING ERROR (MILS)
C       BBC    - BOMB OFF-BORESIGHT CAPABILITY (RAD.)
C       NRADPO - NOISE JAMMING RADAR POLICY IN USE
C
C                  1.1 SCENARIO DEFINITION
C     ------------------------------------------------------------
C
C     1.1.1 INITIALIZE POSITIONS OF AIRCRAFT AT TIME=0
C
C       XS   - DOWNRANGE FROM CARRIER BATTLE GROUP (METERS)
C       YS   - LATERAL DOWNRANGE FROM CARRIER BATTLE GROUP (METERS)
C       ALTS - SURFACE ATTACK ALTITUDE (METERS)
C
      DATA (XS(I),I=1,M)/0.0,0.0/
      DATA (YS(I),I=1,M)/0.0,0.0/
      DATA (ALTS(I),I=1,M)/300.0,300.0/
C
C     1.1.2 INITIALIZE POSITIONS OF DEFENSIVE SITES AND TARGET
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C
C     XDWS   - DOWNRANGE FROM CARRIER BATTLE GROUP (METERS)
C     YDWS   - LATERAL DOWNRANGE FROM CARRIER BATTLE GROUP (METERS)
C
      DATA (XDWS(I),I=1,N)/30000.0,75000.0,125000.0,150000.0,225000./
      DATA (YDWS(I),I=1,N)/0.0,0.0,0.0,0.0,0.0/
C
C     1.1.3 INITIALIZATION OF WAYPOINTS TO DEFINE AIRCRAFT PATHS
C
C     XWIN   - DOWNRANGE FROM CARRIER BATTLE GROUP (METERS)
C     YWIN   - LATERAL DOWNRANGE FROM CARRIER BATTLE GROUP (METERS)
C     VTIN   - TARGET SPEED FOR I TH SEGMENT OF THE ROUTE (M/SEC.)
C     VTOUT  - TARGET SPEED FOR I TH SEGMENT OF THE ROUTE (M/SEC.)
C
      DATA (XWIN(1,J),J=1,W)/20000.,20000.,125000.,175000.,225000.,
     + 250000./
      DATA (XWIN(2,J),J=1,W)/50000.,75000.,125000.,175000.,225000.,
     + 250000./
      DATA (YWIN(1,J),J=1,W)/20000.0,1500.0,3000.0,1000.0,500.0,0.0/
      DATA (YWIN(2,J),J=1,W)/0.0,0.0,0.0,0.0,0.0,0.0/
      DATA (XWOUT(1,J),J=1,W)/225000.,175000.,125000.,75000.,25000.,
     + 0.0/
      DATA (XWOUT(2,J),J=1,W)/225000.,175000.,125000.,75000.,25000.,
     + 0.0/
      DATA (YWOUT(1,J),J=1,W)/-3000.0,-1700.0,-1250.0,-1000.0,
     + -1400.,0.0/
      DATA (YWOUT(2,J),J=1,W)/0.0,0.0,0.0,0.0,0.0,0.0/
      DATA (VTIN(1,J),J=1,W)/280.,280.,280.,280.,280.,280./
      DATA (VTIN(2,J),J=1,W)/280.,280.,280.,280.,280.,280./
      DATA (VTOUT(1,J),J=1,W)/280.,280.,280.,280.,280.,280./
      DATA (VTOUT(2,J),J=1,W)/280.,280.,280.,280.,280.,280./
C     ____________________________________________________________
C           1.2  AIRCRAFT STATE AND CONTROL VARIABLES
C     ____________________________________________________________
C
C     1.2.1 INIATIALIZATION OF AIRCRAFT STATE VARIABLES
C
C     VS    - SURFACE ATTACK AIRCRAFT VELOCITY (M/SEC.)
C     HEADS - SURFACE ATTACK AIRCRAFT HEADING (M/SEC.)
C     MASSS - SURFACE ATTACK AIRCRAFT MASS (KGS.)
C     CBFS  - CARRIER BASED SURFACE ATTACK FIGHTER
C
C
      DATA (VS(I),I=1,M)/250.0,250.0/
      DATA (HEADS(I),I=1,M)/6.0,0.0/
      DATA (EMASS(I),I=1,M)/14000.0,14000.0/
      DATA (FUELW(I),I=1,M)/4000.0,4000.0/
      DATA (CBFS(I),I=1,M)/1.00,1.00/
C
C
C     1.2.2 INITIALIZE AIRCRAFT CONTROL VARIABLES
C
C     TSS   - THROTTLE SETTING (DIM)
C
      DATA (TSS(I),I=1,M)/0.75,0.75/
C
C     ____________________________________________________________
C           1.3 AIRCRAFT AERODYNAMIC CHARACTERISTICS
C     ____________________________________________________________
C
C     S     - AIRCRAFT WING AREA (SQ. METERS)
C     AR    - WING ASPECT RATIO (DIM.)
C     EFF   - AIRCRAFT WING EFFICIENCY FACTOR (OSWALD'S NUMBER)
C     ALPO  - ZERO LIFT ANGLE OF ATTACK (RADIANS)
C     CDOM  - TABLE OF CDO VALUES VS. MACH NUMBER FOR ITH AIRCRAFT
C     MACHD - MACH NUMBERS USED WITH TABLE FOR CDO VALUES
C     ASCDO - CDO INCREMENT PER WEAPON
C     ECMCDO - CDO INCREMENT PER WEAPON
C
      DATA (S(I),I=1,M)/40.0,40.0/
      DATA (AR(I),I=1,M)/3.50,3.50/
      DATA (EFF(I),I=1,M)/0.80,0.80/
```

```
      DATA (ALPO(I),I=1,M)/0.015,.015/
      DATA (CDOM(1,J),J=1,11)/5*.011,.020,.024,.023,3*.022/
      DATA (CDOM(2,J),J=1,11)/5*.011,.020,.024,.023,3*.022/
      DATA (MACHD(1,J),J=1,11)/0.0,.2,.4,.6,.8,1.,1.2,1.4,1.6,1.8,2./
      DATA (MACHD(2,J),J=1,11)/0.0,.2,.4,.6,.8,1.,1.2,1.4,1.6,1.8,2./
      DATA (ASCDO(K),K=1,KK)/0.001,0.001/
      DATA (ECMCDO(I),I=1,M)/0.0035,0.0035/
      DATA (CLALPT(1,J),J=1,11)/4*4.0,2*3.5,4.8,3.7,2*3.1,2.4/
      DATA (CLALPT(2,J),J=1,11)/4*4.0,2*3.5,4.8,3.7,2*3.1,2.4/
      DATA (NCREW(I),I=1,M)/6.5,6.5/
      DATA (NSTRUC(I),I=1,M)/7.3,7.3/
      DATA (CLMAX(I),I=1,M)/1.3,1.3/
      DATA (DRCSW(K),K=1,KK)/0.1,0.15/
C     ____________________________________________________________
C              1.4 AIRCRAFT POWERPLANT CHARACTERISTICS
C     ____________________________________________________________
C
C        NE    - NUMBER OF ENGINES (UNITS)
C        THAB  - MAXIMUM THRUST (NO AFTERBURNER) VS MACH NUMBER TABLE
C        THNAB - MAXIMUM THRUST W/AFTERBURNER VS. MACH NUMBER TABLE
C              (KILOGRAMS OF THRUST)
C        SABT  - THRUST SPECIFIC FUEL COMPSUMPTION (DRY THRUST)
C        SNABT - THRUST SPECIFIC FUEL COMPSUMPTION (AFTERNURNER ON)
C              (BOTH IN KG./HR/KG.)
C
      DATA (NE(I),I=1,M)/2.,2./
      DATA (THAB(1,J),J=1,11)/8131.,7798.,7851.,8248.,8876.,9625.,
     +    10338.,11056.,11526.,11678.,11425./
      DATA (THNAB(1,J),J=1,11)/5320.,5177.,5242.,5465.,5795.,6183.,
     +    6578.,6930.,7190.,7307.,7231./
      DATA (THAB(2,J),J=1,11)/8131.,7798.,7851.,8248.,8876.,9625.,
     +    10338.,11056.,11526.,11678.,11425./
      DATA (THNAB(2,J),J=1,11)/5320.,5177.,5242.,5465.,5795.,6183.,
     +    6578.,6930.,7190.,7307.,7231./
      DATA (SABT(1,J),J=1,11)/1.61,1.67,1.70,1.72,1.73,1.75,1.79,
     +    1.84,1.89,1.96,2.15/
      DATA (SNABT(1,J),J=1,11)/.9,.91,.92,.94,.96,.98,1.03,1.08,
     +    1.14,1.20,1.30/
      DATA (SABT(2,J),J=1,11)/1.61,1.67,1.70,1.72,1.73,1.75,1.79,
     +    1.84,1.89,1.96,2.15/
      DATA (SNABT(2,J),J=1,11)/.9,.91,.92,.94,.96,.98,1.03,1.08,
     +    1.14,1.20,1.30/
C     ____________________________________________________________
C              1.5 SENSOR CHARACTERISTICS
C     ____________________________________________________________
C
C     1.5.1 AIRCRAFT SENSOR CHARACTERISTICS
C
C     1.5.1.1 RADAR CHARACTERISTICS
C
      DATA (THETAA(J),J=1,N)/5*0.7/
      DATA (THETAE(J),J=1,N)/5*3.14159/
      DATA (PAVE(J),J=1,N)/3*30.,100.,30./
      DATA (TS(J),J=1,N)/5*4./
      DATA (RAREA(J),J=1,N)/3*.25,1.0,0.5/
      DATA (TE(J),J=1,N)/5*1000./
      DATA (LOSS(J),J=1,N)/5*100./
      DATA (SNR(J),J=1,N)/5*10./
      DATA KB/1.38E-23/
C
C     1.5.1.2 INFRARED DETECTOR CHARACTERISTICS      (OPTIONAL)
C     1.5.1.3 RADAR WARNING RECEIVER CHARACTERISTICS
C     1.5.1.4 ACTIVE JAMMER CHARACTERISTICS
C
C        NEECM  - NUMBER OF EXTERNAL ECM PODS
C        WEECM  - MASS OF EXTERNAL ECM POD (KG.)
C
      DATA (NEECM(I),I=1,M)/0.0,0.0/
      DATA (WEECM(I),I=1,M)/1200.,1200./
C
      DATA PSOJ,BWSOJ,GSOJ/150.,2.0E8, 35./
      DATA ZSOJ, XSOJ, YSOJ/ 5000., 0.0, 0.0/
```

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C
C     PSOJ    - STAND-OFF JAMMER POWER (WATTS)
C     BWSOJ   - BAND WIDTH OF THE JAMMER (HERTZ)
C     GSOJ    - STAND-OFF JAMMER GAIN (LINEAR DIMENSIONLES)
C
      DATA PSSJ,BWSSJ,GSSJ/50.,2.0E8, 35./
C
C     1.5.1.3 PASSIVE JAMMER CHARACTERISTICS
C
C     1.5.2 DEFENSIVE SITES SENSOR CHARACTERISTICS
C
C     1.5.2.1 EARLY WARNING/SURVEILLANCE RADAR CHARACTERISTICS
C     1.5.2.2 LOCAL TRACKING RADAR CHARACTERISTICS
C     1.5.2.3 INFRARED SENSOR CHARACTERISTICS
C     1.5.2.4 OPTICAL TRACKING DEVICES              (OPTIONAL)
C
C     ____________________________________________________________
C             1.6 VEHICLE AND SITES SIGNATURES
C     ____________________________________________________________
C
C     1.6.1 AIR VEHICLE SIGNATURES
C
C     1.6.1.1 RADAR SIGNATURE
C
      DATA (RCSC(I),I=1,M)/5.,5./
      DATA (RCSAMT(1,J),J=1,5)/1.0,1.5,5.7,2.3,1.5/
      DATA (RCSAMT(2,J),J=1,5)/1.0,1.5,5.7,2.3,1.5/
      DATA (ATNT(1,J),J=1,5)/0.0,.7855,1.571,2.356,3.1415/
      DATA (ATNT(2,J),J=1,5)/0.0,.7855,1.571,2.356,3.1415/
      DATA (RCSEMT(1,J),J=1,5)/1.0,1.5,2.3,3.5,4.0/
      DATA (RCSEMT(2,J),J=1,5)/1.0,1.5,2.3,3.5,4.0/
      DATA (ELEVT(1,J),J=1,5)/0.0,0.393,0.785,1.178,1.57/
      DATA (ELEVT(2,J),J=1,5)/0.0,0.393,0.785,1.178,1.57/
C
C     1.6.1.2 IR SIGNATURE
C
      DATA (ALTALP(I),I=1,6)/0.04,0.031,0.0225,0.0137,0.005,0.003/
      DATA (ALPHT(I),I=1,6)/0.0,3000.,6000.,9000.,12000.,15000./
C
C     1.6.1.3 VISUAL SIGNATURE        (OPTIONAL)
C     1.6.1.4 AUDITORY SIGNATURE        (OPTIONAL)
C
C     ____________________________________________________________
C                     1.7 WEAPONS
C     ____________________________________________________________
C
C     1.7.1 CARRIER BASED FIGHTER AIRCRAFT WEAPONS
C
C     ASWU    - NUMBER OF AIR-TO-SURFACE WEAPONS (UNITS)
C     ASUW    - AIR-TO-SURFACE WEAPON MASSES (KGS.)
C
      DATA (ASWU(1,K),K=1,KK)/6.0, 10.0/
      DATA (ASWU(2,K),K=1,KK)/6.0, 10.0/
C
      DATA (ASWUW(K),K=1,KK)/350.0, 220.0 /
C
      DATA (ASMRB(1,K),K=1,KK)/35000.0,0.0/
      DATA (ASMRB(2,K),K=1,KK)/35000.0,0.0/
      DATA (ASWS(1,K),K=1,KK)/400.0,0.0/
      DATA (ASWS(2,K),K=1,KK)/400.0,0.0/
      DATA (ASMRAT(1,J),J=1,9)/1.0,1.10,1.2,1.3,1.5,1.65,1.8,2.0,2.5/
      DATA (ASMRAT(2,J),J=1,9)/1.0,1.10,1.2,1.3,1.5,1.65,1.8,2.0,2.5/
      DATA (MACAL(1,J),J=1,9)/1000.,2000.,3000.,4000.,5000.,
     + 6000.,7000.,8000.,9000./
      DATA (MACAL(2,J),J=1,9)/1000.,2000.,3000.,4000.,5000.,
     + 6000.,7000.,8000.,9000./
      DATA (ASMRST(1,J),J=1,5)/0.5,0.75,1.0,1.15,1.20/
      DATA (ASMRST(2,J),J=1,5)/0.5,0.75,1.0,1.15,1.20/
      DATA (MACAS(1,J),J=1,5)/0.4,0.60,0.80,1.0,1.2/
      DATA (MACAS(2,J),J=1,5)/0.4,0.60,0.80,1.0,1.2/
C
      DATA (EASMRT(1,J),J=1,6)/1.0,0.95,0.88,0.78,0.65,0.5/
```

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      DATA (EASMRT(2,J),J=1,6)/1.0,0.95,0.88,0.78,0.65,0.5/
      DATA (ANMR(1,J),J=1,6)/0.0,0.204,0.419,0.628,0.838,1.047/
      DATA (ANMR(2,J),J=1,6)/0.0,0.204,0.419,0.628,0.838,1.047/
      DATA (ASWLR(K),K=1,KK)/3.0,100.0/
C
C     ASBMR  - AIR-TO-SURFACE BASELINE MISSILE RANGE (METERS)
C     ASMRA  - AIR-TO-SURFACE MISSILE RANGE VS. ALTITUDE MULT. (DIM.)
C     ASMRS  - AIR-TO-SURFACE MISSILE RANGE VS. SPEED MULTIPLIER (DIM.)
C     MACAL  - MACH NUMBER VALUES CORRESPONDING TO ASMRA MULTIPLIER
C     MACAS  - MACH NUMBER VALUES CORRESPONDING TO ASMRS MULTIPLIER
C     ANMR   - OFF-BORESIGHT ANGLE TABLE USED IN EASMRT (RAD)
C     EASMRT - TABULAR VALUES OF EFFECTIVE MISSILE RANGE VS.
C              OFF-BORESIGHT LAUNCH MULTIPLIER (DIM)
C
C     1.7.2 DEFENSIVE GROUND SITES WEAPONS
C
C     DWS    - INITIAL NUMBER OF SURFACE-TO-AIR WEAPONS (UNITS)
C
      DATA (DWS(1,L),L=1,LL)/8.0, 0.0, 0.0/
      DATA (DWS(2,L),L=1,LL)/8.0, 0.0, 0.0/
      DATA (DWS(3,L),L=1,LL)/8.0, 0.0, 0.0/
      DATA (DWS(4,L),L=1,LL)/8.0, 8.0, 20000.0/
      DATA (DWS(5,L),L=1,LL)/12.0, 8.0, 20000.0/
      DATA (NDWS(J),J=1,N)/1.0,1.0,1.0,1.0,1.0/
      DATA (MDWLR(L),L=1,LL)/2.0,3.0,2000.0/
C
      DATA (DWFET(1,L),L=1,10)/30000.,45000.,40000.,36000.,30000.
     + ,25000.,20000.,13000.,5000.,0.0/
      DATA (DWFET(2,L),L=1,10)/15000.,23000.,20000.,18000.,15000.,
     +  13000.,10000.,7000.,2500.,0.0/
      DATA (DWFET(3,L),L=1,10)/5000.,7500.,6500.,6000.,5000.
     +  ,4000.,3000.,2000.,1000.,0.0/
      DATA (ADWFE(1,L),L=1,10)/50.,1000.,2000.,3000.,4000.,5000.,6000.
     +     ,7000.,8000.,9000./
      DATA (ADWFE(2,L),L=1,10)/25.,700.,1400.,2100.,2800.,3500.,4200.
     +     ,4900.,5600.,6300./
      DATA (ADWFE(3,L),L=1,10)/100.,200.,400.,800.,1000.,1200.,1400.
     +     ,1600.,1800.,2000./
C
      DATA (APS(I),I=1,LL)/600.,500.,400./
      DATA (PAIMN(L),L=1,LL)/.92,.92,.92/
      DATA (NMISS(L),L=1,LL)/30.,25.,2.01/
C
      DATA (AMCT(1,J),J=1,11)/1.0,0.99,0.97,0.93,0.86,0.50,0.22,0.11
     +     ,0.06,0.03,0.0/
      DATA (AMCT(2,J),J=1,11)/1.0,0.99,0.97,0.93,0.86,0.50,0.22,0.11
     +     ,0.06,0.03,0.0/
      DATA (AMCT(3,J),J=1,11)/11*1.0/
C
C           1.7.3 SINGLE SHOT KILL PROBABILITIES
C
      DATA (PSSCBF(L),L=1,LL)/0.1,0.05,0.001/
      DATA (PSSDWS(K),K=1,KK)/0.1,0.05/
C
C     ------------------------------------------------------------
C                    1.8 DETECTION MECHANISMS
C     ------------------------------------------------------------
C
C                    1.8.1 RADAR DETECTION
C
C     DATA FOR UNIVERSAL CUMMULATIVE PROBABILITY OF DETECTION
C
      DATA (PRDTT(1,I),I=1,7)/0.0,0.51,0.65,0.77,0.85,0.87,0.9/
      DATA (PRDTT(2,I),I=1,7)/0.0,0.41,0.75,0.86,0.92,0.98,1.0/
      DATA (PRDTT(3,I),I=1,7)/0.0,0.28,0.57,0.80,0.95,0.98,1.0/
      DATA (PRDTT(4,I),I=1,7)/0.0,0.50,0.69,0.83,0.94,0.98,1.0/
      DATA (PRDTT(5,I),I=1,7)/0.0,0.44,0.66,0.83,0.94,0.99,1.0/
      DATA (RCROTT(1,I),I=1,7)/-2.5,-4.0,-5.0,-6.0,-7.0,-8.0,-9.0/
      DATA (RCROTT(2,I),I=1,7)/-2.0,-3.0,-4.0,-4.5,-5.0,-6.0,-7.0/
      DATA (RCROTT(3,I),I=1,7)/-1.5,-2.0,-2.5,-3.0,-3.5,-4.0,-4.5/
      DATA (RCROTT(4,I),I=1,7)/-1.0,-1.75,-2.0,-2.25,-2.50,-2.75,-3.0/
      DATA (RCROTT(5,I),I=1,7)/-0.75,-1.25,-1.50,-1.75,-2.0,-2.25,-2.5/
C
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C     CRITICAL ALTITUDES FOR PROBABILITY OF LINE OF SIGHT (PALOS)
C
      DATA (ZLOST(I),I=1,8)/0.0,126.2,504.8,1135.,2020.3,3155.4,
     +      4544.5,6186./
      DATA (RLOST(I),I=1,8)/0.0,40000.,80000.,120000.,
     + 160000.,200000.,240000.,280000./
C
      DATA (PSTFT(I),I=1,11)/0.0,0.05,0.11,0.20,0.29,0.44,0.67,
     + 0.85,0.94,0.98,1.0/
      DATA (TEAFT(I),I=1,11)/1.0,0.9,0.8,0.7,0.6,0.5,0.4,0.3,
     +  0.2,0.1,0.0/
C
C              1.8.2 INFRARED DETECTION
C
      DATA (MUSKIN(I),I=1,2)/3.0,5.0/
      DATA (LTEMT(I),I=1,15)/1000.,2000.,3000.,4000.,5000.,6000.,7000.,
     + 8000.,9000.,10000.,11000.,12000.,13000.,14000.,15000./
      DATA (BLACKT(I),I=1,15)/0.0,.06,.25,.48,.60,.70,.77,.83,.88,.9,
     +  .92,.94,.96,.98,1.00/
C
      DATA (MUPLUM(I),I=1,M)/4.30,4.55/
      DATA (MUENG(I),I=1,M)/3.0,5.0/
      DATA (EGTB(I),I=1,M)/980.,980./
      DATA (APB(I),I=1,M)/2.54E4,2.54E4/
      DATA (AEB(I),I=1,M)/10300.,10300./
C
C       MUPLUM  - PLUME IR SPECTRUM UPPER AND LOWER WAVELENGHTS
C       MUENG   - ENGINE IR SPECTRUM UPPER AND LOWER WAVELENGHTS
C       EGTB    - BASELINE ENGINE EXHAUST GAS TEMPERATURE (DEG.K.)
C       APB     - AIRCRAFT ENGINE BASELINE PLUME AREA (SQ.CM.)
C       AEB     - BASELINE ENGINE EXHAUST AREA (SQ.CM.)
C
      DATA (TSAPT(1,I),I=1,6)/0.9,0.94,0.96,0.99,1.0,1.50/
      DATA (TSAPT(2,I),I=1,6)/0.9,0.94,0.96,0.99,1.0,1.50/
      DATA (TSTAP(1,I),I=1,6)/0.5,0.6,0.7,0.8,0.9,1.0/
      DATA (TSTAP(2,I),I=1,6)/0.5,0.6,0.7,0.8,0.9,1.0/
      DATA (TSEGTT(1,I),I=1,6)/0.6,0.78,0.86,0.94,1.0,2.0/
      DATA (TSEGTT(2,I),I=1,6)/0.6,0.78,0.86,0.94,1.0,2.0/
      DATA (TSTEGT(1,I),I=1,6)/0.5,0.6,0.7,0.8,0.9,1.0/
      DATA (TSTEGT(2,I),I=1,6)/0.5,0.6,0.7,0.8,0.9,1.0/
      DATA (TSAET(1,I),I=1,6)/0.9,0.94,0.97,0.98,1.0,0.96/
      DATA (TSAET(2,I),I=1,6)/0.9,0.94,0.97,0.98,1.0,0.96/
      DATA (TSTAE(1,I),I=1,6)/0.5,0.6,0.7,0.8,0.9,1.0/
      DATA (TSTAE(2,I),I=1,6)/0.5,0.6,0.7,0.8,0.9,1.0/
C
C       TSAPT  - VALUES OF THROTTLE SETTING VS. PLUME AREA MULT.
C       TSTAP  - VALUES OF THROTTLE SETTING FOR TSATP
C       TSEGTT - VALUES OF THROTTLE SETTING FOR TSTEGT
C       TSTEGT - VALUES OF THROTTLE SETTING VS. EGT READINGS
C       TSAET  - VALUES OF THROTTLE SETTING VS. ENGINE EXHAUST AREA
C              MULTIPLIER
C       TSTAE  - VALUES OF THROTTLE SETTING ASSOCIATED WITH TSAET
C
      DATA (IRSAMT(1,J),J=1,7)/0.45,0.60,0.72,0.80,0.87,0.95,1.0/
      DATA (IRSAMT(2,J),J=1,7)/0.45,0.60,0.72,0.80,0.87,0.95,1.0/
      DATA (IRATNT(1,J),J=1,7)/0.0,0.524,1.048,1.572,2.096,2.62,3.1415/
      DATA (IRATNT(2,J),J=1,7)/0.0,0.524,1.048,1.572,2.096,2.62,3.1415/
      DATA (IRSEMT(1,J),J=1,7)/1.0,1.05,1.11,1.17,1.25,1.35,1.50/
      DATA (IRSEMT(2,J),J=1,7)/1.0,1.05,1.11,1.17,1.25,1.35,1.50/
      DATA (IELEVT(1,J),J=1,7)/0.0,0.262,0.524,0.785,1.047,1.31,1.572/
      DATA (IELEVT(2,J),J=1,7)/0.0,0.262,0.524,0.785,1.047,1.31,1.572/
C
C       IRSAMT  - IR SIGNATURE VS. AZIMUTH ASPECT ANGLE MULTIPLIER
C       IRATNT  - VALUES OF TARGET ASPECT ANGLE ASSOCIATED WITH IRSAMT
C       IRSEMT  - IR SIGNATURE VS. ELEVATION ANGLE MULTIPLIER
C       IELEVT  - VALUES OF ELEVATION ANGLE ASSOCIATED WITH IRSEMT
C
      DATA (NEI(I),I=1,M)/2.0E-10,2.0E-10/
      DATA (IRPDT(I),I=1,12)/0.0,0.02,0.04,0.08,0.21,0.45,0.65,0.81,
     +      0.93,0.97,0.99,1.0/
      DATA (IRNOIT(I),I=1,12)/2.0,2.4,2.8,3.2,3.6,4.0,4.4,4.8,5.2,5.6
     +      ,6.0,6.5/
```

```
C
C      NEI    - NOISE EQUIVALENT IR RADIANCE (W/SR)
C      IRPDT  - INFRARED PROBABILITY OF DETECTION CURVE VALUES
C      IRNOIT - IR SIGNAL-TO-NOISE RATIO TABLE VALUES
C
C           1.8.3 PROBABILITY OF VISUAL DETECTION
C
      DATA (VISPDT(I),I=1,11)/0.0,.03,0.1,0.28,0.4,0.65,0.7,0.8,0.9
     +      , 0.96,1.0/
      DATA (TSIZET(I),I=1,11)/0.0,0.0029,0.0058,0.0087,0.0116,0.0145,
     +      0.0175,0.0204,0.0233,0.0262,0.0291/
C
C      VISPDT  - PROBABILITY OF VISUAL DETECTION CURVE VALUES
C      TSIZET  - TARGET SIZE TABLE VALUES ASSOCIATED WITH PROB. OF
C              VISUAL DETECTION
C
C     ____________________________________________________________
C              2. HEADING FOR OUTPUT TABLE
C
C     ____________________________________________________________
C
      WRITE ( 6, 700)
      WRITE ( 6, 800)
C     WRITE ( 6, 600)
C     WRITE ( 4, 300)
C
700   FORMAT ( // 2X, 'TIME ', 2X, 'NDWS(1)', 2X, 'S1DWKD(1)'
C     +  , 2X,'DWSKR', 3X, 'DWSKRD', 3X, 'ASFOT', 2X, 'S1DWKR(1)')
C    600  FORMAT ( // 3X, 'TIME ', 3X, 'TS(DIM) ', 3X, 'DELTAV (M/S)',
C     + 3X, 'VS (M/S)', 4X, 'TSSR (1/SEC)')
C
800   FORMAT ( // 2X, 'TIME ', 4X, 'CBFS(1)', 4X, 'S1CBKD(1)'
C     +  , 4X,'CBFKR', 4X, 'CBFKRD', 4X, 'ARFOT', 4X, 'S1CBKR(1)')
C
C     ____________________________________________________________
C              3. SPECIFICATION STATEMENTS
C
C     ____________________________________________________________
C
      TIME  = 0
      DT    = 5
      FTIME = 100
      ITIME = 0
      DTPRT = 5
C
C         TIME = CURRENT SIMILATION TIME (SEC.)
C         DT   = SIMULATION INTERVAL (SEC.)
C         ITIME = INITIAL TIME OF THE SIMULATION RUN (SEC.)
C         FTIME = FINAL TIME OF THE SIMULATION RUN (SEC.)
C         DTPRT = PRINTING INTERVAL (SEC.)
C
C
C     ____________________________________________________________
C              4. CALCULATION OF INITIAL CONDITIONS
C
C     ____________________________________________________________
C
C       THIS PORTION TO BE USED TO COMPUTE THE FOLLOWING:
C
C          FUEL REQUIREMENTS FOR THE MISSION PER AIRCRAFT
C     ____________________________________________
C        4.1  COMPUTATION OF WEAPON PAYLOAD AND ECM PAYLOAD
C     ____________________________________________
C        PAYLD  - WEAPON PAYLOAD (KG)
C        ECMM   - EXTERNAL ECM EQUIPMENT PAYLOAD (KG)
C        DECMCD - INCREMENT CDO DUE TO EXTERNAL ECM POD (DIM)
C
      GAIN = 1./10000.
      DTR = FLOAT (DT)
      CALL MATRIX ( PAYLD, ASWU, ASWUW, M, KK)
      CALL MATRIX (RCSW, ASWU, DRCSW, M, KK)
C
C
      DO 050 I=1,M
        DECMCD(I) = NEECM(I) * ECMCDO(I)
        ECMM(I)   = NEECM(I) * WEECM(I)
        MASSZF(I) = EMASS(I) + PAYLD(I) + ECMM(I)
        EFUEL(I)  = 5000.
```

```
      WINGK(I)  = 1 / (EFF(I) * AR(I) * PI )
      RCS(I)    = RCSC(I) + RCSW(I)
050   CONTINUE
C
C        C) CHECK FOR OPERATIONAL SUITABILITY FROM AIRCRAFT
C          CARRIER
C
       CALL ATMOS (VS, ALTS, MACH, DELTA, THETA, SIGMA, RHO,
     +    TO, PO, GAMMA, M, Q)
C
C     ____________________________________________________________
C        4.2 computation of aircraft fuel mission requirements
C     ____________________________________________________________
C        4.2.1 FUEL REQUIREMENT FOR HIGH ALTITUDE CRUISE SEGMENT
C     ------------------------------------------------------
C
      DO 901 L=1,3
        DO 752 I=1,M
          MFUEL(I)  = 0.0
          MASSTO(I) = MASSZF(I) + EFUEL(I)
          TCRS(I) = 2. * DISTC(I) / VCRS(I)
752     CONTINUE
        CALL ATMOS (VCRS, ALTCRS, MACH, DELTA, THETA, SIGMA, RHO
     +            , TO, PO, GAMMA, M, Q)
          CALL INTER (MACHD, CDOM, MACH, 11, M, CDOB)
          CALL MATRIX (CDOWE, ASWU, ASCDO, M, KK)
          CALL DRAGF (CDOB, MACH, Q, CDOWE, MASSTO, M, S, AR, EFF,
     +                PI, CDI, CD, CL, DRAG)
          CALL INTER (MACHD, SNABT, MACH, 11, M, SFCU)
          CALL FUEL (DRAG, SFCU, TCRS, M, FFLOW, MFUEL, G)
        DO 880 I=1,M
          FUELCR(I) = MFUEL(I)
          MASSEG(I) = MASSTO(I) - FUELCR(I)/2.
880     CONTINUE
C
C     ------------------------------------------------------
C        4.2.2 FUEL REQUIREMENTS FOR INGRESS AND EGGRESS SEGMENTS
C     ------------------------------------------------------
        NH = 2*W - 2
        DO 751 J=1,NH
          DO 750 I=1,M
            RFUEL(I,J) = 0.0
            DISTS(I,J) = 0.0
            DISTS(I,1) = SQRT( ABS(XWIN(I,1)-XS(I))**2 +
     +                   ABS(YWIN(I,1)-YS(I))**2)
            IF (J .LE. 5) THEN
              DISFX     = ABS(XWIN(I,J+1) - XWIN(I,J))
              DISFY     = ABS(YWIN(I,J+1) - YWIN(I,J))
              DISFSE    = SQRT( DISFX**2 + DISFY**2)
              DISTS (I,J)= DISTS(I,J) + DISFSE
              VSEG(I)   = VTIN(I,J+1)
            ELSE
              K = J - 5
              DISFX     = ABS(XWOUT(I,K+1) - XWOUT(I,K))
              DISFY     = ABS(YWOUT(I,K+1) - YWOUT(I,K))
              DISFSE    = SQRT( DISFX**2 + DISFY**2)
              DISTS (I,J)= DISTS(I,J) + DISFSE
              VSEG(I)   = VTOUT(I,K+1)
            ENDIF
            TSEG(I)    = DISTS(I,J)/VSEG(I)
            RFUEL(I,J) = RFUEL(I,J) + MFUEL(I)
            MASSEG(I)  = MASSEG(I) - RFUEL(I,J)
750       CONTINUE
            CALL ATMOS (VSEG, ALTS, MACH, DELTA, THETA, SIGMA, RHO
     +                , TO, PO, GAMMA, M, Q)
            CALL INTER (MACHD, CDOM, MACH, 11, M, CDOB)
            CALL MATRIX (CDOWE, ASWU, ASCDO, M, KK)
            IF (J .LE. 5) THEN
              CALL DRAGF (CDOB, MACH, Q, CDOWE, MASSEG, M, S, AR,
     +                EFF, PI, CDI, CD, CL, DRAG)
            ELSE
              CALL DRAGF (CDOB, MACH, Q, ZERO, MASSEG, M, S, AR,
```

```
     +              EFF, PI, CDI, CD, CL, DRAG)
          ENDIF
          CALL INTER (MACHD, SNABT, MACH, 11, M, SFCU)
          CALL FUEL (DRAG, SFCU, TSEG, M, FFLOW, MFUEL, G)
751     CONTINUE
C
      CALL SUM2 (FUELS, RFUEL, M, 10)
C
      DO 782 I=1,M
         FUELW(I)  = 1.1 * (FUELCR(I) + FUELS(I))
         DELTAF(I) = ABS(EFUEL(I)-FUELW(I))
         IF (DELTAF(I) .GT. 20.) THEN
            EFUEL(I) = FUELW(I)
            MASSTO(I) = MASSZF(I) + FUELW(I)
         ELSE
            FUELR(I)  = FUELW(I) - FUELCR(I) / 2.
            MASS(I)   = MASSTO(I) - FUELCR(I) / 2.
         ENDIF
782     CONTINUE
901   CONTINUE
C
C          MASSTO  - TAKEOFF MASS (KGS.)
C          MASSZF  - ZERO FUEL AIRCRAFT MASS (KGS.)
C          MASSEG  - MASS AT EACH FLIGHT SEGMENT OF FLIGHT PATH (KGS)
C          MASS    - AIRCRAFT CURRENT MASS (KGS.)
C          FUELR   - FUEL REMAINING ON THE MISSION (KGS.)
C          FUELW   - MASS OF FUEL CARRIED FOR THE MISSION (KGS.)
C          DELTAF  - DELTA MASS USED TO ESTIMATE FUEL REQUIREMENT
C          EFUEL   - FIRST ESTIMATE OF MISSION FUEL FUEL (KGS.)
C          ALTCRS  - CRUISE ALTITUDE (METERS)
C          VCRS    - CRUISE SPEED (HIGH ALTITUDE SEGMENT) IN METERS
C          FUELCR  - FUEL MASS CONSUMED IN CRUISE SEGMENT (KGS.)
C          TCRS    - TIME SPENT IN CRUISE SEGMENT (SECONDS)
C     ------------------------------------------------
C      4.3  COMPUTE INITIAL AIRCRAFT STEADY PERFORMANCE PARAMETERS
C     ------------------------------------------------
C
      DO 009 I=1,M
        CL(I)  = MASS(I) * G / (Q(I) * S(I))
        B(I)   = SQRT (S(I) * AR(I))
       AS(I)     = 10. ** (K1 + ALOG10 (MASS(I) ** K2)) * (10000./
     +             10.7584)
009   CONTINUE
C
      DO 098 I=1,M
        DO 098 J=1,N
          DO 098 L=1,LL
            DO 098 K=1,10
              CBFQUE(I,J,L,K) = 0.0
098   CONTINUE
C
      DO 101 I=1,M
        DO 101 J=1,N
          DO 101 K=1,KK
            DO 101 L=1,10
              DWSQUE(I,J,K,L) = 0.0
101   CONTINUE
C
C     ------------------------------------------------
C                4.3 RADAR PARAMETER COMPUTATIONS
C     ------------------------------------------------
C
        JDSSJ = PSSJ * GSSJ / BWSSJ
        JDSOJ = PSOJ * GSOJ / BWSOJ
C
      DO 018 J=1,N
      OMEGA(J) = THETAA(J) * THETAE(J)
        RRPNJ(J) = (PAVE(J) * RAREA(J) * TS(J) / (16.* KB * TE(J) *
     +          LOSS(J) * SNR(J) * OMEGA(J))) **.25
        RRPSSJ(J) = (32. * PAVE(J) * TS(J) / (PI * OMEGA(J) * JDSSJ
     +           * LOSS(J))) ** .5
        RRPSOJ(J) = (32. * PAVE(J) * TS(J) / (PI * OMEGA(J) * JDSOJ
```

```
     +           * LOSS(J))) ** .25
018  CONTINUE
C
C
     CALL YAWRTE (NMISS, APS, LL, G, SAIWEA)
C
C
C     ------------------------------------------------------------
C               5. SIMULATION LOOP (DYNAMIC MODULE)
C     ------------------------------------------------------------
C
     NSTEP = ( FTIME - ITIME ) / DT
     NPSTP = DTPRT / DT
     KP    = NPSTP
     DO 001 T=1,NSTEP
C
C
C     ------------------------------------------------------------
C               6.  COMPUTATION OF AUXILIARY VARIABLES
C     ------------------------------------------------------------
C
C               6.1 ENGAGEMENT GEOMETRY DESCRIPTION
C     ------------------------------------------------------------
C
C       CHECK IF TARGET AREA ( XWIN(1,6) ) HAS BEEN REACHED
C
        DO 021 I=1,M
          IF (XS(I) .GE. XWIN(I,6)) THEN
            RTIMER(I) = 1
          ELSE
            RTIMER(I) = 0
          ENDIF
          TIMER(I) = TIMER(I) + RTIMER(I)
021     CONTINUE
C
C       CHECK IF CARRIER BATTLE GROUP HAS BEEN REACHED
C
        DO 022 I=1,M
          IF (XS(I) .LT. XWOUT(I,6)) THEN
            RTIM(I) = 1
          ELSE
            RTIM(I) = 0
          ENDIF
          ENTIME(I) = ENTIME(I) + RTIM(I)
          IF (ENTIME(I) .GT. 1) GOTO 1000
022     CONTINUE
C
C         TSSR  - THROTTLE SETTING RATE OF CHANGE (1/SEC)
C         LFSR  - LOAD FACTOR FOR AIRCRAFT (G'S)
C         TSS   - THROTTLE SETTING (DIM)
C         LFS   - AIRCRAFT INSTANTANEOUS LOAD FACTOR (G'S)
C
C     ------------------------------------------------------------
C     6.1.1 COMPUTATION OF AIRCRAFT RANGE AND LOS TO TARGET (METERS)
C     ------------------------------------------------------------
C
C           ARTTX  - AIRCRAFT DOWNRANGE TO TARGET (METERS)
C           ARTTY  - AIRCRAFT LATERAL DOWNRANGE TO TARGET (METERS)
C           ARTT   - AIRCRAFT RANGE TO TARGET (METERS)
C
      CALL DISTT (XS, YS, XDWS, YDWS, ARTTX, ARTTY, ARTT, M, N,
     +           LOSATT, PI)
C
C     ------------------------------------------------------------
C     6.1.2 COMPUTATION OF SLANT RANGE AND ELEVATION ANGLE TO TARGET
C     ------------------------------------------------------------
C
        DO 017 I=1,M
          DO 017 J=1,N
            SRL(I,J)   = SQRT (ARTT(I,J)**2 + ALTS(I)**2)
            ELEV(I,J)  = ARCOS (ARTT(I,J)/SRL(I,J))
            TSIZE(I,J) = ATAN (B(I)/SRL(I,J))
017     CONTINUE
C
```

```
C     ------------------------------------------------------
C          6.1.3 COMPUTATION OF TARGET ASPECT ANGLE (RADIANS)
C     ------------------------------------------------------
C
C          LOSATT - LOS VECTOR FROM AIRCRAFT TO TARGET (RADIANS)
C          HEADS  - AIRCRAFT HEADING (RADIANS)
C          ATN    - AIRCRAFT TARGET ASPECT ANGLE (RAD.)
C
          CALL DIRECT (HEADS, LOSATT, YS, YDWS, M, N, PI, ATN)
C
C     ------------------------------------------------------
C       6.1.4 COMPUTATION OF THE LINE-OF-SIGHT TARGET ASPECT ANGLE
C          AND RATE OF CHANGE IN LINE OF SIGHT ASPECT ANGLE
C     ------------------------------------------------------
C
          DO 024 I=1,M
            DO 024 J=1,N
              IF (LOSATT(I,J) .GE. PI) THEN
                  LOSTAA(I,J) = LOSATT(I,J) - PI
              ELSE
                  LOSTAA(I,J) = PI + LOSATT(I,J)
              ENDIF
               VAPPR(I,J) = VS(I) * COS(ATN(I,J))
               VAPPT(I,J) = VS(I) * SIN(ATN(I,J))
               ATND(I,J)  = ATAN(VAPPT(I,J) / SRL(I,J))
024       CONTINUE
C
C          ATND   - RATE OF CHANGE IN AIRCRAFT TARGET ASPECT ANGLE
C          TAAD   - RATE OF CHANGE IN DWS TARGET ASPECT ANGLE R/SEC)
C          VAPPR  - AIRCRAFT RADIAL APPROACHING SPEED TO TARGET
C          VAPPT  - AIRCRAFT TANGENTIAL APPROACHING SPEED TO TARGET
C
C     ------------------------------------------------------
C       6.1.5 COMPUTATION OF AIRCRAFT RANGE AND LOS TO WAYPOINT
C          COMPUTATION OF AIRCRAFT BEARING ANGLE TO WAYPOINT
C     ------------------------------------------------------
C
C          ARTWIX  - AIRCRAFT DOWNRANGE TO WAYPOINT (METERS)
C          ARTWIY  - AIRCRAFT LATERAL DOWNRANGE TO WAYPOINT (METERS)
C          ARTT    - AIRCRAFT TO WAYPOINT (METERS)
C          LOSAWI - LOS VECTOR FROM AIRCRAFT TO WAYPOINT (RADIANS)
C          HEADS  - AIRCRAFT HEADING (RADIANS)
C
          NW = W - 1
          DO 012 I=1,M
            IF (TIMER(I) .GE. 1) THEN
              CALL DISTW (XS, YS, XWOUT,YWOUT,ARTWOX, ARTWOY, ARTWO,
     +              M, W, LOSAWO, PI)
              CALL DIRECW (HEADS, LOSAWO, YS, YWOUT, M, W, PI
     +              , ABAOUT)
              IF (XS(I) .GT. XWOUT(I,1)) THEN
                STVDA(I) = ABAOUT(I,1)
                DELTAV(I) = VTOUT(I,1) - VS(I)
              ELSE
                DO 013 J=1,NW
                  IF (XS(I) .LT. XWOUT(I,J)) THEN
                      STVDA(I) = ABAOUT(I,J+1)
                      DELTAV(I) = VTOUT(I,J+1) - VS(I)
                  ENDIF
013             CONTINUE
              ENDIF
            ELSE
              CALL DISTW (XS, YS, XWIN, YWIN, ARTWIX, ARTWIY, ARTWI
     +              , M, W, LOSAWI, PI)
              CALL DIRECW (HEADS, LOSAWI, YS, YWIN, M, W, PI, ABAIN)
              IF (XS(I) .LT. XWIN(I,1)) THEN
                STVDA(I) = ABAIN(I,1)
                DELTAV(I) = VTIN(I,1) - VS(I)
              ELSE
                DO 016 J=1,NW
                  IF (XS(I) .GT. XWIN(I,J)) THEN
                      STVDA(I) = ABAIN(I,J+1)
```

```
                  DELTAV(I) = VTOUT(I,J+1) - VS(I)
                ENDIF
016           CONTINUE
            ENDIF
          ENDIF
012       CONTINUE
C
C           STVDA  - STEERING VECTOR DIRECTION (TO NEXT WAYPOINT)
C           DELTA  - DIFFERENTIAL SPEED FROM TARGET WAYPOINT SPEED
C           VTOUT  - EGRESS WAYPOINT TARGET SPEED (M/SEC.)
C           VTIN   - INGRESS WAYPOINT TARGET SPEED (M/SEC.)
C           ABAIN  - AIRCRAFT BEARING ANGLE TO EGRESS WAYPOINT (RAD)
C           VTIN   - AIRCRAFT BEARING ANGLE TO INGRESS WAYPOINT (RAD)
C
C     ------------------------------------------------------
C           6.1.6 COMPUTATION OF ATMOSPHERIC CHARACTERISTICS
C     ------------------------------------------------------
C           VS     - AIRCRAFT VELOCITY (MAGNITUDE) IN M/SEC.
C           ALTS   - AIRCRAFT ALTITUDE (METERS ABOVE MSL)
C           MACH   - AIRCRAFT MACH NUMBER (DIM)
C           DELTA  - ATMOSPHERIC PRESSURE RATIO (DIM)
C           THETA  - ATMOSPHERIC TEMPERATURE RATIO (DIM)
C           SIGMA  - ATMOSPHERIC DENSITY RATIO (DIM)
C
      CALL ATMOS (VS, ALTS, MACH, DELTA, THETA, SIGMA, RHO,
     +    TO, PO, GAMMA, M, Q)
C
C     ------------------------------------------------------
C                6.2 COMPUTATION OF THRUST AND DRAG
C     ------------------------------------------------------
C
C       6.2.1 COMPUTE LIFT CURVE SLOPE AND ZERO-LIFT DRAG COEFFICIENT
C
      CALL INTER(MACHD, CLALPT, MACH, 11, 2, CLALP)
      CALL INTER(MACHD, CDOM, MACH, 11, 2, CDOB)
      CALL MATRIX ( CDOWE, ASWU, ASCDO, M, KK)
C
      DO 015 I=1,M
        CDI(I)  = CL(I)**2 /( PI * AR(I) * EFF(I) )
        ALP(I)  = CL(I) / CLALP(I) + ALPO(I)
        CDO(I)  = CDOB(I) + CDOWE(I) + DECMCD(I)
        CD(I)   = CDO(I) + CDI(I)
        DRAG(I) = Q(I) * S(I) * CD (I)
        IF (TSS(I).GT.0.9) THEN
           CALL INTER(MACHD, THAB, MACH, 11, 2, TRUST)
           CALL INTER(MACHD, SABT, MACH, 11, 2, SFCU)
           THRUST(I)  = TSS(I)*TRUST(I)*NE(I)*G*SIGMA(I)
         ELSE
           CALL INTER(MACHD, THNAB, MACH, 11, 2, TRUST)
           CALL INTER(MACHD, SNABT, MACH, 11, 2, SFCU)
           THRUST(I)  = TSS(I)*TRUST(I)*NE(I)*G*SIGMA(I)*1.1111
        ENDIF
        TSFC(I)   = SFCU(I) / THETA(I)
        FFLOW(I)  = THRUST(I) * TSFC(I) / ( G * 3600)
        PTRUST(I) = TRUST(I)*G*NE(I)
        STGTEM(I) = THETA(I) * TO * ( 1 + R * (GAMMA - 1)/ 2 *
     +              MACH(I) )
015     CONTINUE
C
C     DRAG   - TOTAL AIRCRAFT DRAG (NEWTONS)
C     CDOWE  - INCREMENTAL DRAG COEFFICIENT DUE TO WEAPONS
C     TSS    - AIRCRAFT THROTTLE SETTING (DIM)
C     NE     - NUMBER OF ENGINES PER AIRCRAFT (UNITS)
C     Q      - DYNAMIC PRESSURE (PASCALS)
C     S      - AIRCRAFT WING AREA (SQUARE METERS)
C     THRUST - COMMANDED ENGINE THRUST (NEWTONS)
C     TRUST  - MAXIMUM AVAILABLE ENGINE GROSS THRUST AT SEA LEVEL
C     SFCU   - UNCORRECTED SPECIFIC FUEL CONSUMPTION (KG/HR/KG)
C     3600   - CONVERSION FACTOR FROM HOURS TO SECONDS
C
   CALL LOADF (Q, MASS, S, WINGK, PTRUST, CDO, M, G, NFAC)
   CALL YAWRTE (NFAC, VS, M, G, YAWR)
```

```
      CALL PS (VS, MASS, G, PTRUST, DRAG, M, PSA)
C
C     ------------------------------------------------------
C             6.3 COMPUTE MAXIMUM SUSTAINED PERFORMANCE
C     ------------------------------------------------------
C     6.3.1 COMPUTE MAXIMUM USABLE LOAD FACTOR CONSTRAINED BY CREW
C         TOLERANCE,STRUCTURAL INTEGRITY , AND THRUST CONSIDERATIONS.
C     ------------------------------------------------------
C
      DO 014 I=1,M
        NAMAX(I) = AMIN1(NFAC(I), AMIN1(NCREW(I), NSTRUC(I)))
        CLNAX(I) = NAMAX(I)*MASS(I)*G / (Q(I)*S(I))
        CLUS(I)  = AMIN1(CLNAX(I), CLMAX(I))
        NUS(I)   = AMAX1(Q(I)*S(I)*CLUS(I)/(MASS(I)*G), 1.0001)
        SAIRUS(I)= G * SQRT(NUS(I)** 2 - 1)/ VS(I)
C       CALL SVECT (SAIRUS, STVDA, M, PI, SAICO, DT)
          IF (ABS(STVDA(I)). LE. SAIRUS(I)*FLOAT(DT)) THEN
              SAICO(I) = - STVDA(I) / FLOAT(DT)
          ELSE
              IF (STVDA(I). GE. 0) THEN
          SAICO(I) = - SAIRUS(I)
      ELSE
          SAICO(I) = SAIRUS(I)
      ENDIF
    ENDIF
  NCOM(I)  = SQRT(1 + (ABS(SAICO(I)) * VS(I) / G)**2)
  CL(I)    = NCOM(I)*MASS(I)*G / (Q(I)*S(I)) 014   CONTINUE
C
C     ------------------------------------------------------
C          6.4  COMPUTATION OF AIR-TO-SURFACE WEAPON RANGES
C     ------------------------------------------------------
C
  CALL INTER(MACAS, ASMRST, MACH, 5, M, ASMRS)
  CALL INTER(MACAL, ASMRAT, ALTS, 9, M, ASMRA)
  CALL INTE(ANMR, EASMRT, ATN, M, N, 6, ASMRO)
C
        DO 053 I=1,M
          DO 053 J=1,N
            ASMR(I,1)    = ASMRB(I,1) * ASMRS(I) * ASMRA(I)
            TIM(I)       = SQRT (2. * ALTS(I) / G)
            ASMR(I,2)    = TIM(I) * VS(I) /2.
            IF (ABS(ATN(I,J)) .GT. ANMR(I,6)) THEN
               EASMR(I,J,1) = 0.0
            ELSE
               EASMR(I,J,1) = ASMR(I,1) * ASMRO(I,J)
            ENDIF
          EASMR(I,J,2) = ASMR(I,2)
          ASFOT(I,J,1) = SRL(I,J) / ASWS(I,1)
          ASFOT(I,J,2) = TIM(I)
  053     CONTINUE
C
C          ASMR  - AIR-TO-SURFACE MISSILE RANGE (METERS)
C          ASMRA - AIR-TO-SURFACE MISSILE RANGE VS ALT. MULT.(METERS)
C          ASMRS - AIR-TO-SURFACE MISSILE RANGE VS SPEED (METERS)
C          TIM   - BOMB TIME OF FLIGHT (SECONDS)
C          ASBR  - BOMB ANTICIPATION DROP RANGE (METERS)
C          ASMRO - AIR-TO-SURFACE MISSILE RANGE VS. OFF-BORESIGHT
C                  CAPABILITY MULTIPLIER (DIM)
C          EASMR - EFFECTIVE AIR-TO-SURFACE MISSILE RANGE (M.)
C
C     ------------------------------------------------------
C             6.5 COMPUTATION OF RADAR SIGNATURE (RCS)
C     ------------------------------------------------------
C
C
        CALL INTE(ATNT, RCSAMT, ATN, M, N, 5, RCSAM)
        CALL INTE(ELEVT, RCSEMT, ELEV, M, N, 5, RCSEM)
C
        DO 056 I=1,M
          DO 056 J=1,N
            ERCS(I,J) = RCS(I) * RCSAM(I,J) * RCSEM(I,J)
  056     CONTINUE
```

```
C
C       COMPUTATION OF RADAR RANGE (NO JAMMING EQUATION)
C       COMPUTATION OF THE TARGET APPROACHING SPEED TO RADAR
C
        DO 027 I=1,M
          DO 027 J=1,N
            DR(I,J)    = ABS (VAPPR(I,J) * TS(J))
            DXSOJ(I)   = AMAX1(XS(I)-XSOJ,XSOJ-XS(I))
            DYSOJ(I)   = AMAX1(YS(I)-YSOJ,YSOJ-YS(I))
            DZSOJ(I)   = AMAX1(ALTS(I)-ZSOJ,ZSOJ-ALTS(I))
            RJSOJ(I)   = SQRT(DXSOJ(I)**2 + DYSOJ(I)**2 +
     +                   DZSOJ(I)**2)
027     CONTINUE
C
        DO 630 I=1,M
          DO 630 J=1,N
            IF (NRADPO .EQ. 1) THEN
              DRO(I,J)  = RRPNJ(J) * ERCS(I,J)**.25
            ELSE IF (NRADPO .EQ. 2) THEN
              DRO(I,J)  = RRPSOJ(J) * ERCS(I,J)**.25 *
     +                    RJSOJ(I) ** 0.5
            ELSE
              DRO(I,J)  = RRPSSJ(J) * ERCS(I,J)**.50
            ENDIF
630     CONTINUE
C
C       COMPUTATION OF RANGE AND RANGE RATE PARAMETERS USED IN
C       THE ESTIMATION OF THE PROBABILITY OF RADAR DETECTION
C
        CALL RATINV (SRL, DRO, M, N, RCDRO)
        CALL RATINV (DRO, DR, M, N, DRODR)
C
C         SRL   - AIRCRAFT TO TARGET SLANT RANGE (METERS)
C         DRO   - SINGLE SCAN RADAR RANGE (METERS)
C         RCDRO  - RATIO OF AIRCRAFT-TO-TARGET RANGE TO DRO RANGE
C
C   ------------------------------------------------
C       6.6 COMPUTATION OF DEFENSE WEAPONS FIRING ENVELOPES
C   ------------------------------------------------
C
        CALL DWKE(ADWFE, DWFET, ALTS, M, 3, 10, RDWFE)
C
C         ADWFE  - ALTITUDE VALUES ASSOCIATED WITH DWFET (M.)
C         DWFET  - TABLE CONTAINING RANGE VALUES FOR EACH DWFE (M.)
C         ALTS   - AIRCRAFT ALTITUDE FOR A GIVEN SEGMENT (M.)
C         RDWFE  - DWFE RANGE FROM I TH AIRCRAFT TO J TH SITE WITH
C                  L TH WEAPON
C
C   ------------------------------------------------------------
C   6.7 COMPUTATION OF THE PROBABILITY OF AIRCRAFT IN LINE OF SIGHT
C   ------------------------------------------------------------
C
        CALL DOUBL(RLOST, ZLOST, ARTT, M, N, 8, LOS)
        DO 028 I=1,M
          DO 028 J=1,N
            IF (ALTS(I) .GT. LOS(I,J)) THEN
              PALOS(I,J) = 1.0
            ELSE
              PALOS(I,J) = 0.0
            ENDIF
028     CONTINUE
C
C   ------------------------------------------------
C       6.8 COMPUTATION OF PROBABILITY OF RADAR DETECTION
C   ------------------------------------------------
C
        CALL PRADAR(PRDTT, RCROTT, DRODR, RCDRO, M, N, 5, 7, PRAD)
C
C         PRAD  - PROBABILITY OF RADAR DETECTION
C         PRDTT - TABLE CONTAINING VALUES OF PROB. OF DETECTION FOR
C                 SWERLING I MODEL (SEE BROOKNER)
C         RCDRO - RATIO OF SLANT RANGE TO AIRCRAFT AND SINGLE SCAN
C                 RADAR RANGE (DRO)
```

```
C
C   ------------------------------------------------------------
C       6.9 COMPUTATION OF INFRARED PROBABILTY OF DETECTION
C   ------------------------------------------------------------
C
        CALL INTER (TSTAP, TSAPT, TSS, 6, M, TSAPM)
        CALL INTER (TSTEGT, TSEGTT, TSS, 6, M, TSEGTM)
        CALL INTER (TSTAE, TSAET, TSS, 6, M, TSAEM)
C
    DO 039 I=1,M
        AE(I)  = AEB(I) * TSAEM(I) * NE(I)
        EGT(I) = EGTB(I) * TSEGTM(I)
        AP(I)  = APB(I) * TSAPM(I) * NE(I)
        JE(I)  = EMM * SIG * EGT(I) ** 4. * AE(I) / (4.*PI)
        JP(I)  = 0.5 * SIG * (0.85 * EGT(I)) **4. * AP(I)
   +           / (4.*PI)
        JS(I)  = EMM * SIG * STGTEM(I) ** 4. * .25 * AS(I)
   +           / (4.*PI)
039  CONTINUE
C
C         AE     - AIRCRAFT ENGINE EXHAUST AREA (SQ. CM)
C         EGT    - AIRCRAFT ENGINE EXHAUST GAS TEMPERATURE (D.K)
C         AP     - AIRCRAFT ENGINE EXHAUST PLUME AREA (SQ. CM)
C         AS     - AIRCRAFT WETTED AREA (SQ. CM)
C         NE     - NUMBER OF AIRCRAFT ENGINES (UNITS)
C
C         SKIN FRICTION INFRARED SIGNAL
C
C         JSEFF  - EFFECTIVE SKIN FRICTION IR RADIANCE (W/SR)
C         JS     - AIRCRAFT SKIN IR RADIANCE (W/SR)
C         BLACKT - TABLE VALUES FOR UNIVERSAL BLACKBODY CURVES
C         STGTEM - AIRCRAFT STAGNATION TEMPERATURE (DEG. KELVIN)
C         MUSKIN - SKIN FRICTION IR SPECTRAL EMMISSION BAND
C                  VALUES (MICRONS)
C                    MULOW = MUSKIN(1)
C                    MUHIHG = MUSKIN(2)
C
      CALL SPECTR (LTEMT, BLACKT, STGTEM, MUSKIN, M, 15, 2, JS,
   +    JSEFF)
C
C         ENGINE EXHAUST PLUME INFRARED SIGNAL
C
C         JPEFF  - EFFECTIVE ENGINE PLUME IR RADIANCE (W/SR)
C         JP     - PLUME IR RADIANCE (W/SR)
C         MUPLUM - ENGINE PLUME IR SPECTRAL EMMISSION BAND
C                  VALUES (MICRONS)
C                    MULOW = MUPLUM(1)
C                    MUHIHG = MUPLUM(2)
C
      CALL SPECTR (LTEMT, BLACKT, EGT, MUPLUM, M, 15, 2, JP,
   +    JPEFF)
C
C         ENGINE EXHAUST INFRARED SIGNAL
C
C         JEFF   - EFFECTIVE ENGINE EXHAUST IR RADIANCE (W/SR)
C         JE     - ENGINE EXHAUST IR RADIANCE (W/SR)
C         MUENG  - ENGINE EXHAUST IR SPECTRAL EMMISSION BAND
C                  VALUES (MICRONS)
C                    MULOW = MUENG(1)
C                    MUHIHG = MUENG(2)
C
      CALL SPECTR (LTEMT, BLACKT, EGT, MUENG, M, 15, 2, JE,
   +    JEFF)
C
      DO 055 I=1,M
          JTOTE(I) = JEFF(I) + JPEFF(I) + JSEFF(I)
055    CONTINUE
C
C       AZIMUTH AND ELEVATION ANGLE CORRECTIONS TO IR SIGNAL
C
     CALL INTE (IRATNT, IRSAMT, ATN, M, N, 7, IRSAM)
     CALL INTE (IELEVT, IRSEMT, ELEV, M, N, 7, IRSEM)
```

```
      CALL SINGL (ALPHT, ALTALP, ALTS, M, 6, ALF)
C
        DO 043 I=1,M
          DO 043 J=1,N
            JA(I,J)    = JTOTE(I) * IRSAM(I,J) * IRSEM(I,J)
            TAU(I,J)   = EXP(- ALF(I) * SRL(I,J)/1000.)
            HT(I,J)    = JA(I,J) * TAU(I,J) / ( SRL(I,J) *
     +                   100.) ** 2
            SNOISE(I,J) = HT(I,J) / NEI(I)
043     CONTINUE
C
      CALL DOUBL (IRNOIT, IRPDT, SNOISE, M, N, 12, PDIR)
C
C       IRNOIT - INFRARED NOISE TABULAR VALUES ASSOCIATED WITH
C                CURVES OF PROBABILITY OF IR DETECTION (DIM.)
C       IRPDT  - TABULAR VALUES FOR PROB. OF IR DETECTION (DIM.)
C       PDIR   - PROBABILITY OF INFRARED DETECTION (DIM.)
C       SNOISE - INFRARED SIGNAL-TO-NOISE RATIO (DIM.)
C
C   ------------------------------------------------
C             6.10 PROBABILITY OF VISUAL DETECTION
C   ------------------------------------------------
C
      CALL DOUBL (TSIZET, VISPDT, TSIZE, M, N, 11, PVDET)
C
C       TSIZE  - TARGET SIZE (RADIANS)
C       VISPDT - VALUE OF PROBABILITY OF VISUAL DETECTION FOR A
C                GIVEN CONTRAST (DIM.)
C       PVDET  - PROBABILITY OF AIRCRAFT VISUAL DETECTION (DIM.)
C
C   ------------------------------------------------
C           6.10.1 PROBABILITY OF AIRCRAFT DETECTION (PAD)
C   ------------------------------------------------
C
      DO 123 I=1,M
        DO 123 J=1,N
          PAD(I,J) = AMAX1( PRAD(I,J) ,AMAX1( PDIR(I,J),
     +               PVDET(I,J)))
123     CONTINUE
C
C   ------------------------------------------------
C             6.11 PROBABILITIES OF AIRCRAFT TRACKING
C   ------------------------------------------------
C         6.11.1  RADAR TRACKING (THRESHOLD AT PRAD = 0.9)
C   ------------------------------------------------
C
      DO 072 I = 1,M
        DO 072 J = 1,N
          IF (PRAD(I,J) .GE. 0.9) THEN
            PT(I,J,1) = 1.0
          ELSE
            PT(I,J,1) = 0.0
          ENDIF
072     CONTINUE
C
C   ------------------------------------------------
C         6.11.2  INFRARED TRACKING (THRESHOLD AT 90 %)
C   ------------------------------------------------
C
      DO 178 I = 1,M
        DO 178 J = 1,N
          IF (PDIR(I,J) .GE. 0.9) THEN
            PT(I,J,2) = 1.0
          ELSE
            PT(I,J,2) = 0.0
          ENDIF
178     CONTINUE
C
C   ------------------------------------------------
C                 6.11.3  VISUAL TRACKING
C   ------------------------------------------------
C
```

```
      DO 083 I = 1,M
        DO 083 J = 1,N
            PT(I,J,3) = PVDET(I,J)
083    CONTINUE
C
C     ------------------------------------------------------------------
C           6.12 PROBABILITY OF DEFENSE WEAPONS LAUNCH
C     ------------------------------------------------------------------
C
C       6.12.1 PROBABILITY OF HAVING SUFFICIENT TIME FOR FIRING
C
      DO 034 I=1,M
        DO 034 J=1,N
          DO 034 L=1,LL
            AATT(I,J,L)   = 0.0
            DEDWFE(I,J,L) = 2. * RDWFE(I,L) * COS (ABS(ATN(I,J)))
            TAIE(I,J,L)   = DEDWFE(I,J,L) / VS(I)
            ARFOT(I,J,L)  = SRL(I,J) / (APS(L) + VAPPR(I,J))
            ATFOT(I,J,L)  = ARFOT(I,J,L) + AATT(I,J,L)
034    CONTINUE
C
      CALL PTF (PSTFT, TEAFT, TAIE, ATFOT, M, N, LL, 11, PSTF)
C
C       6.12.2 PROBABILITY OF AIRCRAFT IN THE FIRING ENVELOPE
C
      DO 071 I=1,M
        DO 071 J=1,N
          DO 071 L=1,LL
            IF (SRL(I,J) .LE. RDWFE(I,L)) THEN
              PAFE(I,J,L) = 1.0
            ELSE
              PAFE(I,J,L) = 0.0
            ENDIF
          PDWL(I,J,L) = PT(I,J,L) * PAFE(I,J,L) * PSTF(I,J,L)
071     CONTINUE
C
C     ------------------------------------------------------------------
C     6.13 PROBABILITY OF DEFENSE WEAPONS GUIDANCE AND DETONATION
C     ------------------------------------------------------------
C           6.13.1 PROBABILITY OF SUCCESSFUL GUIDANCE
C     ------------------------------------------------------------
C
      DO 078 I=1,M
        DO 078 J=1,N
          DO 078 L=1,LL
            PAIM(I,L)   = PAIMN(L)
            PAMC(I,L)   = 0.94
            PAWC(I,J,L) = 0.92
            PTHAC(I,J,L) = PAMC(I,L) * PAWC(I,J,L)
            PGCMC(I,L)  = 0.91
            PLOHC(I,L)  = 0.90
078    CONTINUE
C
      DO 073 I=1,M
        DO 073 J=1,N
          DO 073 L=1,LL
            PSG(I,J,L) = PAIM(I,L) * PTHAC(I,J,L) *
     +                   PGCMC(I,L) * PLOHC(I,L)
073    CONTINUE
C
C       PAIM   - AIMING PROBABILITY (DIM.)
C       PTHAC  - PROBABILITY OF THREAT HOMING AVOIDANCE
C                CAPABILITY (DIM.)
C       PGCMC  - PROBABILITY OF GUIDANCE COUNTERMEASURE
C                CAPABILITY (DIM.)
C       PLOHC  - PROBABILITY OF LOCK-ON AND HOMMING CAPABILITY
C
C     ------------------------------------------------------------
C           6.13.2 PROBABILITY OF DETONATION
C     ------------------------------------------------------------
C
      DO 175 I=1,M
        DO 175 J=1,N
```

```
            DO 175 L=1,LL
              PDET(I,J,L)  = 0.8
175       CONTINUE
C
C           PDET   - PROBABILITY OF WEAPONS DETONATION (DIM)
C
C     ------------------------------------------------------
C         6.13.3 PROBABILITY OF THREAT SYSTEM EFFECTIVENESS (PTSE)
C              NUMBER OF DEFENSE PROPAGATORS LAUNCHED (DWPL)
C     ------------------------------------------------------
C
          DO 075 I=1,M
            DO 075 J=1,N
              DO 075 L=1,LL
                DWPL(I,J,L) = AMIN1(DWS(J,L) / FLOAT(DT),
     +                MDWLR(L) * DWS(J,L) * PDWL(I,J,L) / 60.)
                PTSE(I,J,L) = PALOS(I,J) * PDWL(I,J,L) * PSG(I,J,L)
     +            * PDET(I,J,L)
075       CONTINUE
C
C           DWPL  - DEFENSE WEAPON PROPAGATORS LAUNCHED (UNITS)
C           MDWLR - MAXIMUM DEFENSE WEAPONS LAUNCH RATE (UNITS/MIN.)
C           DWS   - NUMBER OF DEFENSE WEAPONS (UNITS)
C           PTSE  - PROBABILITY OF THREAT SYSTEM EFFECTIVENESS (DIM.)
C           PALOS - PROBABILITY OF AIRCRAFT IN LINE OF SIGHT (DIM.)
C           PDWL  - PROBABILITY OF DEFENSE WEAPONS LAUNCH (DIM.)
C           PSG   - PROBABILITY OF DWS WEAPON SUCCESSFUL GUIDANCE
C           PDET  - PROBABILITY OF WEAPONS DETONATION (DIM)
C     ------------------------------------------------------
C           6.13.4 PROBABILITY OF AIRCRAFT KILL (PKCBF)
C     ------------------------------------------------------
C
          DO 77 I=1,M
            DO 77 J=1,N
              DO 77 L=1,LL
                PKCBF(I,J,L)  =  PTSE(I,J,L) - PTSE(I,J,L) *
     +                        (1. - PSSCBF(L)) ** DWPL(I,J,L)
77        CONTINUE
C
C           PKCBF - KILL PROBABILITY OF CBF AIRCRAFT (DIM.)
C           PTSE  - PROBABILITY OF THREAT SYSTEM EFFECTIVENESS (DIM.)
C           DWPL  - DEFENSE WEAPON PROPAGATORS LAUNCHED (UNITS)
C           PSSCBF- PROBABILITY OF SINGLE SHOT CBF AIRCRAFT KILL (DIM)
C
C     ------------------------------------------------------
C       6.14 PROBABILITY OF THREAT DETECTION AND IDENTIFICATION
C     ------------------------------------------------------
C
          DO 201 I=1,M
            DO 201 J=1,N
              IF (SRL(I,J) .LE. 35000.) THEN
                TDI(I,J,1) = 1.0
              ELSE
                TDI(I,J,1) = 0.0
              ENDIF
201       CONTINUE
C
          DO 203 I=1,M
            DO 203 J=1,N
              IF (SRL(I,J) .LE. 5000.) THEN
                TDI(I,J,2) = 1.0
              ELSE
                TDI(I,J,2) = 0.0
              ENDIF
203       CONTINUE
C
C           TDI   - PROBABILITY OF TARGET DETECTION AND
C                   IDENTIFICATION (DIM.)
C           SRL   - SLANT RANGE TO TARGET (METERS)
C
C     ------------------------------------------------------
C           6.15 AIR-TO-SURFACE WEAPONS EMPLOYMENT
C     ------------------------------------------------------
C
```

```
      DO 205 I=1,M
        DO 205 J=1,N
          IF (SRL(I,5) .LE. 5000.) THEN
            ASWE(I,J,2) = 1.0
          ELSE
            ASWE(I,J,2) = 0.0
          ENDIF
        ASWE(I,J,1) = 1.0
205     CONTINUE
C
C         ASWE  - PROBABILITY OF AIR-TO-SURFACE WEAPONS EMPLOYMENT
C
C     ------------------------------------------------------------------
C           6.16 AIR-TO-SURFACE WEAPONS LAUNCH
C     ------------------------------------------------------------------
C
C       6.16.1 CHECK IF RANGE TO TARGET IS GREATER THAN ASWR
C
      DO 210 I=1,M
        DO 210 J=1,N
          IF (ARTT(I,J) .LE. EASMR(I,J,1)) THEN
            ASWCF(I,J,1) = 1.0
          ELSE
            ASWCF(I,J,1) = 0.0
          ENDIF
210     CONTINUE
C
      DO 211 I=1,M
        DO 211 J=1,N
          IF (ARTT(I,J) .LE. EASMR(I,J,2) .AND. ABS(ATN(I,J))
     +        .LE. BBC) THEN
            ASWCF(I,J,2) = 1.0
          ELSE
            ASWCF(I,J,2) = 0.0
          ENDIF
211     CONTINUE
C
      DO 221 I=1,M
        DO 221 J=1,N
          DO 221 K=1,KK
            IF (ASWU(I,K) .GT. 0.0) THEN
              ASWL(I,J,K) = TDI(I,J,K) * ASWE(I,J,K) *
     +              ASWCF(I,J,K)
            ELSE
              ASWL(I,J,K) = 0.0
            ENDIF
221     CONTINUE
C
C         ARTT    - AIRCRAFT RANGE TO TARGET (METERS)
C         EASMR   - EFFECTIVE AIR-TO-SURFACE WEAPONS RANGE (METERS)
C         ASWCF   - AIR-TO-SURFACE WEAPONS LAUNCH CONFIDENCE FACTOR
C         ATN     - AIRCRAFT TO TARGET ASPECT ANGLE (RADIANS)
C         ASWL    - AIR-TO-SURFACE WEAPONS LAUNCHED (UNITS)
C
C     ------------------------------------------------------------------
C     6.17 PROBABILITY OF AIR-TO-SURFACE WEAPON SUCCESSFUL GUIDANCE
C     ------------------------------------------------------------------
C
      DO 223 I=1,M
        DO 223 J=1,N
          PASG(I,J,1) = 0.9
          PASG(I,J,2) = 0.85
223     CONTINUE
C
C         PASG  - PROBABILITY OF AIRCRAFT WEAPONS SUCCESSFUL
C                 GUIDANCE (DIM)
C     ------------------------------------------------------------------
C       6.18 PROBABILITY OF AIR-TO-SURFACE WEAPON DETONATION
C     ------------------------------------------------------------------
C
      DO 225 I=1,M
        DO 225 J=1,N
          PAWDET(I,J,1) = 0.9
```

```
            PAWDET(I,J,2) = 0.85
225       CONTINUE
C
C           PAWDET - PROBABILITY OF AIR-TO-SURFACE WEAPONS DETONATION
C
C     ------------------------------------------------------
C          6.19 PROBABILITY OF AIRCRAFT SYSTEM EFFECTIVENESS
C     ------------------------------------------------------
C
          DO 226 I=1,M
            DO 226 J=1,N
              DO 226 K=1,KK
                PASE(I,J,K) = PALOS(I,J) * ASWL(I,J,K) * PASG(I,J,K)
     +                      * PAWDET(I,J,K)
226       CONTINUE
C
C           PASE   - PROBABILITY OF AIRCRAFT SYSTEMS EFFECTIVENESS
C           PASG   - PROBABILITY OF AIRCRAFT WEAPONS SUCCESSFUL
C                    GUIDANCE (DIM)
C           PAWDET - PROBABILITY OF AIR-TO-SURFACE WEAPONS DETONATION
C
C     ------------------------------------------------------
C          6.20 AIR-TO-SURFACE WEAPONS LAUNCHED (ASULA)
C     ------------------------------------------------------
C
          DO 235 I=1,M
            DO 235 J=1,N
              DO 235 K=1,KK
                ASULA(I,J,K) = AMIN1(ASWU(I,K)/FLOAT(DT), ASWLR(K)
     +                     * ASWL(I,J,K)/60.)
235       CONTINUE
C
          CALL SUMACF (ASULA, S1SULA, S2SULA, M, N, KK)
C
C           ASULA  - AIR-TO-SURFACE WEAPONS LAUNCHED (UNITS)
C           ASWL   - PROBABILITY OF AIR-TO-SURFACE WEAPONS LAUNCH
C           ASWU   - NUMBER OF AIR-TO-SURFACE WEAPONS (UNITS)
C           ASWLR  - MAXIMUM AIR-TO-SURFACE WEAPONS LAUNCH RATE
C                    (UNITS/MIN)
C           DT     - SIMULATION STEP SIZE (SECONDS)
C     ------------------------------------------------------
C          6.21 PROBABILITY OF SURFACE THREAT KILL (PKDWS)
C     ------------------------------------------------------
C
          DO 236 I=1,M
            DO 236 J=1,N
              DO 236 K=1,KK
                PKDWS(I,J,K) = PASE(I,J,K) - PASE(I,J,K) *
     +                       (1. - PSSDWS(K)) ** ASULA(I,J,K)
236       CONTINUE
C
C           PKDWS  - PROBABILITY OF DEFENSE WEAPONS KILL (DIM.)
C           ASULA  - AIR-TO-SURFACE WEAPONS LAUNCHED (UNITS)
C           PASE   - PROBABILITY OF AIRCRAFT SYSTEM EFFECTIVENESS
C           PSSDWS - PROBABILITY OF DEFENSE WEAPONS SINGLE SHOT KILL
C     ------------------------------------------------------
C                7. COMPUTATION OF RATE VARIABLES
C     ------------------------------------------------------
C
          DO 100 I=1,M
             ACCS(I) = (THRUST(I)*COS(ALP(I))-DRAG(I))/MASS(I)
             DMASS(I) = FFLOW(I)
             SAIR(I) = SAICO(I)
100       CONTINUE
C
          CALL MATRIX (RCSRW, S2SULA, DRCSW, M, KK)
C
          DO 005 I=1,M
          IF (TSS(I) .GE. 1.0) THEN
             TSSR(I) = 0.0
          ELSE
             TSSR(I) = DELTAV(I) * GAIN
```

```
      ENDIF
005    CONTINUE
C
      DO 112 I=1,M
        DO 112 J=1,N
          DO 112 L=1,LL
            CBFKR(I,J,L) = PKCBF(I,J,L) * CBFS(I)
112    CONTINUE
C
      CALL DELAY3 (CBFKR, CBFKRD, CBFQUE, M, N, LL, 10, ARFOT, DT)
      CALL SUM3 (CBFKR, S1CBKR, S2CBKR, M, N, LL)
      CALL SUM3 (CBFKRD, S1CBKD, S2CBKD, M, N, LL)
C
C
C      DEFENSE WEAPON SITES KILL RATE DUE TO AIR-TO-SURFACE WEAPONS
C
      DO 113 I=1,M
        DO 113 J=1,N
          DO 113 K=1,KK
            DWSKR(I,J,K) = PKDWS(I,J,K) * NDWS(J)
113    CONTINUE
C
      CALL DELAY3 (DWSKR, DWSKRD, DWSQUE, M, N, KK, 10, ASFOT, DT)
      CALL SUMDWS (DWSKR, S1DWKR, S2DWKR, M, N, KK)
      CALL SUMDWS (DWSKRD, S1DWKD, S2DWKD, M, N, KK)
C
C        ACCS   - AIRCRAFT ACCELERATION (M/SEC-SEC)
C        THRUST - AIRCRAFT THRUST (KGS.)
C        DRAG   - AIRCRAFT DRAG
C        ALP    - AIRCRAFT ANGLE OF ATTACK (RADIANS)
C        SAIR   - RATE OF CHANGE IN HEADING ANGLE (RAD/SEC)
C        RCSRW  - RATE OF CHANGE IN RCS DUE TO WEAPONS DELIVERY
C                 - (SQ. METERS/SEC)
C        DMASS  - RATE OF CHANGE IN VEHICLE MASS (KG/SEC.)
C        CBFKR  - CBF AIRCRAFT KILL RATE (AIRCRAFT/SEC.)
C        PKCBF  - PROBABILITY OF CBF AIRCRAFT KILL (DIM.)
C        CBFS   - NUMBER OF CBF AIRCRAFT (AIRCRAFT)
C        CBFKRD - DELAYED CBF AIRCRAFT KILL RATE (AIRCRAFT/SEC.)
C        ARFOT  - SURFACE-TO AIR WEAPON FLYOUT TIME (SEC.)
C        CBFQUE - DUMMY ARRAY TO HOLD TIME HISTORY OF CBFKR
C        DWSKR  - DEFENSE WEAPONS KILL RATE (UNITS/SEC.)
C        PKDWS  - DEFENSE WEAPONS PROBABILITY OF KILL (DIM.)
C        NDWS   - NUMBER OF DEFENSE WEAPONS PER SITE (UNITS)
C        DWSKRD - DELAYED DEFENSE WEAPONS KILL RATE (UNITS/SEC.)
C        ASFOT  - AIR-TO-SURFACE WEAPON FLYOUT TIME (SEC.)
C        DWSQUE - DUMMY ARRAY TO HOLD TIME HISTORY OF DWSKR
C
C  ------------------------------------------------------------
C           8. COMPUTATION OF AIRCRAFT STATE VARIABLES
C  ------------------------------------------------------------
C
      TIME   = TIME   + DT
C
      DO 200 I=1,M
        TSS(I)   = TSS(I)  + DT * TSSR(I)
        VS(I)    = VS(I)   + DT * ACCS(I)
        XS(I)    = XS(I)   + DT * VS(I)*COS(HEADS(I))
        YS(I)    = YS(I)   + DT * VS(I)*SIN(HEADS(I))
        HEADS(I) = HEADS(I)+ DT * SAIR(I)
        MASS(I)  = MASS(I) - DT * DMASS(I)
        RCS(I)   = RCS(I)  - DT * RCSRW(I)
        FUELR(I) = FUELR(I) - DT * FFLOW(I)
         IF (CBFS(I) .GT. 0.0) THEN
           CBFS(I) = CBFS(I) - DT * S1CBKD(I)
         ELSE
           CBFS(I) = 0.0
         ENDIF
200    CONTINUE
C
      CALL YAW (HEADS, M, HEAD, PI)
C
      DO 250 I=1,M
        DO 250 K=1,KK
```

```
            IF (ASWU(I,K) .GT. 0.0) THEN
              ASWU(I,K) = ASWU(I,K) - DT * S2SULA(I,K)
            ELSE
              ASWU(I,K) = 0.0
            ENDIF
250       CONTINUE
C
C           CBFS   - NUMBER OF AIRCRAFT
C           TSS    - AIRCRAFT ENGINE THROTTLE SETTING (DIM.)
C           XS     - AIRCRAFT DOWNRANGE POSITION (METERS)
C           YS     - AIRCRAFT LATERAL DOWNRANGE POSITION (METERS)
C           HEADS  - AIRCRAFT HEADING (RADIANS)
C           RCS    - RADAR CROSS SECTION AREA (SQ. METERS)
C           FUELR  - AIRCRAFT FUEL REMAINING (KGS.)
C
C     ------------------------------------------------------------------
C       9. COMPUTATION OF DEFENSE WEAPONS STATE VARIABLES
C     ------------------------------------------------------------------
C
        DO 302 J=1,N
          IF (NDWS(J) .GT. 0.0) THEN
            NDWS(J) = NDWS(J) - DT * S1DWKD(J)
          ELSE
            NDWS(J) = 0.0
          ENDIF
302       CONTINUE
C
        CALL SUMDWS (DWPL, DWPL1, DWPL2, M, N, LL)
        DO 301 J=1,N
          DO 301 L=1,LL
            DWS(J,L) =  DWS(J,L)  - DT * DWPL2(J,L)
301       CONTINUE
C
C           DWS    - NUMBER OF DEFENSE WEAPON UNITS
C           DWPL2  - DEFENSE WEAPONS PROPAGATORS LAUNCHED (2-D ARRAY)
C
C     ------------------------------------------------------------------
C                   10. OUTPUT COMMANDS
C     ------------------------------------------------------------------
C
C
        KP = KP - 1
        IF ( KP .GT. 0 ) GOTO 001
        KP =NPSTP
C
        WRITE (6,4500) TIME
        WRITE(6,2700) (I,XS(I),I=1,2)
        WRITE(6,2700) (I,YS(I),I=1,2)
        WRITE(6,2700) (I,VS(I),I=1,2)
        WRITE(6,2500) (I,(ATND(I,J),J=1,5), I=1,2)
        WRITE(6,2500) (I,(SRL(I,J),J=1,5), I=1,2)
C       WRITE(6,2500) (J,(DWPL(2,J,L),L=1,3), J=1,5)
C       WRITE(6,2700) (I,FUELR(I),I=1,2)
C       WRITE(6,2500) (I,(S2DWKR(I,J),J=1,5), I=1,2)
C       WRITE(6,2500) (I,(PRAD(I,J),J=1,5), I=1,2)
C       WRITE(6,2500) (I,(PKDWS(I,J,2),J=1,5), I=1,2)
C       WRITE(6,2700) (J,(DWPL2(J,L),L=1,3), J=1,5)
2500    FORMAT(/3X,'ACFT', I2, 5X, 5F10.5)
2700    FORMAT(/3X,'ACFT', I2, 5X, F12.2)
4500    FORMAT (25X, 'TIME = ', I4/)
C
001   CONTINUE
1000  STOP
      END
C
C
C     ------------------------------------------------------------------
C                   11. PROGRAM SUBROUTINES
C     ------------------------------------------------------------------
C
        SUBROUTINE DISTT (AX, AY, TX, TY, DX, DY, DD, NA, NP,ALOS, PI)
C
C       COMPUTES THE DISTANCE FROM AIRCRAFT TO TARGET POINTS
C
```

```
      INTEGER NA, NP, I, J
      REAL  AX(NA), AY(NA), TX(NP), TY(NP), DX(NA,NP)
      REAL  DY(NA,NP), DD(NA,NP), ALOS (NA,NP), PI
      DO 006 I=1,NA
        DO 006 J=1,NP
          DX(I,J) = AMAX1(AX(I)-TX(J),-AX(I)+TX(J))
          DY(I,J) = AMAX1(AY(I)-TY(J),-AY(I)+TY(J))
          DD(I,J)  = SQRT(DX(I,J)**2+DY(I,J)**2)
          IF (AY(I).GE.TY(J)) THEN
            IF (AX(I).GE.TX(J)) THEN
              ALOS(I,J) = ARSIN (DY(I,J)/(DD(I,J)+1.0E-6)) + PI
             ELSE
              ALOS(I,J) = 2.*PI-ARSIN (DY(I,J)/(DD(I,J)+1.0E-6))
            ENDIF
           ELSE
            IF (AX(I).GE.TX(J)) THEN
              ALOS(I,J) = PI - ARSIN (DY(I,J)/(DD(I,J)+1.0E-6))
             ELSE
              ALOS(I,J) = ARSIN (DY(I,J)/(DD(I,J)+1.0E-6))
            ENDIF
          ENDIF
006     CONTINUE
      RETURN
      END
C
      SUBROUTINE DISTW (AX, AY, WX, WY, DX, DY, DD, NA, NP,ALOS, PI)
C
C      COMPUTES THE DISTANCE FROM AIRCRAFT TO WAYPOINTS DEFINING
C      THE AIRCRAFT PATH TO BE FLOWN TO THE TARGET. NOTE THAT THIS
C      SUBROUTINE DIFFERS FROM DISTT IN THE ORDER OF THE ARRAY
C      DIMENSIONS.
C
      INTEGER NA, NP, I, J
      REAL  AX(NA), AY(NA), WX(NA,NP), WY(NA,NP), DX(NA,NP)
      REAL  DY(NA,NP), DD(NA,NP), ALOS (NA,NP), PI
      DO 006 I=1,NA
        DO 006 J=1,NP
          DX(I,J) = AMAX1(AX(I)-WX(I,J),-AX(I)+WX(I,J))
          DY(I,J) = AMAX1(AY(I)-WY(I,J),-AY(I)+WY(I,J))
          DD(I,J)  = SQRT(DX(I,J)**2+DY(I,J)**2)
          IF (AY(I).GE.WY(I,J)) THEN
            IF (AX(I).GE.WX(I,J)) THEN
              ALOS(I,J) = ARSIN (DY(I,J)/(DD(I,J)+1.0E-6)) + PI
             ELSE
              ALOS(I,J) = 2.*PI-ARSIN (DY(I,J)/(DD(I,J)+1.0E-6))
            ENDIF
           ELSE
            IF (AX(I).GE.WX(I,J)) THEN
              ALOS(I,J) = PI - ARSIN (DY(I,J)/(DD(I,J)+1.0E-6))
             ELSE
              ALOS(I,J) = ARSIN (DY(I,J)/(DD(I,J)+1.0E-6))
            ENDIF
          ENDIF
006     CONTINUE
      RETURN
      END
C
      SUBROUTINE DIRECW (AHEAD, ALOS, AY, WY, NA, NP, PI, ANGLE)
C
C      COMPUTES THE DIRECTION OF THE LINE OF SIGHT VECTOR FROM
C      EACH AIRCRAFT TO EACH WAYPOINT OF THE ROUTE(S).
C
      INTEGER NA, NP, I, J
      REAL  AY(NA), WY(NA,NP), AHEAD(NA), ALOS(NA,NP), ANGLE(NA,NP),
     +       PI
      DO 011 I=1,NA
        DO 011 J=1,NP
          IF (AY(I) .GE. WY(I,J)) THEN
            IF (-PI .GE. (AHEAD(I)-ALOS(I,J))) THEN
               ANGLE(I,J) = 2.*PI + (AHEAD(I) - ALOS(I,J))
            ELSE
               ANGLE(I,J) = AHEAD(I) - ALOS(I,J)
```

```
            ENDIF
          ELSE
            IF (PI .GE. (AHEAD(I)-ALOS(I,J))) THEN
              ANGLE(I,J) = AHEAD(I) - ALOS(I,J)
            ELSE
              ANGLE(I,J) = (AHEAD(I) - ALOS(I,J)) - 2.* PI
            ENDIF
          ENDIF
011     CONTINUE
        RETURN
        END
C
C
        SUBROUTINE DIRECT (AHEAD, ALOS, AY, TY, NA, NP, PI, ANGLE)
C
C       COMPUTES THE DIRECTION OF THE LINE OF SIGHT VECTOR FROM
C       EACH AIRCRAFT TO EACH TARGET.
C
        INTEGER NA, NP, I, J
        REAL  AY(NA), TY(NP), AHEAD(NA), ALOS(NA,NP), ANGLE(NA,NP),
     +        PI
        DO 011 I=1,NA
          DO 011 J=1,NP
            IF (AY(I) .GE. TY(J)) THEN
              IF (-PI .GE. (AHEAD(I)-ALOS(I,J))) THEN
                ANGLE(I,J) = 2.*PI + (AHEAD(I) - ALOS(I,J))
              ELSE
                ANGLE(I,J) = AHEAD(I) - ALOS(I,J)
              ENDIF
            ELSE
              IF (PI .GE. (AHEAD(I)-ALOS(I,J))) THEN
                ANGLE(I,J) = AHEAD(I) - ALOS(I,J)
              ELSE
                ANGLE(I,J) = (AHEAD(I) - ALOS(I,J)) - 2.* PI
              ENDIF
            ENDIF
011     CONTINUE
        RETURN
        END
C
        SUBROUTINE ATMOS (SPEED, ALT, MACHN, DEL, THE, SIG, RO,
     +    TZERO, PZERO, GAMA, NA, QA)
C
C       COMPUTES THE CHARACTERISTICS OF THE STANDARD ATMOSPHERE AT
C       ANY ALTITUDE (UP TO 20,000 METERS) AS WELL AS ESTIMATES THE
C       FLIGHT MACH NUMBER OF EACH AIRCRAFT.
C
        INTEGER NA, I, J
        REAL MACHN(NA), ALT(NA), SPEED(NA), DEL(NA), THE(NA), SIG(NA)
        REAL RO, PZERO, TZERO, LAM, GAMA, RCON, QA(NA)
C
        DO 008 I=1,NA
            RO    = 1.225
            TZERO = 288.2
            PZERO = 101300.
            LAM   = .0065
            GAMA  = 1.400
            RCON  = 287.
          IF (ALT(I).LE.11000.) THEN
            THE(I)  = 1 - LAM/TZERO * ALT(I)
            DEL(I)  = THE(I) ** 5.2561
            SIG(I)  = THE(I) ** 4.2561
          ELSE
            THE(I)  = .75189
            DEL(I)  = .2234 * EXP (-(ALT(I)-11000.)/ 6340.64)
            SIG(I)  =  DEL(I) / THE(I)
          ENDIF
            MACHN(I) = SPEED(I) / SQRT(GAMA*RCON*THE(I)*TZERO)
            QA(I)    = 0.5 * PZERO * GAMA * DEL(I)* MACHN(I)**2
008     CONTINUE
        RETURN
        END
```

```
C
      SUBROUTINE INTER(X, F, XVAL, N, NI, FOUT)
      INTEGER N, NI
      REAL FOUT(NI), X(NI,N), F(NI,N), XVAL(NI)
C
C     INTERPOLATES LINEARLY BETWEEN A SET OF N VALUES DEFINED AS TABLE
C     FUNCTIONS. THE OUTPUT IS A ONE-DIMENSIONAL ARRAY AS WELL AS THE
C     VALUE TO BE INTERPOLATED. GENERALLY USED FOR AIRCRAFT FUNCTIONS.
C
      DO 001 I=1,NI
        IF (XVAL(I).LE.X(I,1)) THEN
          FOUT(I) = F(I,1)
        ELSE
          IF (XVAL(I).GE.X(I,N)) THEN
            FOUT(I) = F(I,N)
          ELSE
            DO 002 J=1,N
              IF (XVAL(I).GT.X(I,J)) THEN
                FOUT(I) = F(I,J) + (XVAL(I)-X(I,J))*
     +            (F(I,J+1)- F(I,J))/(X(I,J+1)-X(I,J))
              ELSE
              ENDIF
002           CONTINUE
          ENDIF
        ENDIF
001   CONTINUE
      RETURN
      END
C
C
      SUBROUTINE MATRIX ( A, B, C, IC, JC)
      INTEGER  IC, J C
      REAL A(IC), B(IC,JC), C(JC)
C
C     SUBROUTINE TO FIND THE PRODUCT OF A MATRIX AND A VECTOR AS
C     FOLLOWS:  C(I X 1) = A(I X J) * B(J X 1)
C
      DO 030 I=1,I C
         A(I) = 0.0
         DO 040 J=1,J C
           A(I) = A(I) + B(I,J) * C(J)
040      CONTINUE
030   CONTINUE
      RETURN
      END
C
      SUBROUTINE LOADF (QD, AMAS, WA, WK, TH, DC, NA, G, NF)
      INTEGER  NA, I
      REAL QD(NA), AMAS(NA), WA(NA), WK(NA), TH(NA), DC(NA), NF(NA),G
C
C     COMPUTES THE MAXIMUM SUSTAINED LOAD FACTOR THAT AN AIRCRAFT CAN
C     GENERATE LIMITED BY THRUST (OR DRAG) CONSIDERATIONS.
C
      DO 070 I=1,NA
         IF (TH(I)/(QD(I)*WA(I)) .GT. DC(I)) THEN
           NF(I) = QD(I) * WA(I) / (AMAS(I) * G) * SQRT (1/WK(I) *
     +           (TH(I)/(QD(I)*WA(I)) - DC(I)))
         ELSE
           NF(I) = 1.01
         ENDIF
070   CONTINUE
      RETURN
      END
C
      SUBROUTINE YAWRTE (LOAD, SPEED, NA, G, YAW)
      INTEGER  NA, I
      REAL  LOAD(NA), SPEED(NA), YAW(NA), G
C
C     ESTIMATES THE MAXIMUM SUSTAINED YAW RATE OF THE AIRCRAFT GIVEN
C     THE MAXIMUM SUSTAINED LOAD FACTOR, SPEED, AND GRAVITY FORCE.
C
      DO 080 I=1,NA
```

```
      YAW(I) = G * SQRT(LOAD(I)** 2 - 1)/ SPEED(I)
080  CONTINUE
     RETURN
     END
C
     SUBROUTINE PS (SPEED, AMAS, G, TH, D, NA, APS)
     INTEGER  NA, I
     REAL SPEED(NA), AMAS(NA), TH(NA), APS(NA), G, D(NA)
C
C    COMPUTES THE AVAILABLE SPECIFIC EXCESS POWER OF AN AIRCRAFT AT
C    ANY POINT IN TIME.
C
     DO 085 I=1,NA
       APS(I) = (TH(I) - D(I)) * SPEED(I) / (AMAS(I) * G)
085  CONTINUE
     RETURN
     END
C
C
     SUBROUTINE YAW (ANGLE, NA, NEWAN, PI)
     INTEGER  NA, I
     REAL  ANGLE(NA), NEWAN(NA), PI
C
C    SUBROUTINE TO LIMIT THE YAW ANGLE WITHIN 0 AND 2 PI (RAD)
C
     DO 101 I=1,NA
        IF (ANGLE(I) .GE. 0) THEN
          IF (ANGLE(I) .GE. 2.*PI) THEN
            NEWAN(I) = ANGLE(I) - 2.*PI
          ELSE
            NEWAN(I) = ANGLE(I)
          ENDIF
        ELSE
          NEWAN(I) = 2.*PI + ANGLE(I)
        ENDIF
101  CONTINUE
     RETURN
     END
C
     SUBROUTINE INTE (X, F, XVAL, NA, NT, NP, FOUT)
     INTEGER NA, NT, NP, I, J, K
     REAL FOUT(NA,NT), X(NA,NP), F(NA,NP), XVAL(NA,NT)
C
C    INTERPOLATES LINEARLY BETWEEN A SET OF N VALUES DEFINED AS TABLE
C    FUNCTIONS. THE OUTPUT IS A TWO-DIMENSIONAL ARRAY AS WELL AS THE
C    VALUE TO BE INTERPOLATED.
C
     DO 001 I=1,NA
       DO 001 J=1,NT
         IF (ABS(XVAL(I,J)) .LE. X(I,1)) THEN
           FOUT(I,J) = F(I,1)
         ELSE
           IF (ABS(XVAL(I,J)) .GE. X(I,NP)) THEN
             FOUT(I,J) = F(I,NP)
           ELSE
             DO 002 K=1,NP
               IF (ABS(XVAL(I,J)) .GT. X(I,K)) THEN
                 FOUT(I,J) = F(I,K) + (ABS(XVAL(I,J))-X(I,K))
    +             * (F(I,K+1)- F(I,K))/(X(I,K+1)-X(I,K))
               ELSE
               ENDIF
002          CONTINUE
         ENDIF
       ENDIF
001  CONTINUE
     RETURN
     END
C
     SUBROUTINE DWKE (X, F, XVAL, NA, NWE, NP, FOUT)
     INTEGER NA, NWE, NP, I, J, K
     REAL FOUT(NA,NWE), X(NWE,NP), F(NWE,NP), XVAL(NA)
C
```

```
C    ESTIMATES THE RANGE OF THE WEAPONS KINEMATIC ENVELOPES IN THE
C    DIRECTION OF EACH AIRCRAFT.
C
     DO 001 I=1,NA
       DO 001 J=1,NWE
         IF (XVAL(I) .LE. X(J,1)) THEN
            FOUT(I,J) = 0.0
         ELSE
            IF (XVAL(I) .GE. X(J,NP)) THEN
               FOUT(I,J) = F(J,NP)
            ELSE
               DO 002 K=1,NP
                  IF (XVAL(I) .GT. X(J,K)) THEN
                    FOUT(I,J) = F(J,K) + (XVAL(I)-X(J,K))
     +             * (F(J,K+1)- F(J,K))/(X(J,K+1)-X(J,K))
                  ELSE
                  ENDIF
002            CONTINUE
         ENDIF
       ENDIF
001  CONTINUE
     RETURN
     END
C
     SUBROUTINE DOUBL(X, F, XVAL, NA, NT, NP, FOUT)
     INTEGER NA, NT, NP, I, J, K
     REAL FOUT(NA,NT), X(NP), F(NP), XVAL(NA,NT)
C
C    SUBROUTINE TO INTERPOLATE BETWEEN VALUES PROVIDED BY A ONE
C    DIMENSIONAL ARRAY. INTERPOLATED VARIABLE AND OUTPUT ARE TWO
C    TWO DIMENSIONAL ARRAYS.
C
     DO 001 I=1,NA
       DO 001 J=1,NT
         IF (XVAL(I,J) .LE. X(1)) THEN
            FOUT(I,J) = F(1)
         ELSE
            IF (XVAL(I,J) .GE. X(NP)) THEN
               FOUT(I,J) = F(NP)
            ELSE
               DO 002 K=1,NP
                  IF (XVAL(I,J) .GT. X(K)) THEN
                    FOUT(I,J) = F(K) + (XVAL(I,J)-X(K))
     +             * (F(K+1)- F(K))/(X(K+1)-X(K))
                  ELSE
                  ENDIF
002            CONTINUE
         ENDIF
       ENDIF
001  CONTINUE
     RETURN
     END
C
     SUBROUTINE DINV (A, B, NA, NT, RET)
     INTEGER  NA, NT
     REAL A(NA,NT), RET(NA,NT), B(NA,NT)
C
C    CONVERTS FROM DECIBELS TO A RATIO OF TWO QUANTITIES
C
     DO 086 I=1,NA
       DO 086 J=1,NT
         RET(I,J) = 10. ** (A(I,J) / (10. * B(I,J)))
086  CONTINUE
     RETURN
     END
C
     SUBROUTINE RATINV (A, B, NA, NT, RET)
     INTEGER  NA, NT
     REAL A(NA,NT), RET(NA,NT), B(NA,NT)
C
C    CONVERTS THE RATIO OF TWO QUANTITIES TO DECIBLES
C
```

```
      DO 087 I=1,NA
        DO 087 J=1,NT
        RET(I,J) = 10.* ALOG10 (AMAX1 (A(I,J)/B(I,J) , 0.001))
087   CONTINUE
      RETURN
      END
C
      SUBROUTINE PRADAR (PDRT, RCROT, DRDR, RCDR, NA, NT, NR, NC, PDR)
      INTEGER NA, NT, NC, NR, I, J, K
      REAL DRDR(NA,NT), RCDR(NA,NT), PDR(NA,NT), PDRT(NR,NC)
      REAL  RCROT(NR,NC)
C
C     ESTIMATES THE PROBABILITY OF RADAR DETECTION OF A MULTI-SCATTER
C     TARGET (SWERLING I) USING THE UNIVERSAL CURVES OF RADAR DETECTION
C     FOR SIGNAL-TO-NOISE RATIO OF UNITY (BROOKNER).
C
      DO 001 I=1,NA
        DO 001 J=1,NT
          IF (DRDR(I,J) .LE. 5.0) THEN
            IF (RCDR(I,J) .GE. RCROT(1,1)) THEN
              PDR(I,J) = PDRT(1,1)
            ELSE
              IF (RCDR(I,J) .LE. RCROT(1,NC)) THEN
                PDR(I,J) = PDRT(1,NC)
              ELSE
                DO 003 K=1,N C
                IF (RCDR(I,J) .LE. RCROT(1,K)) THEN
                  PDR(I,J) = PDRT(1,K) + (RCDR(I,J) -
     +                RCROT(1,K))*(PDRT(1,K+1)-PDRT(1,K))/
     +                (RCROT(1,K+1)-RCROT(1,K))
                ENDIF
003              CONTINUE
              ENDIF
            ENDIF
          ELSE
            IF (DRDR(I,J) .GE. 25.0) THEN
              IF (RCDR(I,J) .GE. RCROT(5,1)) THEN
                PDR(I,J) = PDRT(5,1)
              ELSE
                IF (RCDR(I,J) .LE. RCROT(5,NC)) THEN
                  PDR(I,J) = PDRT(5,NC)
                ELSE
                  DO 004 K=1,N C
                  IF (RCDR(I,J) .LE. RCROT(5,K)) THEN
                    PDR(I,J) = PDRT(5,K) + (RCDR(I,J) -
     +                  RCROT(5,K))*(PDRT(5,K+1)-PDRT(5,K))/
     +                  (RCROT(5,K+1)-RCROT(5,K))
                  ENDIF
004               CONTINUE
                ENDIF
              ENDIF
            ELSE
              DO 002 L=1,NR
                IF (DRDR(I,J) .GT. FLOAT(L+4*L)) THEN
                  IF (RCDR(I,J) .GE. RCROT(L,1)) THEN
                    PDR(I,J) = PDRT(L,1)
                  ELSE
                    IF (RCDR(I,J) .LE. RCROT(L,NC)) THEN
                      PDR(I,J) = PDRT(L,NC)
                    ELSE
                      DO 005 K=1,N C
                      IF (RCDR(I,J) .LE. RCROT(L,K)) THEN
                        PDR(I,J) = PDRT(L,K) + (RCDR(I,J) -
     +                    RCROT(L,K))*(PDRT(L,K+1)-PDRT(L,K))/
     +                    (RCROT(L,K+1)-RCROT(L,K))
                      ENDIF
005                   CONTINUE
                    ENDIF
                  ENDIF
                ENDIF
002           CONTINUE
            ENDIF
```

```
          ENDIF
001   CONTINUE
      RETURN
      END
C
      SUBROUTINE PTF (F, X, TA, FOT, NA, NT, NWE, NP, FOUT)
      INTEGER NA, NT, NWE, I, J, K, L
      REAL FOT(NA,NT,NWE), TA(NA,NT,NWE)
      REAL X(NP), F(NP), FOUT(NA,NT,NWE)
C
C     SUBROUTINE TO ESTIMATE THE PROBABILITY OF DWS HAVING SUFFICIENT
C     TIME FOR FIRING. ALSO COULD BE USED TO INTERPOLATE A ONE
C     DIMENSIONAL ARRAY WHERE OUTPUT AND INPUT ARE THREE DIMENSIONAL.
C
      DO 001 I=1,NA
        DO 001 J=1,NT
          DO 001 L=1,NWE
            IF (FOT(I,J,L)/(TA(I,J,L)+.001) .GE. X(1)) THEN
               FOUT(I,J,L) = F(1)
            ELSE
               IF (FOT(I,J,L)/(TA(I,J,L)+0.001) .LE. X(NP)) THEN
                 FOUT(I,J,L) = F(NP)
               ELSE
                 DO 002 K=1,NP
                   IF (FOT(I,J,L)/(TA(I,J,L)+.001) .LT. X(K)) THEN
                      FOUT(I,J,L) = F(K) + (FOT(I,J,L)/
     +                  (TA(I,J,L)+.001)-X(K)) * (F(K+1) - F(K))/
     +                  (X(K+1)-X(K))
                      ENDIF
002                 CONTINUE
               ENDIF
            ENDIF
001   CONTINUE
      RETURN
      END
C
      SUBROUTINE SPECTR (LTEM, REMIRT, TEMP, MUS, NA, NP, NC, JAY ,
     +      EFFR)
      INTEGER  NA, NP, NC, I, J
      REAL TEMP(NA), REMIR(2), REMIRT(NP), LTEM(NP), EFFR(NA)
      REAL MUS(NC), JAY(NA)
C
C     SUBROUTINE TO COMPUTE THE PROBABILITY OF INFRARED DETECTION.
C
      DO 001 I=1,NA
         DO 002 L=1,N C
           IF (TEMP(I)*MUS(L) .LE. LTEM(1)) THEN
             REMIR(L) = 0.0
           ELSE
             IF (TEMP(I)*MUS(L) .GE. LTEM(NP)) THEN
                 REMIR(L) = 1.0
             ELSE
                DO 003 K=1,NP
                  IF ( TEMP(I)*MUS(L) .GT. LTEM(K) ) THEN
                     REMIR(L) =  REMIRT(K) + (TEMP(I)*MUS(L)-
     +                   LTEM(K)) * (REMIRT(K+1) - REMIRT(K))/
     +                   (LTEM(K+1) - LTEM(K))
                  ENDIF
003               CONTINUE
             ENDIF
           ENDIF
002      CONTINUE
         EFFR(I) = JAY(I) * (REMIR(2) - REMIR(1))
001   CONTINUE
      RETURN
      END
C
      SUBROUTINE SINGL (X, F, XVAL, NA, NP, FOUT)
      INTEGER I, J, NP, NA, NPP
      REAL FOUT(NA), X(NP), F(NP), XVAL(NA)
C
C     FULL SINGLE ARRAY INTERPOLATION SUBROUTINE. INPUT, OUTPUT, AND
```

```
C    AND TABLE FUNCTION ARE ALL ONE-DIMENSIONAL
C
     DO 001 I=1,NA
       IF (XVAL(I) .LE. X(1)) THEN
          FOUT(I) = F(1)
        ELSE
          IF (XVAL(I) .GE. X(NP)) THEN
             FOUT(I) = F(NP)
           ELSE
             DO 002 J=1,NP
               IF (XVAL(I) .GT. X(J)) THEN
                  FOUT(I) = F(I) + (XVAL(I)-X(J))*
    +               (F(J+1)- F(J))/(X(J+1)-X(J))
                ELSE
               ENDIF
002           CONTINUE
          ENDIF
       ENDIF
001  CONTINUE
     RETURN
     END
C
     SUBROUTINE SUM2 (A, B, N1, N2)
     INTEGER I, J, N1, N2
     REAL A(N1), B(N1,N2)
C
C    SUBROUTINE TO SUM THE ELEMENTS OF A TWO-DIMENSIONAL ARRAY IN A
C    COLUMN WISE FASHION. OUTPUT IS A 1-D VECTOR.
C
     DO 001 I=1,N1
       A(I) = 0.0
       DO 001 J=1,N2
         A(I) = A(I) + B(I,J)
001  CONTINUE
     RETURN
     END
C
     SUBROUTINE SUM3 (C, A, B, N1, N2, N3)
     INTEGER I, J, K, N1, N2, N3
     REAL A(N1), B(N1,N2), C(N1,N2,N3)
C
C    SUBROUTINE TO SUM THE ELEMENTS OF A THREE-DIMENSIONAL ARRAY IN A
C    COLUMN WISE FASHION. OUTPUTS ARE A 2-D ARRAY AND A ONE DIMENSIONAL
C    VECTOR (B AND A RESPECTIVELY).
C
     DO 001 I=1,N1
       A(I) = 0.0
       DO 002 J=1,N2
         B(I,J) = 0.0
         DO 003 K=1,N3
           B(I,J) = B(I,J) + C(I,J,K)
003      CONTINUE
       A(I) = A(I) + B(I,J)
002    CONTINUE
001  CONTINUE
     RETURN
     END
C
C
     SUBROUTINE SUMACF (C, A, B, N1, N2, N3)
     INTEGER I, J, K, N1, N2, N3
     REAL A(N1), B(N1,N3), C(N1,N2,N3)
C
C    SUBROUTINE TO SUM THE ELEMENTS OF A THREE-DIMENSIONAL ARRAY IN A
C    COLUMN WISE FASHION. OUTPUTS ARE A 2-D ARRAY AND A ONE DIMENSIONAL
C    VECTOR (B AND A RESPECTIVELY).
C
     DO 001 I=1,N1
       A(I) = 0.0
       DO 002 K=1,N3
         B(I,K) = 0.0
         DO 003 J=1,N2
```

```
            B(I,K) = B(I,K) + C(I,J,K)
003         CONTINUE
        A(I) = A(I) + B(I,K)
002       CONTINUE
001     CONTINUE
        RETURN
        END
C
        SUBROUTINE SUMDWS (C, A, B, N1, N2, N3)
        INTEGER I, J, K, N1, N2, N3
        REAL A(N2), B(N2,N3), C(N1,N2,N3)
C
C       SUBROUTINE TO SUM THE ELEMENTS OF A THREE-DIMENSIONAL ARRAY IN A
C       COLUMN WISE FASHION. OUTPUTS ARE A 2-D ARRAY AND A ONE DIMENSIONAL
C       VECTOR (B AND A RESPECTIVELY).
C
        DO 001 J=1,N2
          A(J) = 0.0
          DO 002 K=1,N3
            B(J,K) = 0.0
            DO 003 I=1,N1
              B(J,K) = B(J,K) + C(I,J,K)
003         CONTINUE
          A(J) = A(J) + B(J,K)
002       CONTINUE
001     CONTINUE
        RETURN
        END
        SUBROUTINE DELAY1 (VARIN, VAROUT, VAR, N, MTOF, DT)
        INTEGER I, J, K, N, NP, DT
        REAL VARIN, VAROUT, VAR(N), MTOF
C
C       SUBROUTINE TO INTRODUCE A "FULL" TIME DELAY TO A ONE DIMENSIONAL
C       VARIABLE (VARIN). THE DELAY VARIABLE (MTOF) CAN BE TIME VARIANT
C       AND THE DELAYED HISTORY OF THE VARIABLE IS STORED IN (VAR) WITH
C       N AS THE MAXIMUM NUMBER OF BACKWARD MEMORY SPACES.
C
        NP = N - 1
        DO 004 I=1,NP
          K      = N + 1 - I
          VAR(K) = VAR(K-1)
          VAR(1) = VARIN
          IF ( INT(MTOF)/DT . LE. 1 ) THEN
            VAROUT = VAR(1)
          ELSE
            IF ( INT(MTOF)/DT . GE. N ) THEN
              VAROUT = VAR(N)
            ELSE
              IF ( INT(MTOF)/DT . GE. I ) THEN
                VAROUT = VAR(I) + (INT(MTOF)/DT - I) *
     +                (VAR(I+1) - VAR(I))
              ENDIF
            ENDIF
          ENDIF
004     CONTINUE
        RETURN
        END
C
        SUBROUTINE DELAY2 (VARIN, VAROUT, VAR, N1, N2, N, MTOF, DT)
        INTEGER I, J, K, N1, N2, N, NP, DT, P
        REAL VARIN(N1,N2), VAROUT(N1,N2), VAR(N1,N2,N)
       +  , MTOF(N1,N2)
C
C       SUBROUTINE TO INTRODUCE A "FULL" TIME DELAY TO A 2-DIMENSIONAL
C       VARIABLE (VARIN). THE DELAY VARIABLE (MTOF) CAN BE TIME VARIANT
C       AND THE DELAYED HISTORY OF THE VARIABLE IS STORED IN (VAR) WITH
C       N AS THE MAXIMUM NUMBER OF BACKWARD MEMORY SPACES.
C
        NP = N - 1
        DO 001 I=1,N1
        DO 001 J=1,N2
        DO 002 P=1,NP
```

```
      M     = N + 1 - P
      VAR(I,J,M) = VAR(I,J,M-1)
      VAR(I,J,1) = VARIN(I,J)
      IF ( INT(MTOF(I,J))/DT . LE. 1 ) THEN
        VAROUT(I,J) = VAR(I,J,1)
      ELSE
        IF ( INT(MTOF(I,J))/DT . GE. N ) THEN
          VAROUT(I,J) = VAR(I,J,N)
        ELSE
          IF ( INT(MTOF(I,J))/DT . GE. P ) THEN
            VAROUT(I,J) = VAR(I,J,P) +
     +                  (INT(MTOF(I,J))/DT-P) *
     +                  (VAR(I,J,P+1) - VAR(I,K,P))
          ENDIF
        ENDIF
      ENDIF
002   CONTINUE
001   CONTINUE
      RETURN
      END
C
      SUBROUTINE DELAY3 (VARIN, VAROUT, VAR, N1, N2, N3, N, MTOF, DT)
      INTEGER I, J, K, N1, N2, N3, N, NP, DT, P
      REAL VARIN(N1,N2,N3), VAROUT(N1,N2,N3), VAR(N1,N2,N3,N)
     +  , MTOF(N1,N2,N3)
C
C     SUBROUTINE TO INTRODUCE A "FULL" TIME DELAY TO A 3-DIMENSIONAL
C     VARIABLE (VARIN). THE DELAY VARIABLE (MTOF) CAN BE TIME VARIANT
C     AND THE DELAYED HISTORY OF THE VARIABLE IS STORED IN (VAR) WITH
C     N AS THE MAXIMUM NUMBER OF BACKWARD MEMORY SPACES.
C
      NP = N - 1
      DO 001 I=1,N1
      DO 001 J=1,N2
      DO 001 K=1,N3
      DO 004 P=1,NP
        M     = N + 1 - P
        VAR(I,J,K,M) = VAR(I,J,K,M-1)
        VAR(I,J,K,1) = VARIN(I,J,K)
        IF ( INT(MTOF(I,J,K))/DT . LE. 1 ) THEN
          VAROUT(I,J,K) = VAR(I,J,K,1)
        ELSE
          IF ( INT(MTOF(I,J,K))/DT . GE. N ) THEN
            VAROUT(I,J,K) = VAR(I,J,K,N)
          ELSE
            IF ( INT(MTOF(I,J,K))/DT . GE. P ) THEN
              VAROUT(I,J,K) = VAR(I,J,K,P) +
     +                  (INT(MTOF(I,J,K))/DT-P) *
     +                  (VAR(I,J,K,P+1) - VAR(I,J,K,P))
            ENDIF
          ENDIF
        ENDIF
004   CONTINUE
001   CONTINUE
      RETURN
      END
C
C$ENTRY
```

Appendix D. ASALT II Glossary

A

ABAIN	Aircraft Bearing Angle to Waypoint (Ingress)
ABAOUT	Aircraft Bearing Angle to Waypoint (Egress)
ALTS	CBF Aircraft Altitude (meters)
ACCS	CBF Aircraft Acceleration (m/sec-sec)
ABS	Absolute Value
ACM	Close-in and Short Range Air Combat Maneuvering
ADA	CBF Aircraft radar Antenna Diameter (meters)
AE	CBF Aircraft Engine Exhaust Area (sq. meters)
AEB	CBF Aircraft Baseline Engine Exhaust Area (sq. meters)
AF	RCS vs. Azimuth Angle Correction Factor (dim.)
AIMEK	CBF Aiming Error Constant (dim.)
ALOS	Line-of-Sight Angle (rad.)
ALP	Aircraft Wing-Body Angle of Attack (rad.)
ALPO	Aircraft Wing-Body Zero Lift Angle of Attack (rad.)
ALTSOJ	altitude of Stand-off Jammer Post (meters)
ANEMLE	CBF Aircraft Weapons Never Escape Weapons Envelope (meters)
ANMIS	Maximum CBF Weapon Manuevering Load Factor (g's}
AP	Aircraft Plume Area (sq. cm.)
APS	Average Propagator Speed (m/sec.)
AR	CBF Aircraft Aspect Ratio (dim.)
ARFOT	Average Propagator Flyout Time (sec.)
ARTT	Aircraft Range to Target (meters)
ARTTX	Aircraft Downrange to Target (meters)
ARTTY	Aircraft Lateral Range to Target (meters)
ARTWIX	Aircraft Downrange to Ingress Waypoint (meters)
ARTWIY	Aircraft Range to Ingress Waypoint (meters)
ARTWI	Aircraft Range to Ingress Waypoint (meters)
ARTWOX	Aircraft Downrange to Egress Waypoint (meters)
ARTWOY	Aircraft Range to Egress Waypoint (meters)
ARTWO	Aircraft Range to Egress Waypoint (meters)
AS	Aircraft Wetted Area (sq. cm.)
ASALT	Aircraft Survivability and Lethality Tradeoffs Model
ASCDO	Air-to-Surface Weapon Drag Coefficient Increment (dim.)
ASULA	Air-to-Surface Weapons Launched (units/sec)
ASWE	Air-to-Surface Weapons Probability of Employment Employment (dim.)
ASWL	Probability of Air-to-Surface Weapons Launch (dim.)
ASWLR	Maximum Air-to-Surface Weapons Launch Rate (units/minute)
ASWU	Air-to-Surface CBF Aircraft Weapons Mass (kg.)
ASWUI	Initial Number of CBF Aircraft Weapons (units)
ATAWN	Number of CBF Aircraft Weapons (units)
ATAWR	CBF Aircraft Weapons Launch Rate (units/sec)
ATFOT	Average Acquisition Tracking and Flyout Time (sec.)
ATN	Target Aspect Angle Measured SAM Sites to CBF Aircraft (rad.)
AVATN	Average ATN Angle in BVR Combat Phase (rad.)

AVCBF	Average Number of CBF Aircraft (aircraft)
AWACS	Airborne Early Warning System
ASWCF	Air-to-Surface Weapon Launch Confidence Factor (dim.)
B	
BK	Stephan-Boltzman Constant (W $cm^2 rad.K^4$)
BVR	Beyond Visual Range
BWSOJ	Stand-off Jammer Bandwidth (Hz.)
BWSSJ	Self-screening Jammer Bandwidth (Hz.)
C	
CAIME	Aiming Error Constant (dim.)
CBCM	CBF Countermeasure Capability (Dim)
CBF	Number of CBF Aircraft (aircraft)
CBFDEL	CBF Aircraft Weapon Time Delay (sec.)
CBFKR	CBF Aircraft Kill Rate (aircraft/sec.)
ASWU	CBF Aircraft Weapons (units)
ASWR	CBF Aircraft Weapons Launch Rate (units/sec.)
CBG	Carrier Based Group
CBMC	CBF Aircraft Maneuverability Multiplier (dim.)
CBWC	CBF Aircraft Warning Capability (dim.)
CD	Complete CBF Aircraft Drag Coefficient (dim.)
CDO	Aircraft Zero-Lift Drag Coefficient (Dim)
CDOM	Aircraft Zero-Lift Drag Coefficient vs. Mach Number (Dim)
CDOWE	Aircraft Air-to-Surface Drag Coefficient (dim.)
CDI	Induced Drag Coefficient
CL	Aircraft Lift Coefficient (Dim)
CLALP	Wing-Body Curve Lift Slope (1/rad)
CLALPT	Tabular Values of Wing-Body Curve Lift Slope (1/rad)
CLMAX	CBF Aircraft Stall Lift Coefficient (dim.)
CLUS	Maximum Usable Aircraft Lift Coefficient (dim.)
D	
DB	Decibels
DBINV	Subroutine to Convert a Ratio to Decibels
DEG	Degrees
DET	Detonation
DEXPC	CBF Aircraft Rate of Change of Expendables (cartridges/sec.)
DEXPG	AGG Aircraft Rate of Change of Expendables (cartridges/sec.)
DINV	Macro to Convert Decibels to a Ratio
DIRECT	Subroutine to Estimate the Line-of-Sight Vector to Target
DIRECW	Subroutine to Estimate the Line-of-Sight Vector to Waypoint
DISTT	Subroutine to Estimate the Line-of-Sight Vector to Target
DISTW	Subroutine to Estimate the Line-of-Sight Vector to Waypoint
DIXJ	X-Component of Jammer Location (meters.)
DIYJ	Y-Component of Jammer Location (meters.)
DIZJ	Z-Component of Jammer Location (meters.)
DRAG	Complete Aircraft Drag (Newtons)
DRC	Delta Range from CBF Aircraft (m/sec.)
DRCSWG	Aggressor Delta RCS due to Weapons Carriage (sq. meters)
DR0DR	Ratio of Delta Range to that of radar Nominal Range
DT	Simulation Step Size (sec.)
DTECT	Subroutine to Find the Probability of Detection
DWPL	Defense Weapons Propagators Launched (units)
DWPL1	Single Dimensional Array Containing Values of DWPL for Each Defense Weapons Site
DWPL2	Two-Dimensional Array Containing Values of DWPL for Each Defense Weapon Site and Weapon Type
DWSKR	Defense Weapon Sites Kill Rate (units/sec.)
DWSKRD	Delayed Defense Weapon Sites Kill Rate (units/sec.)
DWSQUE	Dummy Queuing Array Containing the Time History of a Variable to

	be Delayed b
DXSOJ	Downrange Position of Stand-off Jammer Post (meters)
DYSOJ	Lateral Downrange Position of Stand-off Jammer Post (meters)
E	
ECM	Electronic Countermeasures
ECMCDO	Electronic Countermeasures Pod Incremental Drag Coefficient
EFF	CBF Aircraft Wing Efficiency Factor (dim.)
EGT	CBF Aircraft Exhaust Gas Temperature (rad. absolute)
EGTBG	Aggressor Aircraft Baseline EGT (rad. absolute)
EMASS	Aircraft Empty Mass (kgs.)
EMM	Gray Body Emmisitivity Constant (dim..)
ER	Exchange Ratio (dim..)
ESM	Electronic Suppression Measures
F	
FACP	Forward Air Control Post
FFLOW	Aircraft Engine Fuel Flow (kg/sec.)
FTIME	Final Simulation Time (sec.)
FUELN	Initial CBF Aircraft Fuel (kg.)
FUELR	Aircraft Fuel Remaining (kg.)
G	
GAMMA	Ratio of Specific Heats (dim.)
GCI	Ground Control Intercept
GSOJ	CBF Aircraft Stand-off Jammer Gain (dim.)
GSSJ	CBF Aircraft Self-Screen Jammer Gain (dim.)
H	
HT	CBF Aircraft Infrared radiance (w./sq. cm.)
HUD	Head-up Display
I	
ICAO	International Civil Aviation Organization
IR	Infrared
IRDET	Subroutine to Estimate the Probability of Infrared Detection
IRDT	Tabular Values for the Probability of Infrared Detection
ISA	International Standard Atmosphere
ITIME	Initial Time Used in Dynamic Loop
J	
JA	Effective Total Infrared Radiance (W/sq. cm.)
JDSOJ	CBF Aircraft Stand-off Noise Jamming Power (watts)
JDSSJ	CBF Aircraft Self Screening Noise Jamming Power (watts)
JE	Engine Infrared Radiance (W/sq. cm.)
JEFF	Engine Exhaust Infrared Radiance (W/sq. cm.)
JPEFF	Engine Plume Infrared Radiance (W/sq. cm.)
JS	CBF Aircraft Skin IR radiance (w./sq. cm.)
JTOTE	Total Infrared Radiance (W/sq. cm.)
K	
KDET	CBF Aircraft Weapons Detonation Constant (dim.)
KDETC	Numerical Values for KDET Constants (dim.)

L

LOADF	Subroutine to Estimate the Load Factor Pulled at Any Point in Time
LOSATT	Line-of-Sight Vector from Aircraft to Target (rad.)
LOSAWI	Line-of-Sight Vector from Aircraft to Ingress Waypoint (rad.)
LOSAWO	Line-of-Sight Vector from Aircraft to Egress Waypoint (rad.)
LOSTAA	Line-of-Sight Vector from DWS to Aircraft (rad.)
LRAAM	Long Range Air-to-Air Missile

M

MACH	CBF Aircraft Flight Mach Number (dim.)
MACHD	Aircraft Cdo Values vs. Mach Number (dim.)
MIEM	CBF Aircraft Increase vs. Engine Modification Multiplier (dim.)
MRALM	Weapon Range vs. Launching Platform Altitude Multiplier (dim.)
MRALMT	Numerical Values of MRALM Multiplier (dim.)
MRASM	Weapon Range vs. Launching Platform Flight Speed Multiplier (dim.)
MRASMT	Numerical Values of MRASM Multiplier (dim.)
MRBASE	Baseline Weapons Maximum Range (meters)
MUSKIN	Skin Friction Infrared Spectrum Wavelenght Values (microns)
MUPLUM	Plume IR Spectrum Wavelenght Values (microns)
MUENG	Engine IR Spectrum Wavelenght Values (microns)

N

NCOM	CBF Commanded Load Factor (g's)
NCREW	Physiological Limit on Human Tolerance to Normal Load Factor (g's)
NE	CBF Aircraft Number of Engines (units)
NEECM	Number of ECM Pods (units)
NEI	Noise Equivalent Infrared Radiance (w/sr.-sq.m.)
NEIB	Baseline Noise Equivalent Infrared radiance (w/sr.-sq.m.)
NEIMT	Tabular Values for Noise Equivalent Infrared radiance vs. Number of Aircraft (dim.)
NEINAM	Multiplier of Noise Equivalent radiance (NER) vs. Number of CBF Aircraft (dim.)
NEXLC	Number of CBF Aircraft Expendables Launched (cartridges)
NEXLG	Number of AGG Aircraft Expendables Launched (cartridges)
NEXPC	CBF Aircraft Number of Expendables (cartridges)
NEXPCN	Initial Number of CBF Aircraft Expendables (cartridges)
NEXPGN	Initial Number of AGG Aircraft (cartridges)
NMISS	Surface-to-Air Missile Maximum Sustained Load Factor (g's)
NSTRUC	Maximum Aircraft Structural Load Factor (g's)
NTRUST	Maximum Load Factor Limited by Thrust (g's)
NUA	CBF Aircraft Antenna Effective Aperture Factor (dim.)
NUS	CBF Aircraft Maximum Sustained Load Factor (g's)

O

OMEGAA	CBF Aircraft radar Azimuthal Coverage (radrees)

P

PALOS	Probability of Target Aircraft in Line of Sight (dim.)
PAFE	Prob. A/C in Firing Envelope (dim.)
PASE	Probability of Aircraft Systems Effectiveness (dim.)
PASLO	Prob. Air-to-Surface Launch Opportunity (dim.)
PDECM	Propagator Detonation CM
PDET	Probability of Defense Weapon Detonation
PDETB	Baseline Propagation Detonation Prob.
PDIR	Prob. of IR Detection

PDWL	Prob. of Defense Weapons Launch
PIA	Prob. of Initial Acquisition
PJCAR	Percent of Jammers Allocated to
PLOHC	Propagator Lock-on Homing Capability
PLOHCN	Normal Propagator Lock-on Homing Capability
PASG	Probability of Aircraft Weapons Successful Guidance (dim.)
PASSK	Probability of CBF Aircraft Single Shot Kill (dim.)
PASSKB	Baseline Probability of Single Shot Kill (dim.)
PASE	Probability of CBF Aircraft System Effectiveness (dim.)
PATE	Probability of CBF Aircraft in Firing Envelope (dim.)
PT	Probability of CBF Aircraft Tracking (dim.)
PASG	Probability of Aircraft Weapons Successful Guidance (dim.)
PAVA	Average Radar Power for CBF Aircraft (watts)
PAWDET	Probability of CBF Aircraft Weapons Detonation (dim.)
PAYLD	CBF Aircraft Payload Mass (kg.)
PCBFD	Probability of CBF Aircraft Detection (dim.)
PCBFE	Probability of CBF Aircraft System Effectiveness (dim.)
PCBFFE	Probability of CBF Aircraft in Firing Envelope (dim.)
PCBFLA	Probability of CBF Aircraft in Launch Attitude (dim.)
PCBFT	Probability of CBF Aircraft Tracking (dim.)
PCBWDE	Probability of CBF Aircraft Weapons Detonation (dim.)
PCBWSG	Probability of CBF Aircraft Weapons Guidance (dim.)
PDRT	Tabular Values of Cummulative Probability of Detection (dim.)
PCLOH	Probability of CBF Aircraft Weapons Lock-on and Homing Capability (dim.)
PRAD	Probability of CBF Aircraft Radar Detection (dim.)
PKCBF	Probability of CBF Aircraft Kill (dim.)
PMLEC	Percent Maximum Weapons Allocated as MINMLE
PO	Sea Level Atmospheric Pressure (Pascals)
PRATIO	Macro to Compute Atmospheric Pressure Ratio
PS	Specific Excess Power (m/sec)
PSA	Aircraft Specific Excess Power (m/sec.)
PSCBF	Probability of CBF Aircraft Survival (dim.)
PSG	Prob. of Defense Weapon Succesful Guidance (dim.)
PSSCBF	CBF Aircraft Prob. of Single-Shot Kill (dim.)
PSSDWS	Prob. Defense Weapon Site Single Shot Kill (dim.)
PSTF	Prob. Defense Weapons Having Sufficient Time for Firing (dim.)
PSTRM	Excess-Energy-Turn-Rate-Product Mult., the
PSWM	Propagator Speed vs. Warning Capability Mult.
PT	Prob. of Aircraft Tracking (dim.)
PTRUST	Maximum Instantaneous Thrust Available at Altitude (Newtons)
PVDET	Prob. of Visual Detection

R

RAD	radians
RATINV	Subroutine to Convert an Amplitude Ratio to Decibels
RCDR0	Ratio of Line of Sight Range to Delta Range (dim.)
RCR0	Ratio of Line of Sight Range to Detection Range (dim.)
RCS	CBF Aircraft radar Cross section Area (sq. meters)
RCSAM	CBF Aircraft radar radar Cross Section Azimuth Multiplier (dim.)
RCSRW	CBF Aircraft RCS Reduction Rate due to Weapons Delivery (sq.m.)
RHO	Sea Level Atmospheric Density (kg/cu. meter)
RGAIN	CBF Aircraft radar Antenna Gain (dim.)
RMAX	CBF Aircraft Maximum Weapon Range (meters)
RMIN	CBF Aircraft Minimum Weapon Range (meters)
RRPSOJ	Radar Range Parameter Associated with Stand-off Jammer
RRPSSJ	Radar Range Parameter Associated with Stand-off Jammer
RRPNJ	Radar Range Parameter in a Clear Environment
RWR	CBF Aircraft radar Warning Receiver Range (meters)

S

SABT	Afterburning Thrust Specific Fuel Consumption Table (kg./kg./hr.)
SNABT	Military Power Thrust Specific Fuel Consumption (kg./kg./hr.)
SAI	Corrected CBF Aircraft Heading Angle (rad.)
SAIWEA	CBF Aircraft Weapon Maximum Turn Rate Capability (rad/sec.)
SAIRUS	Aircraft Maximum Useful Sustained Turn Rate Capability (rad./sec.)
SAWE	Subroutine to Estimate The Situational Awareness of the Aircrew
SFCU	Specific Fuel Consumption (kg./kg./hr.)
SIGMA	Atmospheric Density Ratio for Aircraft (dim.)
SSL	Sea Level Standard Conditions
SNOISE	CBF Aircraft Infrared Signal-to-Noise Ratio (dim.)
SOJ	Stand-off Jammer
SPECTR	Subroutine to Find the Relative Infrared Energy radiance of a Black Body
SQRT	Square Root Intrinsic Function
SRAAM	Short Range Air-to-Air Missile
SRL	Slant Range from Aircraft to Target (meters)
STD	Standard Deviation (dim.)
STVDA	CBF Return Steering Vector Direction (rad.)
S1DWKR	One Dimensaional Array Containing Values of DWSKR
S2DWKR	Two Dimensaional Array Containing Values of DWSKR
S1SULA	One Dimensaional Array Containing Values of ASULA
S2SULA	Two Dimensaional Array Containing Values of ASULA

T

TAA	Target Aspect Angle (rad.)
TAU	Atmospheric Transmittance Term (W/m.)
TE	Ground Radar Noise Temperature (degrees absolute)
THAB	Full Afterburner CBF Aircraft Engine Thrust vs. Mach Number (kg.)
THNAB	Dry CBF Aircraft Engine Thrust vs. Mach Numerical Values (kg.)
THETA	Atmospheric Pressure Ratio (dim.)
TIM	IR-Guided Bomb Time of Flight (sec.)
TO	Sea Level Atmospheric Temperature Associated (rad. absolute)
TOF	Time of Flight (sec.)
TS	Ground Radar Scanning Time (seconds)
TSS	CBF Aircraft Throttle Setting (dim.)
TSAEGT	CBF Throttle Setting vs. Exhaust Area Multiplier (dim.)
TSAEMG	AGG Throttle Setting vs. Exhaust Area Multiplier (dim.)
TSAPGM	Throttle Setting vs. Exhaust Area Multiplier (dim.)
TSEGGT	Tabular AGG Aircraft Throttle Setting vs. EGT Mutiplier
TSEGTG	Throttle Setting vs. EGT Parameter
TSFC	Thrust Specific Fuel Consumption (kg./kg./hr.)
TSR	Throttle Setting Rate of Change (1/sec)
TSTAG	CBF Aircraft Skin Stagnation Temperature (degrees absolute)

U

UWEXPC	CBF Aircraft Expendable Cartridge Mass (kg./cartridge)
UWEXPG	AGG Aircraft Expendable Cartridge Mass (kg./cartridge)

V

VAPPT	CBF Aircraft Tangential Speed to Target (m/sec.)
VAPPr	CBF Aircraft Radial "Approaching" Speed to Target (m/sec.)
VS	CBF Aircraft Speed Flight Speed (m/sec.)
VTS	Aircraft Targetted Speed at Waypoint i (m/sec.)

X

XS	CBF Aircraft Downrange Position (meters).
XWIN	Downrange Position of Ingress Waypoints.
XWOUT	Lateral Range Position of Ingress Waypoints

Y

YS	CBF Aircraft Lateral Downrange Position (meters)
YTS	Navigation Waypoint Lateral Downrange Position (meters)
YAWRTE	Subroutine to Estimate the Aircraft Maximum Sustained Yaw Rate

Appendix E. Radar Range Equation Simplifications

This appendix is meant to provide insight into some of the simplifications made to the radar detection range equation in order to estimate the importance of radar performance and operational features in the sortie survivability of a given aircraft. This appendix briefly states the assumptions and equations used to estimate radar baseline range in a clear environment as well as in the presence of stand-off and self-screening jamming.

E.1 No Jamming Radar Equation

The radar range equation for a high pulse repetition frequency (PRF) doppler radar is [Hovanessian, 1984],

$$\frac{S}{N} = \frac{\bar{P} G^2 \lambda^2 \sigma T_I}{64 \pi^3 R^4 K T L} \qquad E.1$$

where, S/N is the signal-to-noise ratio (SNR), $\bar{P}$ is the average radar power, G is the antenna gain, λ the transmition wavelength, σ the radar cross section of the target, T_I the illumination

time, R the radar range to the target, K is Boltzman constant, T the equivalent receiver noise temperature, and L the ratio of transmition and reception losses. Assuming detection is possible at the minimum SNR of one and solving for R one obtains.

$$R = \frac{\bar{P} G^2 \lambda^2 \sigma T_i}{64 \pi^3 K T L} \qquad E.2$$

if the radar is operated in a search mode (PDS) the on-target time (T_i) for a search scan coverage Ω and bandwidth of main lobe θ_{3db} is given as,

$$T_i = \frac{t_s \theta_{3db}^2}{\Omega} \qquad E.3$$

For fighter aircraft with planar array antennas and tapered illumination [Stimpson, 1985] the bandwidth can be approximated as follows.

$$\theta_{3db} = 1.25 \left(\frac{\lambda}{d} \right) \qquad E.4$$

where, d is the antenna diameter and λ the wavelength. Expressing the antenna gain (G) in terms of the antenna physical parameters and wavelength one obtains E.5.

$$G = 4\pi \left(\frac{A_e}{\lambda} \right) \qquad E.5$$

where A_e is the antenna effective aperture area. Introducing the aperture efficiency η , ratio of the effective aperture area (A_e) and the physical antenna size [Stimpson, 1985], Eq. E.5 becomes,

$$G = 4\pi \left(\frac{A \eta}{\lambda} \right) \qquad E.6$$

Stimpson [1985] offers a good compromise to estimate the gain for circular aperture antennas operating in the X-band (typical of fighter aircraft) as follows,

$$G = 9\left(\frac{d^2}{\lambda^2}\right)\eta \qquad E.7$$

Turning for a moment back to Eq. E.3 the on-target time (T_i) becomes E.8 after substituting E.4 into E.3.

$$T_i = \frac{t_s (1.25)^2 \lambda^2}{\Omega d^2} \qquad E.8$$

defining the scan coverage as the product of the elevation and azimuth angular coverage, θ_e and θ_a, respectively.

$$T_i = \frac{(1.5625)\, t_s \lambda^2}{\theta_e \theta_a d^2} \qquad E.9$$

substituting eqs. E.9 and E.7 into E.2 yields the following approximation

$$R^4 = \frac{2 \bar{P} d^2 t_s \sigma \eta}{\pi^3 K T L \theta_e \theta_a} \qquad E.10$$

which contains the essential radar operational and design elements necessary to perform sensitivity analysis on radar technology improvements and/or operational modes. A particularly useful expansion to this model would be incorporation of switching rules that could vary the radar angular scan coverage according to the geometry of the engagement and to the LOS range parameter.

E.2 Stand-off Jamming Radar Equation

A modification to Eq. E.1 is necessary to estimate the new nominal radar range in the presence of a stand-off jammer. The noise jamming power (NJP) is given below for main lobbe jamming [1984].

$$NJP = \frac{P_j G_j A_e}{4\pi R_j^2 B_j} \qquad E.11$$

where, P_j is the jammer power, G_j the jammer gain, A_e the effective aperture, R_j the range between radar and jammer, and B_j the jammer bandwidth. Substituting Eq. E.11 into E.10 for SNR of one.

$$R^4 = \frac{2\bar{P} d^2 t_s \sigma \eta^2}{\pi^3 L \theta_e \theta_a} \quad \frac{4\pi R_j^2 B_j}{P_j G_J A_e} \qquad E.12$$

knowing that the radar gain can be expressed as in Eq. E.5, solving for A_e and substituting back into E.12 yields,

$$R^4 = \frac{32\bar{P} t_s \sigma \eta}{\pi L \theta_e \theta_a} \quad \frac{B_j}{P_j G_J} R_j^2 \qquad E.13$$

where the second term on the right hand side of this equation constitutes the effective radiated power of the jammer.

E.3 Self-screen Jamming Radar Equation

In this particular case R_j , distance from the jammer to the radar, is equal to the radar range from the aircraft to the target (i.e. jammer on board the target aircraft). This fact simplifies E.13 to the following,

$$R^2 = \frac{32\,\bar{P}\,t_s\,\sigma\,\eta}{\pi\,L\,\theta_e\,\theta_a} \quad \frac{B_j}{P_j\,G_J} \qquad E.14$$

which constitutes the burnthrough range under self-screen jamming operations.

Appendix F. Elementary Infrared Principles

F.1 General Principles

This appendix familiarizes the reader with some basic infrared principles that are used in ASALT II. A large portion of the energy radiated by a solid, gas, or plasma is confined to a very radiation band which is usually part of the infrared spectrum. In the analysis of aircraft survivability the incorporation of a realistic infrared model is necessary due to the large infrared (IR) emissions resulting from the aircraft engines, exhaust plume, and aircraft skin. Since all infrared sources have a unique power spectrum it is necessary to describe targets in terms of an idealized "perfect absorber" of infrared energy whose radiated energy is a function of temperature alone. This concept, denoted "black body" theory is fairly well documented and useful for preliminary analysis of infrared systems [Hudon, 1969].

The spectral radiation of a blackbody is given by Planck's Law as follows,

$$W_\lambda = \frac{k_1}{\lambda^5} \left[\frac{1}{e^{-k_2/\lambda T} - 1} \right] \quad in \quad \left(\frac{W}{cm^2 \mu} \right) \qquad F.1$$

where, W_λ is the spectral radiant emittance, k_1 and k_2 are two constants, λ is the emission wavelength, and T is the absolute temperature of the blackbody. Integration of W_λ over all the IR emission spectrum yields the total infrared radiance (N),

$$N = \int_{\lambda_1}^{\lambda_2} \left[\frac{k_1}{\lambda^5} \frac{1}{e^{-k_2/\lambda T} - 1} \, d\lambda \right] \qquad in \left(\frac{W}{cm^2 \mu}\right) \qquad F.2$$

In order to simplify matters, it is possible to plot the spectral radiance as a function of the product of λ and T to obtain a spectral distribution curve representing the blackbody irradiance characteristics for a large range of temperatures as shown in fig. F.1. Two important curves are obtained from this analysis one representing the spectral emittance and another one the result of the integral F.2 for a given portion of the IR spectrum. The importance of this universal infrared radiation curves for a blackbody, as they are named, resides in the fact that it is possible to find the fraction of IR radiance from a given target once the spectral bandwidth of the sensor and the radiation characteristics of the target are known. The later point presents the problem that not all substances behave as perfect absorbers and thus a correction factor needs to accounted for if their IR radiance is to be measured. In practice it is assumed that all IR targets radiate energy in a similar spectral pattern as that of a blackbody but their emission is degraded by a factor denoted the radiant emissitivity (ε). Integration of F.1 from zero to infinity results in the well-known Stefan-Boltzmann law for evaluating the total radiance (N).

$$W = N\pi = k_3 T^4 \qquad (W/cm^2) \qquad F.3$$

where, k_3 is the so called Stefan-Boltzmann constant (5.7×10^{12} $Wcm^{-2}\,{}^oK^{-4}$ and T is the temperature. Correcting this value due to "imperfect radiation" (gray body) by introducing the radiant emissitivity yields the following,

$$N\pi = \varepsilon k_3 T^4 \qquad (W/cm^2) \qquad F.4$$

the radiant intensity (J) is just the product of radiance (N) and the effective area of radiation, A_e.

$$J = \varepsilon k_3 T^4 \frac{A_e}{4\pi} \qquad F.5$$

notice that the factor 4π accounts for the complete upper hemisphere radiation pattern of a gray body. For gases it is known that the spectral emissions occur at discrete bands due to intermolecular interactions that are outside the scope of this analysis. Suffice to say that high absorption bands present in gases are also bands of high emissitivity and hence the only ones needed to be considered in the analysis of infrared detection systems. Another important characteristic of gases is that of transmitance. This particular one is necessary to account atmospheric effects, such as attenuation, acting on infrared systems as will be described later.

F.2 General Range Expression

In order to develop a generalized infrared range expression it is necessary to introduce some assumptions that, although simplify extensively the problem, retain enough accuracy to warrant reasonable first order performance predictions [Hudson, 1969].

The spectral IR radiance for an unresolved target is given as,

$$H_\lambda = J \mathrm{T}_A \frac{(\lambda)}{r^2} \qquad (W/cm^2 sr\mu) \qquad F.6$$

where, J is the spectral radiant intensity of the target, and r the distance from the sensor to the target. Assuming a passive detection system the voltage signal (V_s) generated by the system is,

$$V_S = \frac{A_e}{R^2} \int_{\lambda_1}^{\lambda} 2\, J\, T_A\, T_0\, R_\lambda\, d\lambda \qquad F.7$$

where, A_e is the effective apperture area of the detector, T_0 is the spectral transmittance of the system, T_A is the spectral transmittance between the sensor and the target, R_λ is the responsivity of the system, and $\lambda_1 \wedge \lambda_2$ represent the limits of the sensor bandwidth . Converting terms depending upon λ into integrated values and dividing by the sensor voltage noise (V sub N) one obtains the signal-to-noise ratio (SNR).

$$SNR = \frac{V_S}{V_N} = A_e\, T_0\, \frac{R_\lambda}{V_N}\, \frac{J\, T_A}{r^2} \qquad F.8$$

defining noise equivalent infrared radiance (NEI) as that radiance producing SNR of unity (signal equals to noise generated) yields,

$$NEI = \frac{V_N}{A_e\, T_0\, R_\lambda} \quad (W/cm^2 sr) \qquad F.9$$

then F.8 becomes,

$$SNR = J\, \frac{T_A}{NEI\, r^2} \qquad F.10$$

The atmospheric transmittance T_A is assumed to have the following form [Hudson, 1969],

$$T_A = e^{-\alpha r} \qquad F.11$$

where, α is the transmittance coefficient dependent upon atmospheric characteristics (i.e. density, rain, humidity, etc.) and r is the distance from the sensor to the target. Eq. F.9 becomes,

$$SNR = \frac{J}{NEI}\, \frac{e^{-\alpha r}}{r^2} \qquad F.12$$

from which R could be solved using a quadratic solution once the sensor characteristics, NEI and λ are known. Notice also that the IR radiant intensity term, J, is the only parameter that contains the target model characteristics.

F.3 Target Characteristics

Three principal infrared signature contributions are accounted for in ASALT II: 1) the engine nozzle "hot" parts, 2) the engine exhaust plume, and 3) the aircraft skin. These will be briefly described in the following paragraphs.

The engine exhaust nozzle "hot" parts constitute the most important source of infrared radiation emanating from an aircraft flying at subsonic speeds with no afterburner [Hudson, 1969]. The modeling of this IR source is performed assuming that the exhaust nozzle area (A_e) is, in fact, the only gray body area of radiation. Also, the temperature of the exhaust gases (EGT) is a generaly known parameter that is taken to be the average temperature of the gases at the reference area. Assuming a typical radiant emissitivity (ε) is then possible to evaluate the exhaust nozzle radiant emissitivity as follows,

$$J_{ENG} = \varepsilon k_3 EGT^4 \frac{A_e}{4\pi} \quad (W/sr) \qquad F.13$$

It is known that incomplete products of combustion, CO_2 and H_2O, have most of their radiation spectrum confined to wavelengths between 3 and 5 microns (μ) hence it is possible to estimate the effective IR radiant intensity directly using the integrated universal blackbody curves shown in fig. B.1

A similar approach can be used to deal with the engine exhaust plume radiation if a suitable average temperature is found for the entire plume area, A_s. , and if the IR radiation limits of

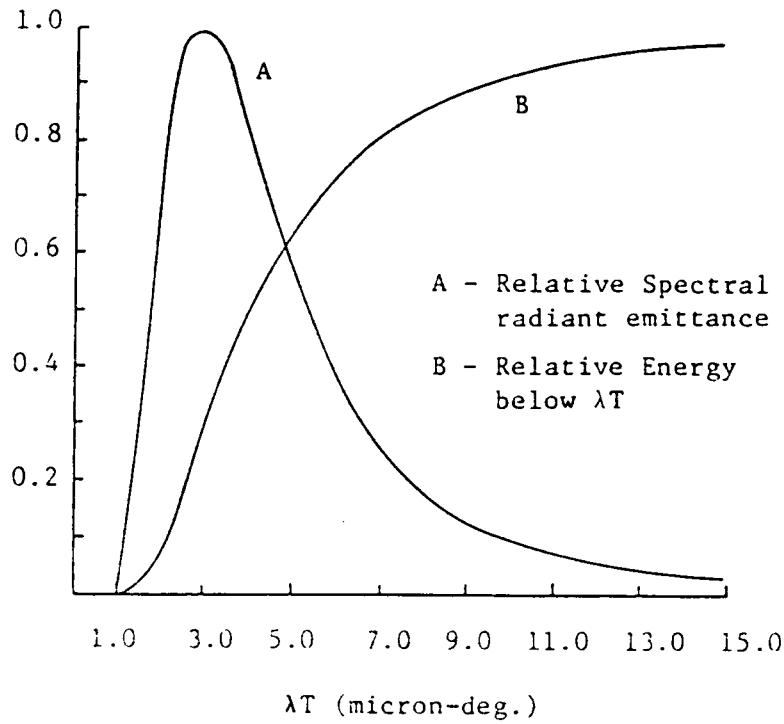


Figure F.1 Universal Infrared Blackbody Curves.

the plume gases are known. The temperature of the plume gases after an adiabatic expansion, T_2 , is given by,

$$T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \qquad F.14$$

where, T_1 is the temperature before the expansion (assumed for convinience to be EGT), P_2 is the pressure after the expansion, P_1 the pressure before the expansion, and γ is the ratio of specific heats. It can be further assumed that the quotient P_2/P_1 does not vary considerably for high subsonic and low supersonic flight conditions and thus can be considered as a constant typically on the order of 0.5 [Hudson, 1969]. Then eq. F.14 reduces to,

$$T_2 = 0.85\, T_1 = 0.85\, EGT \qquad F.15$$

expression which is used in this model. The limits of the IR radiance spectrum for the exhaust plume are somewhat narrower that those previously used. The emission band in this case ranges from 4.3 to 4.55 μ and is approximated by a rectangle as shown in fig. B.2 centered at 4.4 μ.

The exhaust plume area (A_s) constitutes an exogenous parameter which is heavily dependent upon nozzle geometry, flight speed, atmospheric density, afterburning level, etc. which cannot be modeled in an explicit way at this level. The model incorporates an exhaust plume area multiplier to capture at least partially some of these effects (see section 5.2.5.1).

Finally, the skin IR signature can be estimated by computing the stagnation temperature at a given flight mach number from the well known quasi-isentropic relationship for temperature as follows,

$$T_o = T_\infty \left[1 + r\,\frac{\gamma - 1}{2}\, M^2\right] \qquad F.16$$

where, T_∞ is the free stream ambient temperature, r is the airflow recovery factor (0.85 for mixed flow conditions), γ is the ratio of specific heats, and M is the free stream mach number.

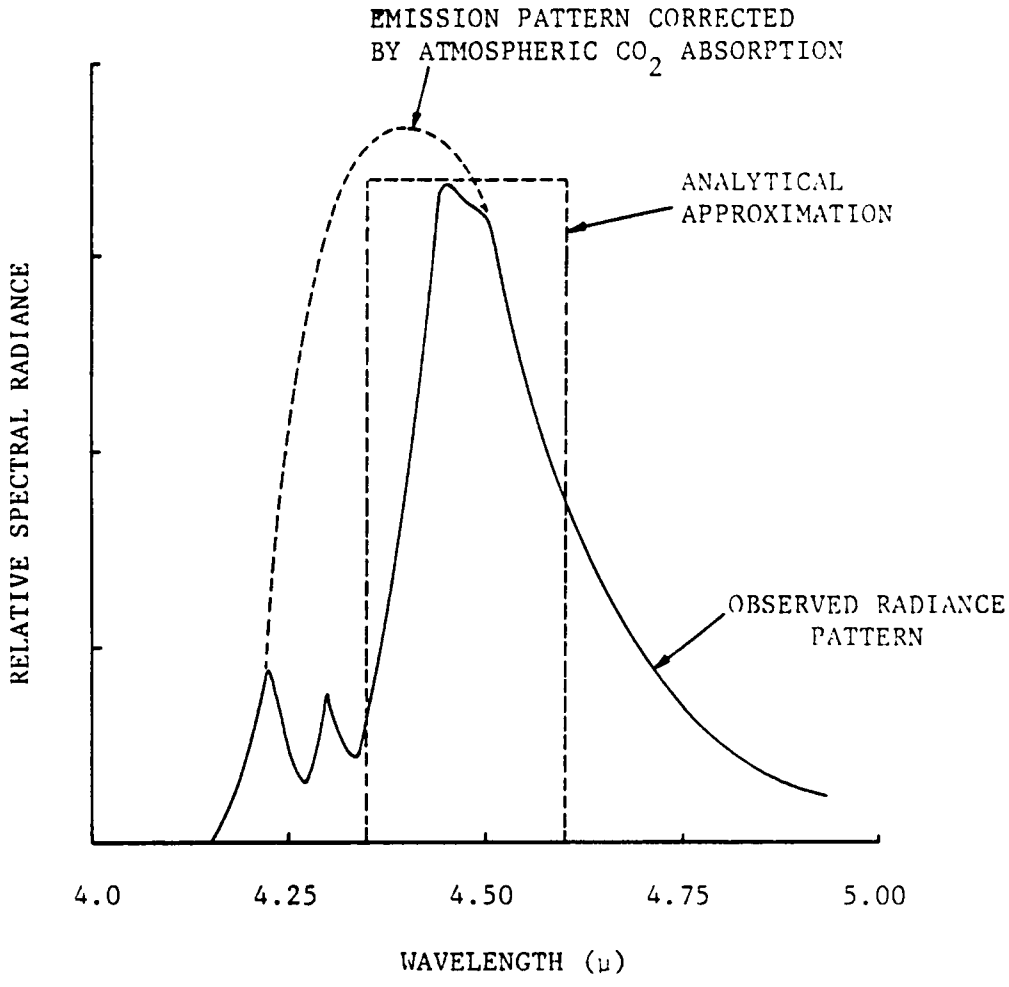


Figure F.2 4.4 μ Exhaust Plume Emission Band (adapted from Hudson)

The representative area to be used in eq. F.13 associated with this computation is the aircraft wetted area (S_{WET}). Young [1986] estimates that 25 percent of S_{WET} can be considered to be affected by stagnant flow for preliminary analysis. Introducing this assumptions and substituting F.16 into F.6 yields,

$$J_{SKIN} = \frac{1}{4\pi} \varepsilon_s k_3 [T_\infty \{1 + r \frac{\gamma - 1}{2} M^2\}]^4 (.25) S_{WET} \qquad F.17$$

where, ε_s is the skin radiant emissitivity and J_{SKIN} the IR radiant intensity of the aircraft skin. A first order approximation of the aircraft wetted area (S_{WET}) can be found, according to Roskam [1981], as function of aircraft maximum gross takeoff gross weight (W_O).

$$S_{WET} = Antilog [C + \log_{10} W_O^D] \qquad F.18$$

where, C and D are regression coefficients particular to each class of aircraft. For 20 modern fighter type aircraft Roskam [1981] found C = -0.1289 and D = 0.7506 and thus are the values implemented in this model. Note that S_{WET} is expressed in squared feet and W_O in pounds for these coefficients to be applicable.

Appendix G. Basic Aircraft Aerodynamics and Performance.

In order to represent the aerodynamic characteristics of the aircraft modeled it is necessary to understand some of the basic aerodynamic and performance concepts that are relevant in the subsonic regime. The most simplistic approach to model the drag of an aircraft is to consider he drag to be a quadratic function of mach number as follows.

$$D = \frac{1}{2} \gamma P_0 \delta M^2 S C_D \qquad G.1$$

where,γ is the air ratio of specific heats, P_0 is the air pressure at sea level standard conditions, δ is the air pressure ratio at flight altitude. S is the wing area, and C_D is the drag coefficient. Further breaking down C_D in its lifting and non-lifting terms yields,

$$C_D = C_{DI} + C_{D0} \qquad G.2$$

where C_{DI} is the induced drag coefficient (i.e. lift dependent) and C_{D0} is the zero-lift drag coefficient (i.e. function of mach number).

The zero-lift drag coefficient (C_{D0}) is a lumped parameter that accounts for the parasite drag of the aircraft components that do not produce lift. Most of drag breakdown analyses

constitute bookeeping methods to account for many drag components that are usually present in geometrically complex, modern aircraft. For the purpose of simplification in this model only three zero-lift drag contributions are considered in this analysis: 1)The clean aircraft zero-lift drag, 2) the external stores drag, and 3) electronic countermeasures equipment drag.

$$C_{D0\ a/c} = C_{D0\ c} + C_{D0\ ecm} + C_{D0\ ord} \qquad G.3$$

where, $C_{D0\ a/c}$ is the complete aircraft zero-lift drag coefficient, $C_{D0\ c}$ is the clean aircraft zero-lift drag coefficient, $C_{D0\ ecm}$ is the zero-lift coefficient for the external ECM equipment carried externally, and $C_{D0\ ord}$ is the zero-lift drag contribution due to external ordnance carriage. For this model the last two contributions have been assumed constant with mach number though it should be realized that at the conceptual design level little is known about the behavior of these two important contributions due to the strong dependence upon the particular aircraft external stores configuration used. To simplify the notation $C_{D0\ a/c}$ will just be referred as C_{D0} as well as C_{Di} for the complete aircraft.

For non-accelerated flight and neglecting thrust offset angles it is known that thrust (T) and drag (D) are equal. Writing explicitely the expression for drag

$$T = D = q\ S\ C_D \qquad G.4$$

where q is the dynamic pressure, a parameter including $\frac{1}{2}\gamma$, δ, and M^2; S is the wing area, and C_D is the drag coefficient. Writing C_{Di} in terms of lift coefficient C_L, wing efficiency factor e, and wing aspect ratio AR,

$$C_{Di} = \frac{C_L^2}{\pi\ AR\ e} \qquad G.5$$

for straight and level flight lift (L) equals weight ($W_{a/c}$), Therefore,

$$C_L = \frac{2\ W_{a/c}}{\gamma\ P_0\ \delta\ M^2\ S} \qquad G.6$$

substituting Eqns. G.1, G.2, G.5, and into G.3 yields,

$$T = \frac{1}{2}\gamma P_0 \delta M^2 S C_{D0} + \frac{4 W_{a/c}^{\ 2}}{\pi AR e \gamma^2 P_0^2 \delta^2 M^4} \qquad G.7$$

which represents a general form to express the thrust requirements of an aircraft in steady flight at a given mach number.

Of importance are also the performance characteristics of the aircraft because they can be associated with the aircraft capablity to manuever in a hostile environment to avoid threat propagators. Traditional measures of performance for fighter and attack aircraft center in sustained maneuverability capabilities. The maneuvering metrics used in this model are the maximum sustained turn rate ($\dot{\psi}$) and the specific excess power (P_s). The former describes the maximum continuous aircraft turning capability without loss in altitude and it can be shown to be as follows.

$$\dot{\psi} = g \frac{\sqrt{n^2 - 1}}{V} \qquad G.8$$

where g is the gravity constant, n is the maximum aerodynamic load factor, and V is the aircraft speed. Notice however that only aerodynamic constraints are present in this expression and hence structural integrity as well as thrust limitations need to be included in this analysis to effectively predict the maximum sustained turning performance at any given flight condition (i.e. mach number and altitude combination). Introducing constraints for the thrust available at any altitude equation G.9 governs the maximum load factor due to thrust limitations.

$$n = \frac{q}{W_{a/c}/S} \sqrt{1/k\,(T/q\,S - C_{D0})} \qquad G.9$$

where 1/k is the wing efficiency factor, q is the dynamic pressure, T is the engine thrust, S is the wing area, and C_{D0} the zero lift drag coefficient. Nicolai [1975] provides a full derivation of this equation.

The specific excess power represents a balance between kinetic and potential energy of the aircraft at any point in time. Energy maneuverability is then used to quantify the potential capability of the aircraft to change its state. The idea is that the rate of change of the energy is also the rate at which the aircraft can climb and/or decelerate [Nicolai, 1975]. The expression for P_s is as follows.

$$P_s = \frac{V}{W}(T - D) \qquad G.10$$

where V is the aircraft speed, T is the engine thrust, D is the total aircraft drag, and W is the aircraft weight. It is concluded then that in order to quantify the potential aircraft maneuverability at a given point in time the problem reduces to compute the values of thrust, drag, weight, and speed using the steady-state approximation. Finally to assess the flight envelope of the particular aircraft modeled it is possible to plot the locus of all point for which $P_s = 0$which bounds the velocity-height region where flight is admissible. Non-steady maneuvers are feasible to be executed outside the boundaries of this one-G envelope for short periods of time although are not considered in this model.

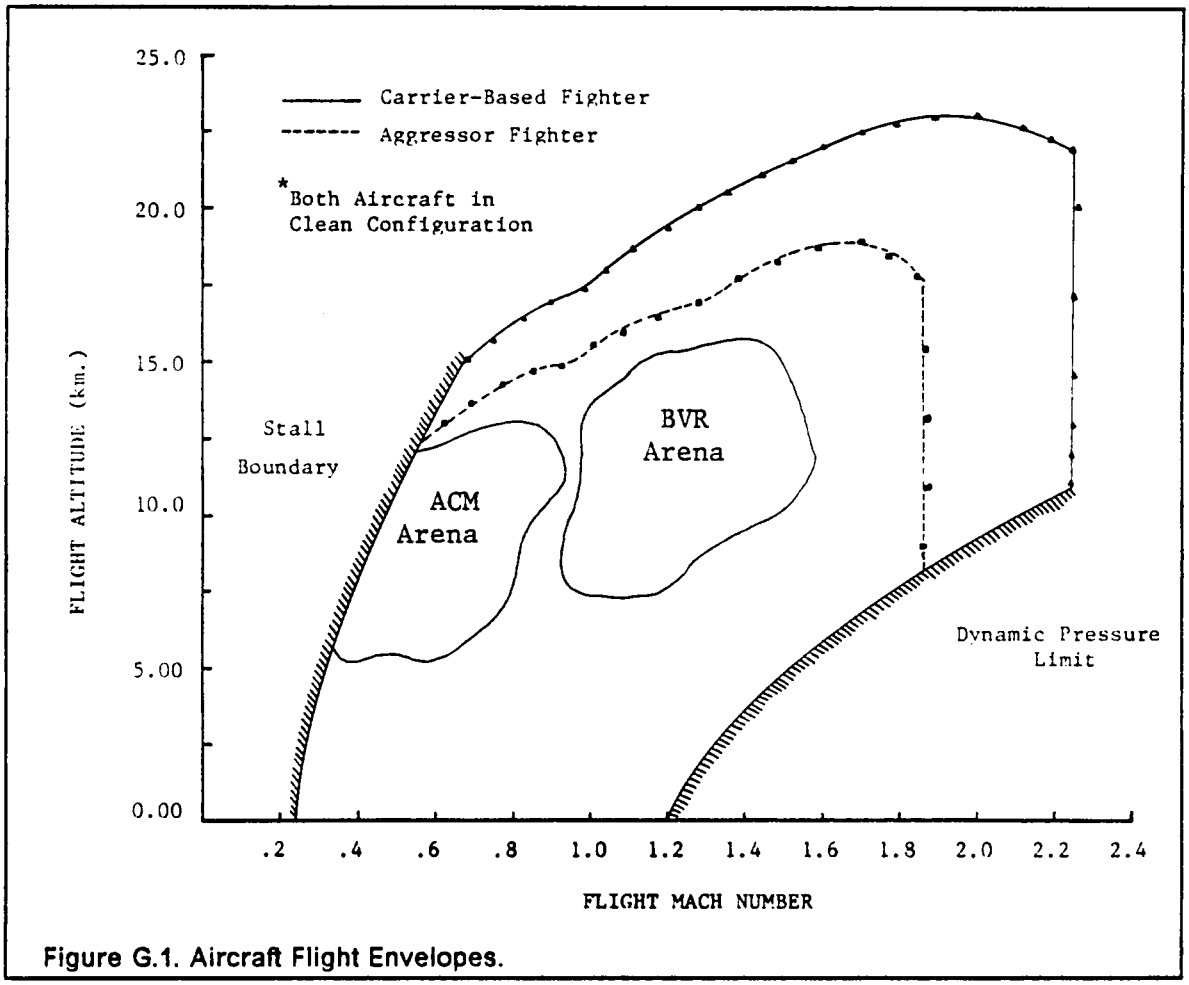


Figure G.1. Aircraft Flight Envelopes.

Appendix H. Aircraft Characteristics

For the purpose of this research two high performance fighter aircraft were chosen to represent the carrier based and aggressor forces. The principal aircraft geometric characteristics as well as their performance are sumarized in this appendix.

H.1 Carrier Based Aircraft

Aircraft Masses	
Maximum takeoff gross mass	25000 kg.
Empty mass	14000 kg.
Maximum fuel mass	6000 kg.
Maximum payload mass	6500 kg.
Mission mass	19300 kg.
Wing Characteristics	
Aspect ratio	3.5
Wing area	40 sq. m.
Wing efficiency factor	.79
Engine Characteristics	
Number of engines	2
Static sea level thrust	5320 kg. dry 8131 kg. max. afterburner
Engine diameter	.950m.
Engine frontal area	0.762 sq. m.
Engine length	4.04 m.
Engine mass	1054 kg.
Engine thrust/mass	7.7:1
Engine mass flow rate	94.8 kg./sec.(SL)
Aircraft Signature	
Aircraft radar cross section	5 sq. meters

Weapon δRCS	.30 sq. m./LRAAM .20 sq. m./MRAAM .10 sq. m./SRAAM
Aircraft Aerodynamic Characteristics	
Aircraft C_{D0} (clean)	0.011 below mach .8
Aircraft C_{D0} (loaded)	0.024 below mach .8
Missile δC_{D0}	20 counts/LRAAM 15 counts/MRAAM 10 counts/SRAAM
Ordnance	
Air-to-Air missiles	4 LRAAM @ 450 kg. each 2 MRAAM @ 160 kg. each 2 SRAAM @ 90 kg. each Cannon 1000 rounds (250 kg. total)
Performance	
Maximum level speed (clean)	Mach 2.4 @ 36000 ft. Mach 1.25 @ sea level
Maximum level speed (loaded)	Mach 1.6 @ 36000 ft. Mach 1.10 @ sea level
Maximum combat ceiling	60000 ft. @ $P_s = 100 ft/sec.$
Absolute Ceiling	70000 ft.
Maximum combat radius	1000 km. with 4/2/2 missile mix

H.2 Aggressor Aircraft

Aircraft Weights	
Maximum takeoff gross mass	25000 kg.
Empty mass	14000 kg.
Maximum fuel mass	6000 kg.
Maximum payload mass	6000 kg.
Mission mass	19300 kg.
Wing Characteristics	
Aspect ratio	3.5
Wing area	40
Wing efficiency factor	.79
Engine Characteristics	
Number of engines	2
Static sea level thrust	5113 kg. dry 8320 kg. max. afterburner
Engine diameter	1.02 m.
Engine frontal area	0.817 sq. m.
Engine length	4.1 m.
Engine mass	1200 kg.
Engine thrust/mass	6.93:1
Engine mass flow rate	100.0 kg./sec.
Aircraft Signature	
Aircraft radar cross section	5 sq. meters
Weapon δRCS	.40 sq. m./LRAAM .30 sq. m./MRAAM .20 sq. m./SRAAM
Aircraft Aerodynamic characteristics	
Aircraft C_{D0} (clean)	0.014 below mach .8
Aircraft C_{D0} (loaded)	0.026 below mach .8
Missile δC_{D0}	30 counts/LRAAM

	20 counts/MRAAM 10 counts/SRAAM
Ordnance	
Air-to-Air missiles	4 LRAAM @ 500 kg. each 2 MRAAM @ 170 kg. each 2 SRAAM @ 110 kg. each Cannon 1000 rounds (250 kg. total)
Performance	
Maximum level speed (clean)	Mach 2.1 @ 36000 ft. Mach 1.15 @ sea level
Maximum level speed (loaded)	Mach 1.25 @ 36000 ft. Mach 1.04 @ sea level
Maximum combat ceiling	55000 ft. @ $P_s = 100 ft/sec.$
Absolute Ceiling	63000 ft.
Maximum combat radius	600 km. with 4/2/2 missile mix

Appendix I. End-Game Simulation Example

This appendix is meant to exemplify some of the off-line studies that can complement the large scale simulation models described in Chapter 5 of this dissertation. It also provides some insight in the implementation and derivation of multipliers. The particular example chosen here represents a typical end-game simulation model where a surface-to-air radar guided missile is launched to an attacking aircraft. The missile dynamics are modeled as sixth order model with full three dimensional capabilities while those of the aircraft are constrained to a plane parallel to the earth. The model includes realistic time delays for both, missile and aircraft, as well as aerodynamic actuator saturation constraints (i.e. the missile is limited by actuator size to command 36 g's of maximum total normal acceleration). The equations of motion of the aircraft are as follows:

$$\frac{dX}{dt} = V\cos\psi \qquad I.1$$

$$\frac{dY}{dt} = V\sin\psi \qquad I.2$$

$$\frac{dV}{dt} = \frac{T\cos(\alpha) - D}{m_a} \qquad I.3$$

and

$$\frac{d\psi}{dt} = DELAY\ \frac{T\ \sin(\alpha) - D}{m_a V}\ \sin(\phi) \qquad I.4$$

where, X and Y are aircraft position coordinates, V is the aircraft velocity, ψ is the heading angle, T is the installed thrust, D the total aircraft drag, α is the angle of attack, and ϕ the bank angle. Note that $\dot{\psi}$ is delayed through the same cyclic procedure described in Chapter 5 to account for pilot reaction time. As before, control variables are ϕ and T which are assumed to behave in a "bang-bang" fashion (i.e. full throttle and maximum bank angle are commanded) in order to maximize miss distance from the threat. The missile dynamics are as follows, follows:

$$\frac{dX_m}{dt} = V_m \cos\psi_m\ \cos\theta_m \qquad I.5$$

$$\frac{dY_m}{dt} = V_m \sin\psi_m\ \cos\theta_m \qquad I.6$$

$$\frac{dZ_m}{dt} = V_m \sin\psi_m \qquad I.7$$

$$\frac{dV_m}{dt} = \frac{T_m - D_m}{m_m} \qquad I.8$$

and

$$\frac{d\psi}{dt} = DELAY\ \{\frac{a_\psi}{V_m}\} \qquad I.9$$

$$\frac{d\psi}{dt} = DELAY\ \{\frac{a_\theta}{V_M \cos\theta_m}\} \qquad I.10$$

where, X_m, Y_m, and Z_m are the missile position coordinates, V_m is the missile magnitude of the velocity vector, ψ_m is the missile heading angle, θ_m is the pitch angle, T_m the missile thrust, and D_m the total missile drag. This last term is assumed to vary quadratically with the total

commanded acceleration [44]. The missile thrust is assumed constant throughout burnout time (i.e. 15 seconds for the baseline model) and the commanded accelerations a_ψ and a_θ are limited to 30 and 20 g's, respectively. A time delay of 0.3 seconds is introduced in Eqs. I.9 and I.10.

Appendix J lists the complete FORTRAN model developed for this example. Note that most of the variables are consistent with previous models and thus will not be described. Some of the results of the simulation model are depicted graphically in Figs. I.1 through I.4. The results are driven towards the estimation of the probability of threat homing avoidance capability (THAC), part of the probability of threat susccesful guidance (PSG), for a one-on-one missile and aircraft engagement. In fact these two can be used interchangeably in the the absence of passive or active countermeasure use and assuming that the probability of missile lock-on is always unity. Figs. I1 and I.2 constitute parametric studies of the intercept for various aspect angles, downranges, and initial aircraft speeds. These parameters were known to have significant leverage in the outcome of the engagement and thus were selected for illustrative purposes. It is seen from Fig. I.1 that an increase in aircraft speed greatly increases the chances of evading the threat. This is specially true for a high altitude intercept (e.g. 6000 m. line). From Fig. I.2 it is observed that low THAC are schieved below 5000 meters due to the limited missile maneuverability in the acceleration phase of its flight. From these two figures a general trend can be established for THAC with respect to the three variables used in the parametric study. Selecting a point in the two curves as baseline value it is possible to derive three multipliers that could approximate to first degree the curves shown in Figs. I.1 and I.2. The resulting trends of these multipliers are shown in Fig. I.4. Although this analysis has been restricted to three variables it is possible to extend the same notion for higher dimensions by including as many multipliers as necessary. The benefits of this seemingly painful process can be better appreciated if one considers the computational advantages of having tabulated matrix data available for events that although important cannot be modeled explicitly in a macroscopic model such as ASALT. In this particular example the differences in the simulation step size are one or two orders of magnitude apart. Consider that in order to obtain

a reasonable resolution for the end-game model a step size of 50 miliseconds or less is generally required to estimate miss distances within one aircraft wingspan (e.g. 15-20 m.) while the macro model could be simulated with step sizes on the order of 1 to 5 seconds.

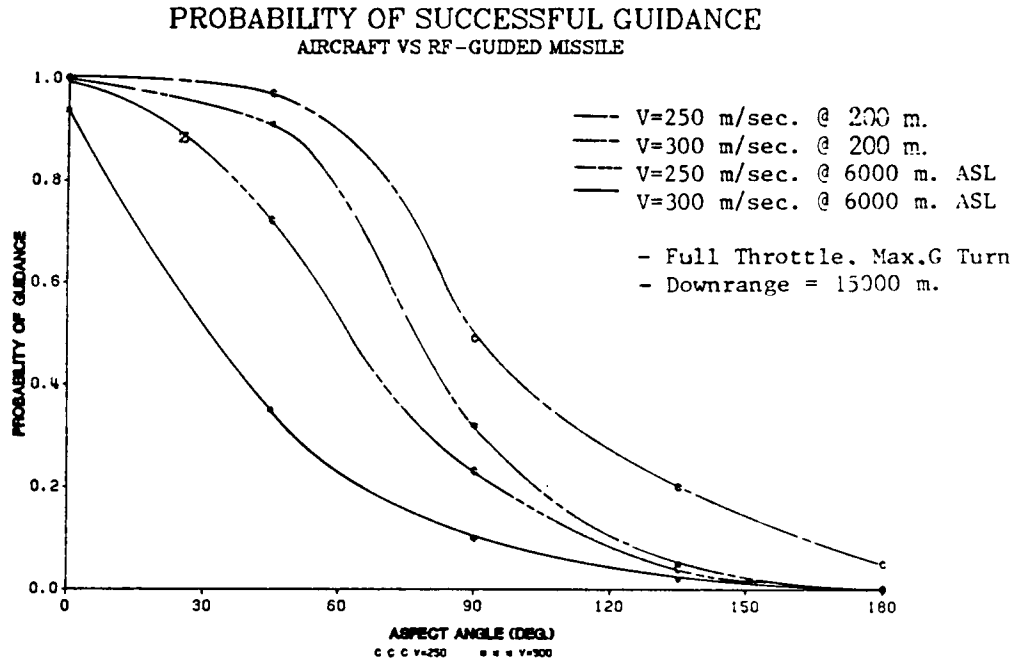


Figure I.1 Probability of Successful Guidance vs. Aspect Angle

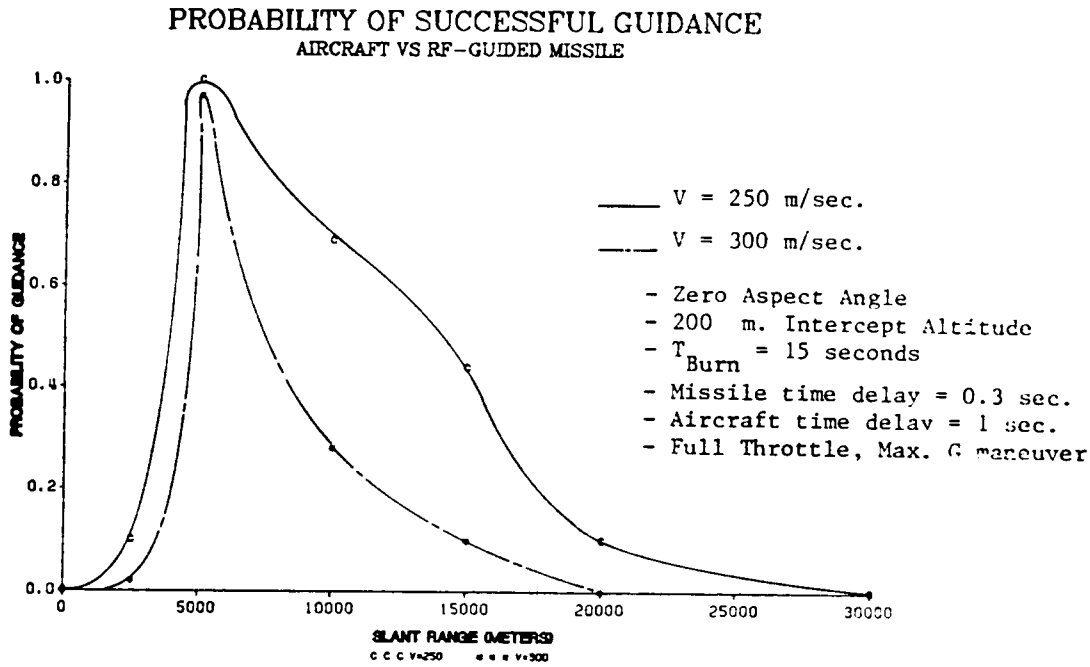


Figure I.2 Probability of Successful Guidance vs. Slant Range.

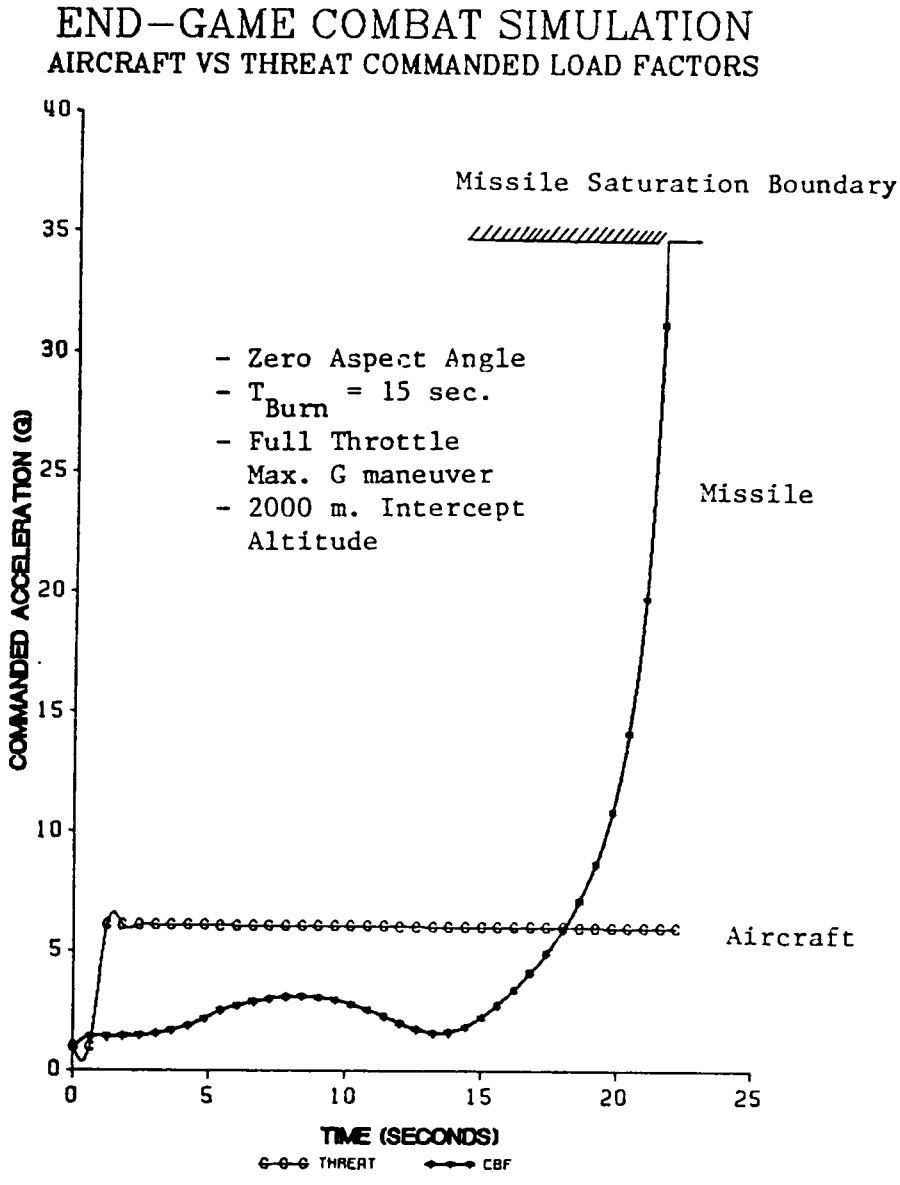
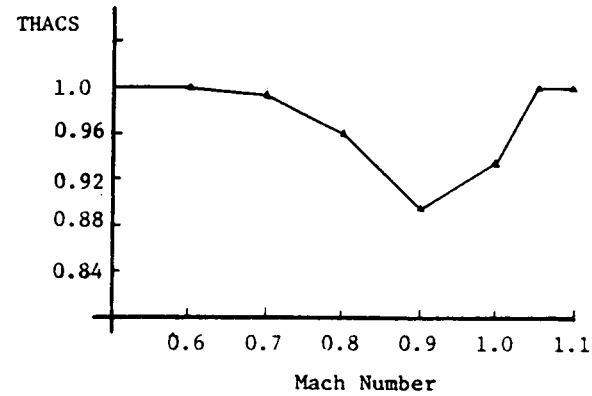
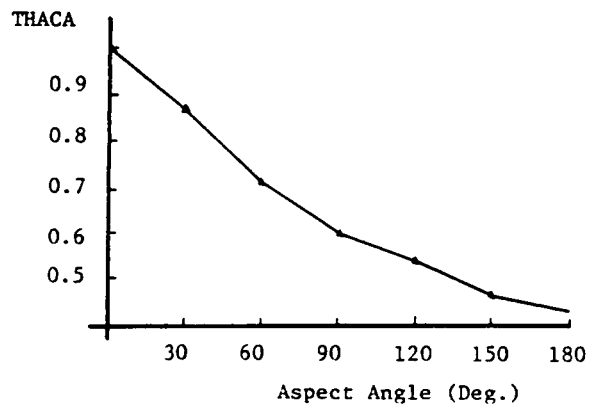


Figure I.3 Typical Simulation Commanded Load Factor Histories.





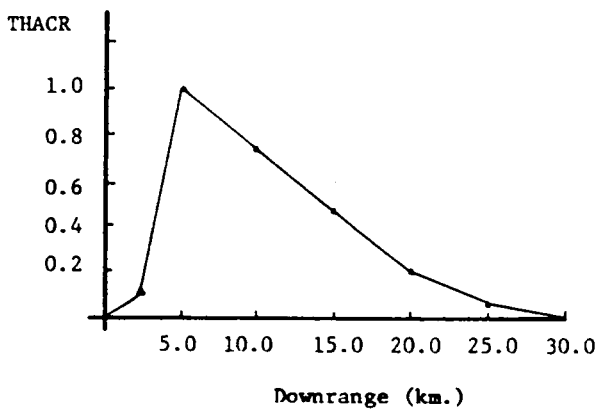


Figure I.4 Approximated Trends of Multipliers Affecting THAC.

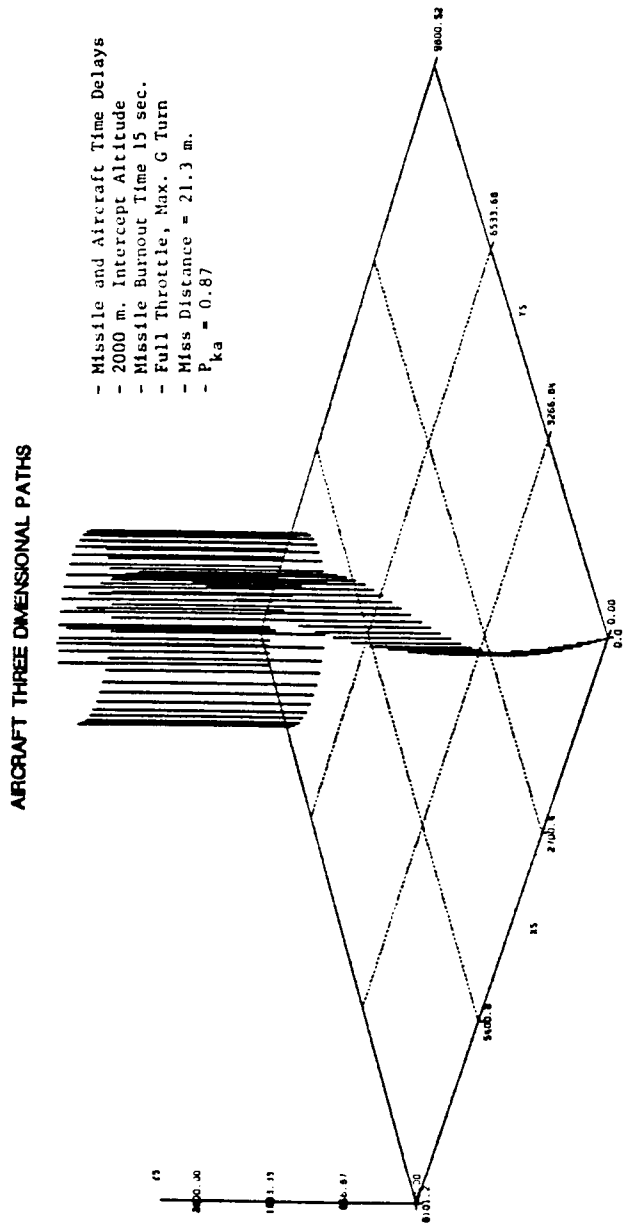


Figure I.5 Typical Three-dimensional Missile Intercept.

Appendix J. MISSILE Model Code

```
C$JOB
C
C     ------------------------------------------------------------
C       PROGRAM : MISSILE
C
C       USE     : ESTIMATES MISSILE PARAMETERS FOR A TYPICAL
C                 INTERCEPT
C
C       LANGUAGE : WATFOR 77
C
C     ------------------------------------------------------------
C
C             DEFINITION OF VARIABLES USED IN THE PROGRAM
C
C     ------------------------------------------------------------
      INTEGER I, J, M, N, KOUNT
      REAL MASS, R, RX, RY, RZ, MMASS, RD
      REAL XS, YS, ALTS, VS, ACCA, ACCM, ACCT, ZM
      REAL XM, YM, ALTM, VM, ATETA, ASAI
      REAL TA, TM, DRAGA, DRAGM, ACLOS, MILOS
      REAL THRUST, SAI, HEAD, DRAG, NE
      REAL TIME, ITIME, FTIME, DT, NPSTP, DTPRT
      REAL AR, EFF, S, ALPO, CLALP, CL, B
      REAL ALP, CDI, CD, CDO, K1, K2
      REAL MACHA, DELTAA, SIGMAA, THETAA, QA
      REAL MACHM, DELTAM, SIGMAM, THETAM, QM
      REAL POA, TOA, RHOA, GAMMAA, G, PI
      REAL POM, TOM, RHOM, GAMMAM
      REAL CDOM(11),  MACHD(11), CDOB, CLALPT(11)
      REAL NCREW, NSTRUC, NAMAX, CLNAX, CLMAX, NFA C
      REAL SAIRUS, SAICO, CLUS, NCOM, NUS, TELOS
      REAL SAIM, SAIMS, STAA, TBURN, STMSA, STMTE, STVDA
      REAL SAIM1, TEM1, SAMCO, TEMCO, TETAM, SAIMD
      REAL RKEEP(2), RXDOT, RYDOR, RZDOT, SGXDOT, SGYDOT, SGZDOT, SGDOT
      REAL RDOT, SGTDOT, SGSDOT, TEMCOD, SAMCOD, TEMQUE(5), SAMQUE(5)
      REAL RPKT(8), PKT(8), PKA, SAICOD, SAIQUE(5)
C     ------------------------------------------------------------
C                 INITIALIZATION OF VARIABLES
C     ------------------------------------------------------------
C     1.1.0 INITIALIZE INTEGER SUBSCRIPTS USED IN THE CODE
C
C
      DATA G, PI/ 9.81, 3.14159/
C
C       G     - GRAVITY FORCE (M/SEC-SEC.)
C       GAMMA  - RATIO OF SPECIFIC HEATS (DIM.)
C
C         INITIALIZE POSITIONS OF AIRCRAFT AT TIME=0
C
C       XS  - DOWNRANGE FROM ORIGIN (METERS)
C       YS  - LATERAL DOWNRANGE FROM ORIGIN (METERS)
C       ALTS - SURFACE ATTACK ALTITUDE (METERS)
C
      DATA XS, YS, ALTS, VS/ 10600., 10600.0, 2000., 300./
      DATA SAI, MASS/3.92, 21000./
```

```
C
C              AIRCRAFT AERODYNAMIC CHARACTERISTICS
C
C      S     - AIRCRAFT WING AREA (SQ. METERS)
C      AR    - WING ASPECT RATIO (DIM.)
C      EFF   - AIRCRAFT WING EFFICIENCY FACTOR (OSWALD'S NUMBER)
C      ALPO  - ZERO LIFT ANGLE OF ATTACK (RADIANS)
C      CDOM  - TABLE OF CDO VALUES VS. MACH NUMBER FOR ITH AIRCRAFT
C      MACHD - MACH NUMBERS USED WITH TABLE FOR CDO VALUES
C      ASCDO - CDO INCREMENT PER WEAPON
C      ECMCDO - CDO INCREMENT PER WEAPON
C
      DATA S, AR, EFF, ALPO/ 40.0, 3.5, 0.8, 0.015/
      DATA NCREW, NSTRUC, CLMAX/ 7.0, 7.0, 1.1/
      DATA (CDOM(J),J=1,11)/5*.011,.020,.024,.023,3*.022/
      DATA (MACHD(J),J=1,11)/0.0,.2,.4,.6,.8,1.,1.2,1.4,1.6,1.8,2./
      DATA (CLALPT(J),J=1,11)/4*4.0,2*3.5,4.8,3.7,2*3.1,2.4/
      DATA (RKEEP(I),I=1,2)/0.0,0.0/
C
        DATA THRUST, NE/150000., 2./
C
C                  MISSILE PARAMETERS
C
C      XM   - DOWNRANGE FROM ORIGIN (METERS)
C      YM   - LATERAL DOWNRANGE FROM ORIGIN (METERS)
C      ZM   - MISSILE ALTITUDE
C
      DATA XM, YM, ZM, VM/ 0., 0., 0.0, 100.0/
      DATA KOUNT/ 0/
      DATA MMASS/800.0/
      DATA TM,FFLOWM,TBURN,ACCM,ACCT/100000.,10.0,5.,0.0,0.0/
      DATA (PKT(I),I=1,8)/1.,0.95,0.9,0.82,0.7,0.5,0.25,0.0/
      DATA (RPKT(I),I=1,8)/20.0,30.,45.,65.,95.,120.,150.,200./
C
C
C     ____________________________________________________________
C                      INITIAL VALUES
C     ____________________________________________________________
        CALL ATMOS(VS, ALTS, MACHA, DELTAA, THETAA, SIGMAA, RHOA, TOA,
     +        POA, GAMMAA, QA)
C
       CL = MASS / (S * QA)
C
        RX = AMAX1(XS-XM,-XS+XM)
        RY = AMAX1(YS-YM,-YS+YM)
        RZ = AMAX1(ALTS-ZM,-ALTS-ZM)
        R = SQRT(RX**2+ RY**2 + RZ**2)
C
       TETAM  = ARSIN (RZ/R)
      SAIM   = ATAN (RY/RX)
C
       VSX = VS * COS(SAI)
        VSY = VS * SIN(SAI)
C
        VMX = VM * COS(TETAM)*COS(SAIM)
        VMY = VM * COS(TETAM)*SIN(SAIM)
        VMZ = VM * SIN(TETAM)
C
        DO 300 I=1,5
          TEMQUE(I) = 0.0
          SAMQUE(I) = 0.0
          SAIQUE(I) = 0.0
300     CONTINUE
C     ____________________________________________________________
C                 SIMULATION LOOP (DYNAMIC MODULE)
C     ____________________________________________________________
C
      TIME  = 0.0
      DT    = 0.20
      FTIME = 60.
      ITIME = 0.0
      DTPRT = 3.0
      NPSTP = DTPRT / DT
```

```
      KP    = NPSTP
C
C
C     ____________________________________________________________
C                 ENGAGEMENT GEOMETRY DESCRIPTION
C
C     ____________________________________________________________
5900          RX = AMAX1(XS-XM,-XS+XM)
            RY = AMAX1(YS-YM,-YS+YM)
            RZ = AMAX1(ALTS-ZM,-ALTS-ZM)
            R = SQRT(RX**2+ RY**2 + RZ**2)
C
C           RXDOT = VMX - VSX
C           RYDOT = VMY - VSY
C           RZDOT = VMZ - ALTS
C
C           SGXDOT  = (RY * RZDOT - RZ * RYDOT)/R**2
C           SGYDOT  = (RZ * RXDOT - RX * RZDOT)/R**2
C           SGZDOT  = (RX * RYDOT - RY * RXDOT)/R**2
C           SGDOT   = SQRT( SGXDOT**2 + SGYDOT**2 +SGZDOT**2)
C
C           SGSDOT  = -SIN(SAIM) * SGXDOT + COS(SAIM) * SGYDOT
C           SGTDOT  = SIN(TETAM) * (COS(SAIM) * SGXDOT + SIN(SAIM)*
C     +                SGYDOT) + COS(TETAM) * SGZDOT
C           RDOT    = -1/R *(RX * RXDOT + RY * RYDOT + RX * RXDOT)
C
            IF (YS .GE. YM) THEN
              IF (XS .GE. XM) THEN
                ACLOS = ARSIN (RY/(R+1.0E-6)) + PI
               ELSE
                ACLOS = 2.*PI-ARSIN (RY/(R+1.0E-6))
              ENDIF
             ELSE
              IF (XS .GE. XM) THEN
                ACLOS = PI - ARSIN (RY/(R+1.0E-6))
               ELSE
                ACLOS = ARSIN (RY/(R+1.0E-6))
              ENDIF
            ENDIF
C
      IF (TIME .GE. 3.) THEN
C
      CALL DELAY1 (R, RD, RKEEP, 2, 0., DT)
       IF (RKEEP(1) .GE. RKEEP(2)) THEN
          KOUNT = KOUNT + 1
          IF (KOUNT .EQ. 2) THEN
             WRITE (6,2000) TIME, RKEEP(2)
2000           FORMAT(/5X, 'INTERCEPT TIME = ', F8.4,
     +              5X, 'MISS DIST.=', F14.5//)
             GOTO 1005
          ENDIF
        ENDIF
      ENDIF
C
C         SAIA  - AIRCRAFT HEADING (RADIANS)
C         ATN   - AIRCRAFT TARGET ASPECT ANGLE (RAD.)
C
C
            IF (XS .GE. XM) THEN
              IF (-PI .GE. SAI-ACLOS) THEN
                 ATN = 2.*PI + SAI - ACLOS
              ELSE
                 ATN = SAI - ACLOS
              ENDIF
            ELSE
              IF (PI .GE. SAI-ACLOS) THEN
                 ATN = SAI - ACLOS
              ELSE
                 ATN = SAI - ACLOS - 2.* PI
              ENDIF
            ENDIF
C
            IF (ATN . GT . 0.0) THEN
```

```
            STVDA  = ACLOS + PI/2.
          ELSE
            STVDA  = ACLOS - PI/2.
          ENDIF
C
C
C     ------------------------------------------------------------
C          COMPUTATION OF THE LINE-OF-SIGHT TARGET ASPECT ANGLE
C     ------------------------------------------------------------
C
          IF (ACLOS .GE. PI) THEN
             MILOS = ACLOS - PI
          ELSE
             MILOS = PI + ACLOS
          ENDIF
C
C
          IF (XM .GE. XS) THEN
            IF (-PI .GE. SAIM-MILOS) THEN
               STAA = 2.*PI + SAIM - MILOS
            ELSE
               STAA = SAIM - MILOS
            ENDIF
          ELSE
            IF (PI .GE. SAIM-MILOS) THEN
               STAA = SAIM - MILOS
            ELSE
               STAA = SAIM - MILOS - 2.* PI
            ENDIF
          ENDIF
C
          IF (ZM .LE. ALTS) THEN
             TELOS = ARSIN (RZ/(R + 1.0E-6))
          ELSE
             TELOS = - ARSIN (RZ/(R + 1.0E-6))
          ENDIF
C
          TTAA   = TETAM - TELOS
          STMSA  = STAA
          STMTE  = TTAA
C
C     ------------------------------------------------------------
C          COMPUTATION OF ATMOSPHERIC CHARACTERISTICS
C     ------------------------------------------------------------
C          VS    - AIRCRAFT VELOCITY (MAGNITUDE) IN M/SEC.
C          ALTS  - AIRCRAFT ALTITUDE (METERS ABOVE MSL)
C          MACH  - AIRCRAFT MACH NUMBER (DIM)
C          DELTA - ATMOSPHERIC PRESSURE RATIO (DIM)
C          THETA - ATMOSPHERIC TEMPERATURE RATIO (DIM)
C          SIGMA - ATMOSPHERIC DENSITY RATIO (DIM)
C
       CALL ATMOS(VS, ALTS, MACHA, DELTAA, THETAA, SIGMAA, RHOA, TOA,
     +       POA, GAMMAA, QA)
C
C
C     ------------------------------------------------------------
C                    AIRCRAFT PERFORMANCE
C     ------------------------------------------------------------
C
       CALL INTER(MACHD, CLALPT, MACHA, 11, CLALP)
       CALL INTER(MACHD, CDOM, MACHA, 11, CDOB)
C
          WK  = 1/(AR*EFF*PI)
          ALP = CL / CLALP + ALPO
          CDO = CDOB
          CDI = CL**2/(PI * AR* EFF)
          CD  = CDO + CDI
          DRAGA = S*QA*CD
          TA = THRUST
C
C         DRAGA  - TOTAL AIRCRAFT DRAGA (NEWTONS)
C         Q      - RYNAMIC PRESSURE (PASCALS)
C         S      - AIRCRAFT WING AREA (SQUARE METERS)
C         TA     - AIRCRAFT THRUST (NEWTONS)
C
```

```
C
      IF (TA/(QA*S) .GT. CDO) THEN
        NFAC = QA * S /( MASS * G) * SQRT (1/WK *
     +           (TA/(QA*S) - CDO))
      ELSE
        NFAC = 1.01
      ENDIF
C
      APS = (TA - DRAGA) * VS / (MASS * G)
C
      VSX = VS * COS(SAI)
      VSY = VS * SIN(SAI)
C
C
C
C     ------------------------------------------------------------
C           AIRCRAFT MAXIMUM SUSTAINED PERFORMANCE
C     ------------------------------------------------------------
      NAMAX = AMIN1(NFAC, AMIN1(NCREW, NSTRUC))
      CLNAX = NAMAX*MASS*G / (QA*S)
      CLUS  = AMIN1(CLNAX, CLMAX)
      NUS   = AMAX1(QA*S*CLUS/(MASS*G), 1.0001)
      SAIRUS= G * SQRT(NUS** 2 - 1)/ VS
        IF (ABS(STVDA). LE. SAIRUS*DT) THEN
            SAICO = - STVDA / DT
        ELSE
            IF (STVDA. GE. 0) THEN
                SAICO = - SAIRUS
            ELSE
                SAICO = SAIRUS
            ENDIF
        ENDIF
C
C
      CALL DELAY1 (SAICO, SAICOD, SAIQUE, 5, 1.0, DT)
      NCOM  = SQRT(1 + (ABS(SAICOD) * VS / G)**2)
      CL    = NCOM*MASS*G / (QA*S)
C
C
C     ------------------------------------------------------------
C                  MISSILE  PERFORMANCE
C
C     ------------------------------------------------------------
C
      CALL ATMOS(VM, ZM, MACHM, DELTAM, THETAM, SIGMAM, RHOM, TOM,
     +       POM, GAMMAM, QM)
C
        NMAXTE = 25.
        NMAXSA = 40.
C
        K1   = 0.015
        K2   = 105000.
        DM   = K1 * VM**2 + K2 * (ACCT / VM) ** 2
        IF (TIME .LE. TBURN) THEN
          TM = TM
        ELSE
          TM = 0.0
        ENDIF
C
      VMX = VM * COS(TETAM)*COS(SAIM)
      VMY = VM * COS(TETAM)*SIN(SAIM)
      VMZ = VM * SIN(TETAM)
C
C      DM    - TOTAL MISSILE DRAGA (NEWTONS)
C      QM    - MISSILE RYNAMIC PRESSURE (PASCALS)
C      TM    - MISSILE THRUST (NEWTONS)
C
C
      SAIM1 = G * SQRT(NMAXSA** 2. - 1.)/ VM
      TEM1  = G * SQRT(NMAXTE** 2. - 1.)/ VM
C
C
C
C     ------------------------------------------------------------
C           MISSILE NAVIGATION (PURE PURSUIT)
C     ------------------------------------------------------------
```

```
C
      IF (ABS(STMSA). LE. SAIM1*DT) THEN
         SAMCO = - STMSA / DT
      ELSE
         IF (STMSA. GE. 0) THEN
            SAMCO = - SAIM1
         ELSE
            SAMCO = SAIM1
         ENDIF
      ENDIF
C
      IF (ABS(STMTE). LE. TEM1*DT) THEN
         TEMCO = - STMTE / DT
      ELSE
         IF (STMTE. GE. 0) THEN
            TEMCO = - TEM1
         ELSE
            TEMCO = TEM1
         ENDIF
      ENDIF
C
    CALL DELAY1 (TEMCO, TEMCOD, TEMQUE, 5, 0.3, DT)
    CALL DELAY1 (SAMCO, SAMCOD, SAMQUE, 5, 0.3, DT)
C
    ATETA  = SQRT(1 + (ABS(TEMCO) * VM / G)**2)
     ASAI  = SQRT(1 + (ABS(SAMCO) * VM / G)**2)
C
C
C   ____________________________________________________________
C                  RATE VARIABLES
C
C   ____________________________________________________________
C
        ACCA  =  (TA*COS(ALP)-DRAGA)/MASS
C
        ACCM  = (TM - DM)/MMASS - G* SIN(TETAM)
        ACCT  = SQRT (ATETA**2 + ASAI**2)
C
C   ____________________________________________________________
C                aircraft STATE VARIABLES
C
C   ____________________________________________________________
C
        TIME    =  TIME    +  DT
C
        SAI     =  SAI     +  DT * SAICOD
        VS      =  VS      +  DT * ACCA
        XS      =  XS      +  DT * VS *COS(SAI)
        YS      =  YS      +  DT * VS   *SIN(SAI)
C
     IF (SAI  .GE. 0) THEN
       IF (SAI  .GE. 2.*PI) THEN
         SAI = SAI  - 2.*PI
       ELSE
         SAI  = SAI
       ENDIF
     ELSE
       SAI = 2.*PI + SAI
     ENDIF
C
C       XS    - AIRCRAFT DOWNRANGE POSITION (METERS)
C       YS    - AIRCRAFT LATERAL DOWNRANGE POSITION (METERS)
C       SAIA  - AIRCRAFT SAIING (RADIANS)
C
C   ____________________________________________________________
C              COMPUTATION OF MISSILE STATE VARIABLES
C
C   ____________________________________________________________
C
        SAIM   =  SAIM  +  DT * SAMCOD
        TETAM    = TETAM    +  DT * TEMCOD
        VM      =  VM      +  DT * ACCM
        XM      =  XM      +  DT * VM *COS(SAIM)*COS(TETAM)
        YM      =  YM      +  DT * VM *SIN(SAIM)*COS(TETAM)
        ZM      =  ZM      +  DT * VM * SIN(TETAM)
        MMASS    =  MMASS   +  DT * FFLOWM
C
     IF (SAIM .GE. 0) THEN
```

```
          IF (SAIM .GE. 2.*PI) THEN
            SAIM = SAIM - 2.*PI
          ELSE
            SAIM = SAIM
          ENDIF
        ELSE
          SAIM = 2.*PI + SAIM
        ENDIF
C
        IF (TETAM .GE. 0) THEN
          IF (TETAM .GE. 2.*PI) THEN
            TETAM = TETAM - 2.*PI
          ELSE
            TETAM = TETAM
          ENDIF
        ELSE
          TETAM = 2.*PI + TETAM
        ENDIF
C
C
C     ____________________________________________________________
C                    OUTPUT STATEMENTS
C
C     ____________________________________________________________
      KP = KP - 1
      IF ( KP .GT. -1 ) GOTO 001
      KP =NPSTP
C
C       WRITE ( 6, 800) TIME
800     FORMAT (//25X, 'TIME=', F10.1)
C       WRITE ( 6, 600) XS, YS, VS
600     FORMAT (/3X, 'XS= ',F10.3, 3X, 'YS=', F10.4, 3X, 'ALTS', F10.4)
001   IF (TIME .LT. FTIME) THEN
      GOTO 5900
    ENDIF
C
1005    CALL INTER(RPKT, PKT, RKEEP(2), 8, PKA)
      WRITE ( 6, 650) PKA
650    FORMAT (3X, 'AIRCRAFT KILL PROB.= ',F10.5//)
C
1000  STOP
    END
C     ____________________________________________________________
C                    PROGRAM SUBROUTINES
C     ____________________________________________________________
C
C
    SUBROUTINE INTER(X, F, XVAL, N,  FOUT)
    INTEGER N
    REAL FOUT, X(N), F(N), XVAL
C
C    INTERPOLATES LINEARLY BETWEEN A SET OF N VALUES DEFINED AS TABLE
C    FUNCTIONS. THE OUTPUT IS A ONE-DIMENSIONAL ARRAY AS WELL AS THE
C    VALUE TO BE INTERPOLATED. GENERALLY USED FOR AIRCRAFT FUNCTIONS.
C
      IF (XVAL .LE.X(1)) THEN
         FOUT = F(1)
       ELSE
         IF (XVAL .GE. X(N)) THEN
            FOUT = F(N)
          ELSE
            DO 002 J=1,N
              IF (XVAL .GT. X(J)) THEN
                 FOUT = F(J) + (XVAL-X(J))*
     +             (F(J+1)- F(J))/(X(J+1)-X(J))
               ELSE
              ENDIF
002          CONTINUE
         ENDIF
      ENDIF
    RETURN
    END
C
```

```
C
      SUBROUTINE SINGL (X, F, XVAL, NA, NP, FOUT)
      INTEGER I, J, NP, NA, NPP
      REAL FOUT(NA), X(NP), F(NP), XVAL(NA)
C
C     FULL SINGLE ARRAY INTERPOLATION SUBROUTINE. INPUT, OUTPUT, AND
C     AND TABLE FUNCTION ARE ALL ONE-DIMENSIONAL.
C
      DO 001 I=1,NA
        IF (XVAL(I) .LE. X(1)) THEN
          FOUT(I) = F(1)
        ELSE
          IF (XVAL(I) .GE. X(NP)) THEN
            FOUT(I) = F(NP)
          ELSE
            DO 002 J=1,NP
              IF (XVAL(I) .GT. X(J)) THEN
                FOUT(I) = F(I) + (XVAL(I)-X(J))*
     +            (F(J+1)- F(J))/(X(J+1)-X(J))
              ELSE
              ENDIF
002         CONTINUE
          ENDIF
        ENDIF
001   CONTINUE
      RETURN
      END
C
      SUBROUTINE DELAY1 (VARIN, VAROUT, VAR, N, DC, DT)
      INTEGER I, J, K, N
      REAL VARIN, VAROUT, VAR(N), DC, DT
C
C     SUBROUTINE TO INTRODUCE A "FULL" TIME DELAY TO A ONE DIMENSIONAL
C     VARIABLE (VARIN). THE DELAY VARIABLE (MTOF) CAN BE TIME VARIANT
C     AND THE DELAYED HISTORY OF THE VARIABLE IS STORED IN (VAR) WITH
C     N AS THE MAXIMUM NUMBER OF BACKWARD MEMORY SPACES.
C
      NP = N - 1
      DO 004 I=1,NP
        K     = N + 1 - I
        VAR(K) = VAR(K-1)
        VAR(1) = VARIN
        IF ( INT(DC/DT) . LE. 1 ) THEN
          VAROUT = VAR(1)
        ELSE
          IF ( INT(DC/DT) . GE. N ) THEN
            VAROUT = VAR(N)
          ELSE
            IF ( INT(DC/DT) . GE. I ) THEN
              VAROUT = VAR(I) + (INT(DC/DT) - I) *
     +            (VAR(I+1) - VAR(I))
            ENDIF
          ENDIF
        ENDIF
004   CONTINUE
      RETURN
      END
C
      SUBROUTINE ATMOS (SPEED, ALT, MACHN, DEL, THE, SIG, RO,
     +    TZERO, PZERO, GAMA, Q)
C
C       COMPUTES THE CHARACTERISTICS OF THE STANDARD ATMOSPHERE AT
C       ANY ALTITUDE (UP TO 20,000 METERS) AS WELL AS ESTIMATES THE
C       FLIGHT MACH NUMBER OF EACH AIRCRAFT.
C
      INTEGER NA, I, J
      REAL MACHN, ALT, SPEED, DEL, THE, SIG
      REAL RO, PZERO, TZERO, LAM, GAMA, RCON, Q
C
          RO    = 1.225
          TZERO = 288.2
          PZERO = 101300.
```

```
            LAM   = .0065
            GAMA = 1.400
            RCON  = 287.
          IF (ALT .LE. 11000.) THEN
            THE     = 1 - LAM/TZERO * ALT
            DEL     = THE   ** 5.2561
            SIG     = THE   ** 4.2561
          ELSE
            THE     = .75189
            DEL     = .2234 * EXP (-(ALT   -11000.)/ 6340.64)
            SIG     =  DEL   / THE
          ENDIF
            MACHN   = SPEED   / SQRT(GAMA*RCON*THE   *TZERO)
            Q       = 0.5 * PZERO * GAMA * DEL   * MACHN   **2
        RETURN
        END
C
C$ENTRY
```

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