Integrated Modeling of Air Traffic, Aviation Weather, and Communication Systems

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Abstract

Aviation suffers many delays due to the lack of timely air traffic flow management. These delays are also caused by the uncertainty weather information; and the lack of efficient dissemination of weather products to pilots. It is clear that better models are needed to quantify air traffic flow in three flight regions - en-route, in the terminal, and on the ground, to determine aviation weather information requirements at each region, and to quantify their bandwidth requirements. Furthermore, the results from those models can be used to select alternative future aviation communication systems.

In this research, the ‘ITHINK’ and ‘MATLAB’ software packages have been used to develop a lumped Air Traffic Flow Model (ATFM) and an Aviation Weather Information and Bandwidth Requirements Model (AWINBRM). The ATFM model is used to quantify the volume of air traffic in each phase of flight in three flight regions. This model can be used to study navigation, surveillance, and communication requirements. The AWINBRM model is used to study aviation weather information requirements in different flight phases of flight. Existing and potential communication systems used for transmitting aviation weather information are explored in this research. Finally, a usable and practical computer model - Aircraft Impacted and Detour Model (AIDM) around an aviation weather system is developed. This model is used to compare the costs between detoured flights around a weather system and delayed flights at the airports.

The purpose of this research is to study air traffic flow and aviation weather information and bandwidth requirements through modeling. The ultimate goal of the models described here is to serve as a living laboratory where policies can be tried before implementing them into the real system. Moreover, these computer models can evolve dynamically through time allowing decision makers to exercise policies at various points in time to quantify results with ease.

This research would be a first integrated model for combing air traffic flow and aviation weather requirements and determining the quantity of aviation weather information between pilot and ground service centers. This research would be a guideline for aviation industry to build an efficient and timely aviation weather information transmission system with minimum budget. Consequently, this research will reduce aviation delays and improve aviation safety.

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Finally, I would like to dedicate this dissertation to my mother, who passed away during this research, but she is always with me in all the sadness and joy in my life.

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CHAPTER 1 Introduction

1.1 Background

In just 100 years since the Wright brothers' first successful flight, air transportation has grown into a very large industry, essential to modern society. There are fifty thousands commercial flights every day over the U.S. alone. Commercial air transportation is safe and affordable. Aircraft are extremely reliable. The U.S. commercial air transportation operations have steadily increased for decades, a trend which is likely to continue in the forseeable future. Passenger enplanements, for example, have historically grown at about 7% per year **[Air Transport Association (ATA), 1999]** before 2000. In 2000, U.S. airlines enplaned a record 670 million passengers **[ATA, 2000]**. Although the events of September 11, 2001, shocked the U.S. and hurt the air transportation industry when the average seating capacity of the U.S. carriers declined 15 percent. However, due to lower fares and a solid economy recovery, it is reported that airlines in 2004 have flown 685 million passengers. On a typical day in the United States, over 1.8 million people fly safely aboard some 50,000 flights **[Federal Aviation Administration (FAA), 2005]**. The United States maintains an excellent aviation safety record. In economic terms the U.S. civil aviation industry contributes about 6 percent of the annual U.S. gross domestic product, so there are also economic incentives to maintain a safe and healthy civil aviation industry **[FAA,**

2000].

The National Airspace System (NAS) constitutes a network of airspace links/nodes, airports, navigation aids, air traffic control equipment across the United States. The NAS operates non-stop - 24 hours a day, every day of the year - providing safe air transportation for millions of passengers. The NAS includes more than 20,000 airports, 21 air route traffic control centers, over 460 air traffic control towers and 75 flight service stations, and approximately 4,500 air navigation facilities. Over 34,000 pieces of maintainable equipment including radars, communications switches, ground-based navigation aids, computer displays, and radios are used in NAS operations **[NAS 5.0, 2004].**

1.2 Problem Statement

If the claim that “all roads lead to Rome” was the key indicator of that city's economic greatness in ancient times, a modern city's equivalent claim would have to be “all airlines land here.” Just as in the past shipping, railway and then highway systems have played vital roles in determining a city's economic power. Today global air transportation systems play a substantial role in the regional and national economies. Undoubtedly, air transportation is an “engine” of the economy. However, economic growth and record air travel demand during the late 1990s and early in the twenty first century have created problems in the air transportation industry. These include capacity and throughput issues which often lead congestion and delays. The congestion and delays can also increase controller and pilot workloads, threatening aviation safety.

1.2.1 Aviation Problems

1.2.1.1 Aviation System Congestion and Delay

The year 2000 was a memorable one for U.S. air travelers. This superlative, however, was not a positive one. Delays, Cancellations, and Congestion! It seemed as though this spared no airport throughout the nation’s large hub-and-spoke air traffic system. Historically, the FAA has spent billions of dollars modernizing the NAS through the development, acquisition, and implementation of new technologies.

Many of these capabilities entrenched in the FAA programs have made claims that delays will be reduced significantly as air traffic demand grows. However, some recent developments indicate that air transportation delays are increasing at a faster pace than justified by the demand for air transportation service. In 2000, one in every four flights was delayed, canceled or diverted according to FAA statistics. The equivalent of 163 million fliers were delayed according to data compiled by the Transportation Department's inspector general **[http://www.dot.gov, 2001]**. Departure and arrival delays increased 126% between 1997 and 2000 **[http://www.usatoday.com, 2001]**. For travelers, this means a simple trip from A to B now feels more like A to Z. Based on work done by Russ Chew at ATA, if the air traffic control system is not fixed and if the events of September 11, 2001 would not have occurred, ATA estimates that delays would have increase by some 250% by 2005 **[ATA, 2000]**. Although this situation would not occur due to the impact of September 11 terrorist attacks, the flight delays have started to creed up after the spring 2004 as air traffic reaches or exceeds the record levels experienced in the year 2000. Based on current statistical data from the Bureau of Transportation Statistics **[BTS, 2006]** 23 percent of flights were delayed, canceled or diverted in the first five-month in 2006, which is close to the situation in 2000. Before September 11, 2001, air traffic delays were costing airlines and their passengers an estimated $6 billion a year **[http://www.usatoday.com, 2001]**. Today, individual airlines say delay costs are mounting on them.

1.2.1.2 Flight Accidents and Incidents

Congestion and delays can also increase controller and pilot workloads, ultimately affecting aviation safety. The National Transportation Safety Board (NTSB) statistics show that the U.S. airlines' safety record has improved steadily through the years, most notably including the years since deregulation. The commercial aviation major accident rate (as judged by hull losses per million departures) has been nearly constant over the past two decades. Although the rate is very low, increasing traffic over the years has resulted in the absolute number of accidents to increase. The worldwide demand for air travel is expected to increase even further over the coming two decades—doubling by 2025 with the requirement for $1 trillion in new aircraft deliveries **[Boeing, 2001]**. If these predictions materialize the congestion and delays in air transportation system will hit record level. Without an improvement in the accident rate, such a traffic volume would lead to 50 or more major accidents a year—a nearly weekly occurrence (**Figure 1.1**). Given the very visible, damaging, and tragic effects of even a single major accident, this number of accidents would clearly have an unacceptable impact upon the public's confidence in the aviation system and impede the anticipated growth of commercial air-travel.

The safety of the general aviation (GA) system is also critically important. The current GA accident rate is 20 times greater than that of scheduled commercial transport operations. Eighty-five percent of aviation accidents occurring from 1990-1996 involved small GA aircraft. With the GA market also poised to grow significantly in future years, safety considerations must be removed as a barrier if this growth is to be realized.

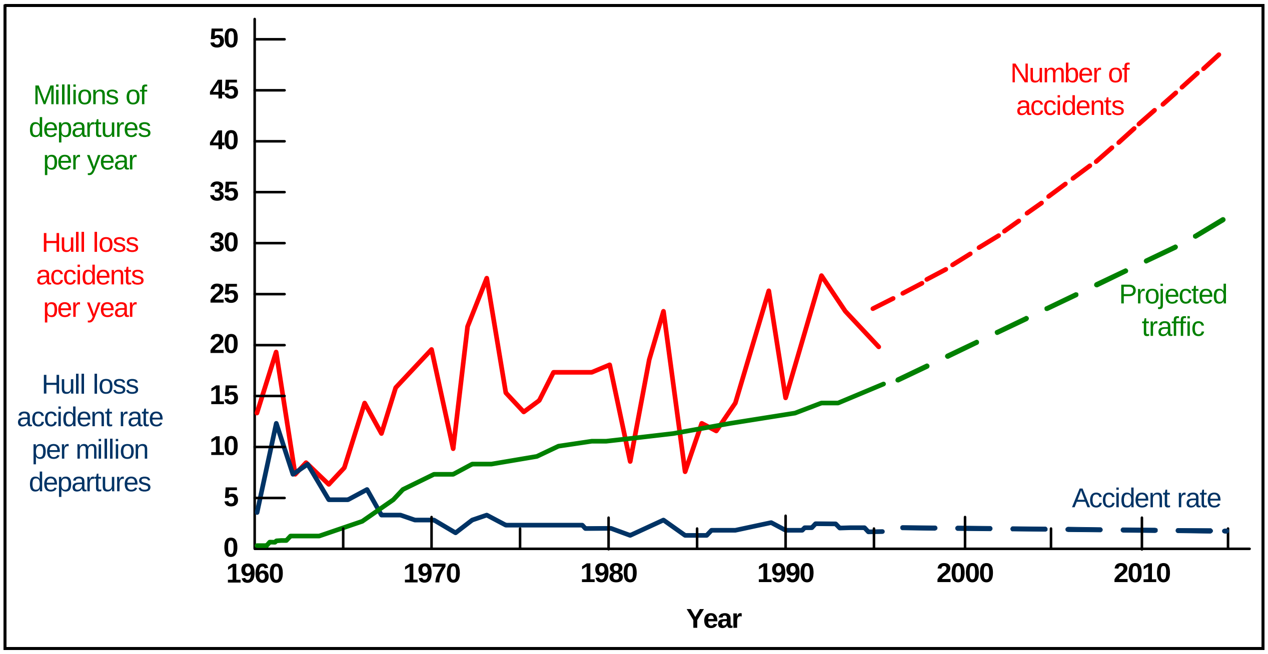


Figure 1.1 Projected Air Traffic Growth and Number of Accidents (Data obtained from the Boeing Company (2000)[128] and the FAA[83]).

1.2.2 Causal Factors

1.2.2.1 Aviation Weather

Aviation safety and efficiency are affected by a number of factors, weather system is one of them. Weather is a major contributor to aviation delays, congestion, accidents, and incidents. In the past five years weather has accounted for 68% of all delays in the NAS and forty percent of the GA accidents are attributed to weather according to statistics compiled and published by the FAA. Atmospheric weather varies in size and in shape from few of square miles to thousands of square miles. The connection between air traffic and weather is that both sometimes occupy the same airspace.

Figure 1.2 indicates the cause of flight delays. Except when the delay is caused by weather, the next largest category of delay is due to traffic volume but it just represents eight percent of the total delays in the system.

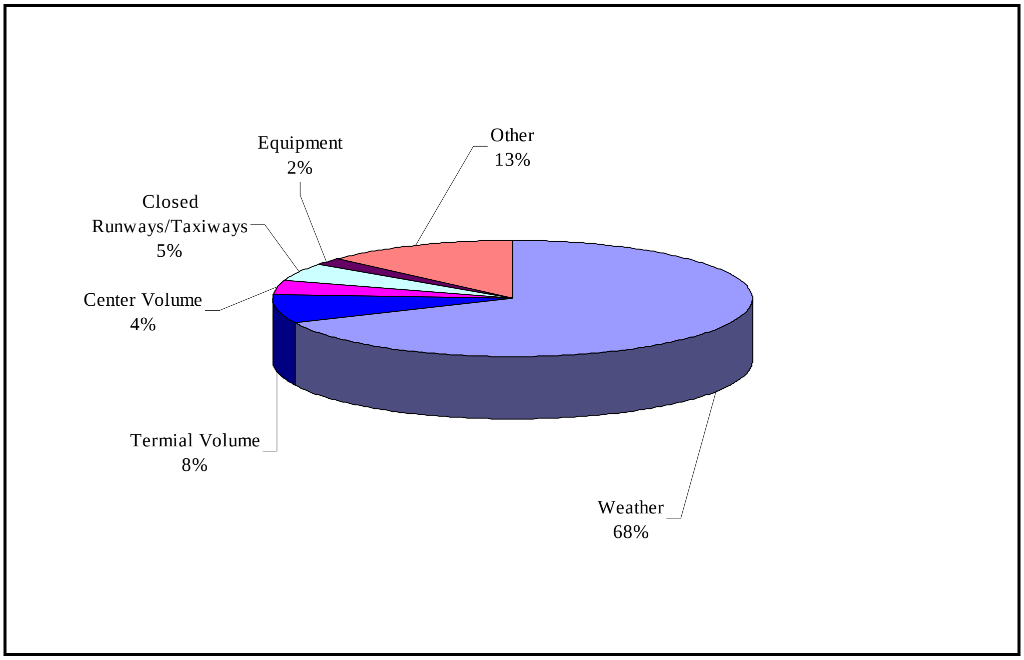


Figure 1.2 Cause of Flight Delay (Data obtained from the FAA[85]).

1.2.2.2 Communication

The capacity of the NAS is a complex combination of the collective capacities of airports, airspace, airlines asset, and air traffic control. It is obvious that such systems will not work in isolation. The communication among pilots, air traffic controllers, and weather providers plays an important role in the operational capabilities of the NAS. Unfortunately, the frequencies used to obtain aviation weather information often become saturated, limiting access to the information at times when it is needed most. Pilots tune radios to receive automated weather services such as Hazardous In-flight Weather Advisory Service (HIWAS) and Automated Terminal Information Service (ATIS) to obtain a broadcast over large areas or specific reporting stations. The information from these aural sources is limited and may be relevant only for a very localized area.

1.3 Research Motivation

In 1997, the United States set a national goal to reduce the fatal accident rate for aviation by 80% within ten years based on the recommendations by the Presidential Commission on Aviation Safety and Security. Achieving this goal would require the combined efforts of government, industry, and academia in the areas of technology research and development, implementation, and operations. To respond to the national goal, the National Aeronautics and Space Administration (NASA) has developed a program that will focus resources on performing research and developing technologies that will enable improvements in many areas of aviation safety. The NASA Aviation Safety Program (AvSP) is organized into six research areas: Aviation System Modeling and Monitoring, System Wide Accident Prevention, Single Aircraft Accident Prevention, Weather Accident Prevention, Accident Mitigation, and Synthetic Vision. Specific project areas include Turbulence Detection and Mitigation, Aviation Weather Information, Weather Information Communications, Propulsion Systems Health Management, Control Upset Management, Human Error Modeling, Maintenance Human Factors, Fire Prevention, and Synthetic Vision Systems for Commercial, Business, and General Aviation aircraft. Research is been performed at all four NASA aeronautics centers and closely coordinated with the FAA and other government agencies, industry, academia, as well as the aviation user community. Many research projects to achieve the program goals are related to weather systems.

Based on the national aviation to improve air traffic management goal and two projects - “Integration of Reusable Launch Vehicle (RLV) into Air Traffic Management” and “Use of Next-generation Satellite Systems for Aeronautical Communications” performed by the National Center of Excellence for Aviation Operation Research (NEXTOR) at Virginia Tech we developed a research topic on an “Integrated of Modeling of Air Traffic, Aviation Weather, and Communication Systems”.

1.4 Objectives

The purpose of this research effort is to study air traffic flow and aviation weather information and bandwidth requirements through modeling and simulation. The ultimate goal of the models described here is to serve as a living laboratory where policies can be tried before implementing them into the real system. Moreover, these computer models can evolve dynamically through time allowing decision makers to exercise policies at various points in time to quantify results with ease.

Three areas of research have been analyzed in this project: 1) Air Traffic Flow Analysis, 2) Aviation Weather Information, Products, and Requirements Analysis, and 3) Aviation Weather Communication Systems Analysis. Three computer models have been developed to study these areas of research using MATLAB 6.1, a general engineering software package developed by the Mathworks **[Mathworks, 1997]** and ITHINK 7.0, a Systems Dynamics software package used to develop conceptual frameworks for underlying construction and subsequent simulation of mental models **[High Performance, 2001]**. These models are: 1) the Air Traffic Flow Model (ATFM), 2) the Aviation Weather Information and Bandwidth Requirement Model (AWINBRM) and 3) the Aircraft Impacted and Detour Model (AIDM). All models can be executed on any Windows 98/2000/XP/NT compatible PC. Macintosh, or Lunix Workstation without modifications.

The ATFM model is used for quantifying the volume of air traffic at each phase of flight including en-route, terminal, and on the ground traffic regions. The results of the ATFM model are used as inputs for the AWINBRM model. The AWINBRM model is an aviation weather information and bandwidth requirement model. This model is used to define required aviation weather information and their sizes at each phase of flight in three flight regions. This provides detailed information for planning aviation weather communication systems in the future. For example, if weather in the cockpit requirements are conceptualized, AWINBRM could determine the bandwidth necessary to satisfy. The AIDM model is used to detect the impacted flights by an aviation weather system and to generate detoured flight paths around the aviation weather system in a case study. The aviation weather communication system analysis is focus on the examination of aviation weather information communication requirement, current and planned aviation weather communication systems, and potential solutions from non-aviation communication systems.

1.5 Organization of the Dissertation

This dissertation is composed of eight chapters organized according to the following sequence:

Chapter 1 presents an introduction to the problem and a brief description of the air transportation system. This chapter also presents the motivation, objectives, and scope of this research.

Chapter 2 reviews pertinent literature about the air transportation industry, the National Airsapce System, air traffic management, aviation weather information and products, aviation weather communication system, and aviation weather economic impacts. Several air traffic flow models and weather models are reviewed in this chapter.

Chapter 3 outlines the research requirements and the corresponding methodology adopted in this research. A review of the Systems Approach and Systems Dynamics is presented.

Chapter 4 examines the current state of the National Airspace System and the features of each phase of flight pertinent to this research. Phases of flight examined are: at the airport, in the terminal, and en-route airspace. In order to quantify the air traffic flows in one Air Route Traffic Control Center (ARTCC), the Air Traffic Flow Model (ATFM) is developed.

Chapter 5 describes Aviation Weather Information, Products, Requirements Analysis. In this chapter, the fundamentals of weather phenomena and aviation weather systems are discussed. Based on airborne weather-related decision-making activities, two aviation weather domains - tactical and strategic are defined. Aviation weather information requirements at each phase of flight are also defined. In this analysis, the aircraft is considered both a source and a user of aviation weather information, aircraft as aviation weather sensor is analyzed. Finally, the Aviation Weather Information and Bandwidth Requirements Model (AWINBRM) is developed to quantify aviation weather information at each phase of flight.

Chapter 6 describes communication systems. This chapter focuses on the exploration of current and planned aviation weather communication systems and potential communication solutions from non-aviation communication systems.

Chapter 7 conducts model applications and economic impact analysis of aviation weather. Atlanta air route traffic control center is used to run the ATFM and AWINBRM models. The analyses of the models' results are provided in this chapter. For the further research - a cost effectiveness analysis for the flights impacted by weather system is conducted. The Modified Airspace Occupancy Model (MAOM) and Aircraft Impacted and Detour Model (AIDM) are explained and developed in this chapter.

In Chapter 8, the conclusions and recommendations for this research are discussed.

CHAPTER 2

Literature Review

2.1 Air Transportation Industry

Air transportation industry has three major components which are: 1) airlines, 2) airports, and 3) airspace and air traffic control systems. The U.S. scheduled airlines, as air transportation operators, are classified by the government on the basis of the amount of revenue generated from operations. These classifications are air carrier, air taxi/commuter, general aviation, cargo carrier, and military. **Air carriers** generally provide nationwide, and in some cases, worldwide service and operate mostly medium- and large-sized jets. As their name implies, **air taxi/commuter carriers** are airlines whose service, for the most part, is limited to a single region of the country, transporting travelers between the major cities of their region and smaller, surrounding communities. They usually use regional jets and small size turboprops. This has been one of the fastest growing and most profitable segments of the industry since deregulation, especially after September 11. **General aviation** (GA) encompasses all aviation other than scheduled airline flights and military flights. It includes everything from privately-owned light single-engine aircraft to business jets, news gathering, police, pipeline patrol, emergency medical flights, crop-dusting, rotorcraft, gliding, sport ballooning and many other aerial activities. Aircraft in use by principally all **cargo carriers**, called freighters, carry nothing but freight. Military is special category which is operated by military including air force, national guard etc. Military flight are controlled by military controllers but they require coordination with the FAA's air traffic control center.

As discussed above, aircraft is a major asset in various airlines categories. Similar to airlines classifications, aircraft are also divided into four categories in this research: 1) air carrier aircraft, 2) air taxi/ commuter aircraft, 3) GA aircraft, and 4) military aircraft. Large cargo aircraft are considered in the air carrier aircraft category and small cargo aircraft such as turboprop engine aircraft belong to GA category. Since Orville and Wilbur Wright made the first powered flight in a heavier-than-air machine on December 17, 1903; aircraft have developed rapidly in its size and speed. In the early year of air transportation most airplanes were relatively small with single or twin piston or turboprop engines and flew at low speeds. In 1952, a 36-seat British-made jet, the Comet I, flew from London to Johannesburg, South Africa, at speeds of up to 500 miles per hour. In 1958, the first U.S. passenger jet, the Boeing 707 could carry up to 181 passengers and travel at speeds of 550 miles per hour. The year 1969 marked the debut of another revolutionary aircraft, the Boeing 747. It was the first widebody jet, with two aisles, a distinctive upper deck over the front section of the fuselage, and four large engines. With seating for as many as 450 passengers, it was twice as big as any other Boeing jet of the time.

During the same period, efforts were underway in both the United States and Europe to build a supersonic commercial aircraft. The former Soviet Union was the first to succeed, testing the Tupolev 144 in December of 1968. A consortium of West European aircraft manufacturers first flew the Concorde two months later and eventually produced fourteen fast, but small, jets for commercial service. Recently, aviation industry is moving forward a new generation aircraft, such as, Airbus's A380 and the Boeing 787 Dreamliner. In 2007, air travelers will step onto a double-deck jetliner A380 capable of carrying up to 650 passengers over 7000 miles at a cruise speed of 560 MPH. The Boeing 787 Dreamliner would fly 300 passengers at 550 MPH with 15 percent in saving per seat-mile compared to existing twin engine aircraft today.

The United States has the largest, most extensive aviation system in the world with more than 20,000 airports **[NAS 5.0, 2004]**, ranging from large commercial transportation centers enplaning more than 40 million passengers annually, to small grass strips serving only a few aircraft each year. Of these, 3,304 are designated as part of the national plan for an integrated airport system (NPIAS). The airspace and air traffic control systems will described in the following paragraphs.

2.2 National Airspace System

2.2.1 Overall National Airspace System

The national airspace system (NAS) spans all U.S. territories and extends beyond the continental shelf. The NAS includes all air traffic control (ATC) and air traffic management facilities and personnel as well as equipment used for communication, navigation, and surveillance such as VHF/UHF voice transmitters and receivers, navigation beacons, weather and wind-shear radars, and instrument landing equipment. The FAA procures, operates, and maintains this equipment.

The overall airspace above the continental United States is divided into 20 areas which are shown in **Figure 2.1**, with the control of each area assigned to a facility known as an air route traffic control center (ARTCC). The airspace of each center is further divided into numerous sectors which are generally small enough to be managed by one, two or three controllers. Most large airports have an air traffic control tower (ATCT) and/or a terminal radar approach control (TRACON), which may assume responsibility for the separation of aircraft in the vicinity of the airport.

2.2.2 Airspace Classification

To organize air traffic and facilitate Air Traffic Control (ATC), the U.S. airspace is divided into six classes: A, B, C, D, E, and G. In addition to these classes of normal airspace, there are also several types of Special Use Airspace. Since September 16, 1993, airspace classifications have been divided as follows **[Aviation Communication, 1997]**:

- *Class A Airspace* is the region from 18,000 to 60,000 feet above mean sea level (MSL).
- *Class B Airspace* is often specified around the busiest airports, generally from 0 to about 10,000 feet, and may consist of layers stacked like an inverted wedding cake.

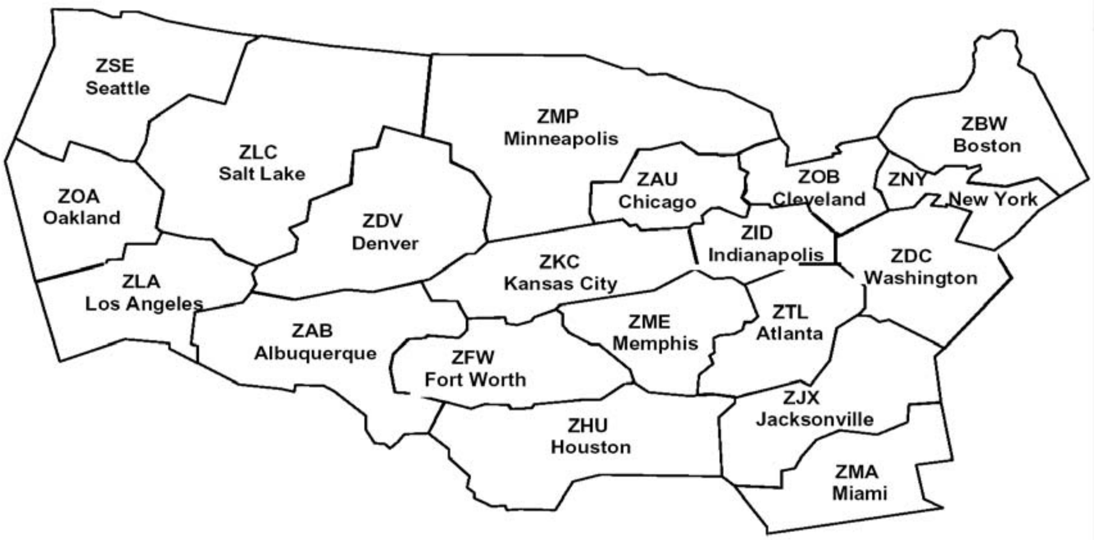


Figure 2.1 Air Route Traffic Control Centers (Modified from the FAA[98])

- *Class C Airspace* may be specified around an airport that is serviced by a control tower and radar approach control, and has a certain amount of IFR traffic. Class C airspace usually consists of a circular region of radius 5 nm from 0 to 1,200 feet, beneath a larger region of radius 10 nm, from 1,200 to 4,000 feet.
- *Class D Airspace* surrounds all airports that have control towers but are not associated with Class B or C airspace. Class D airspace surrounds the airport area from 0 to 2,500 feet (lateral dimensions vary).
- *Class E Airspace* - also called Controlled Airspace - applies, in short, to all controlled airspace not designated as Class A - D.
- *Class G Airspace* - also called Uncontrolled Airspace - applies to all uncontrolled airspace.
- *Special Use Airspace* is designed to restrict aircraft operations, or in some cases to prohibit flights entirely, within certain areas. Among the categories of SUA are prohibited areas,

restricted areas, military operations areas, alert areas, warning areas, controlled firing zones, and areas under temporary flight restrictions. SUA areas can also be used to establish a safety buffer around all space operations, such as Space Shuttle launches and landings, to keep air traffic that is not involved in the operation at a safe distance.

2.3 Air Traffic Management

2.3.1 Air Traffic

There are up to 5,500 aircraft operating in the NAS during peak periods today. This equates to approximately 50,000 aircraft operations per day **[FAA, 2005]**. **Figure 2.2** shows over 5,000 aircraft operating in the system at one time.

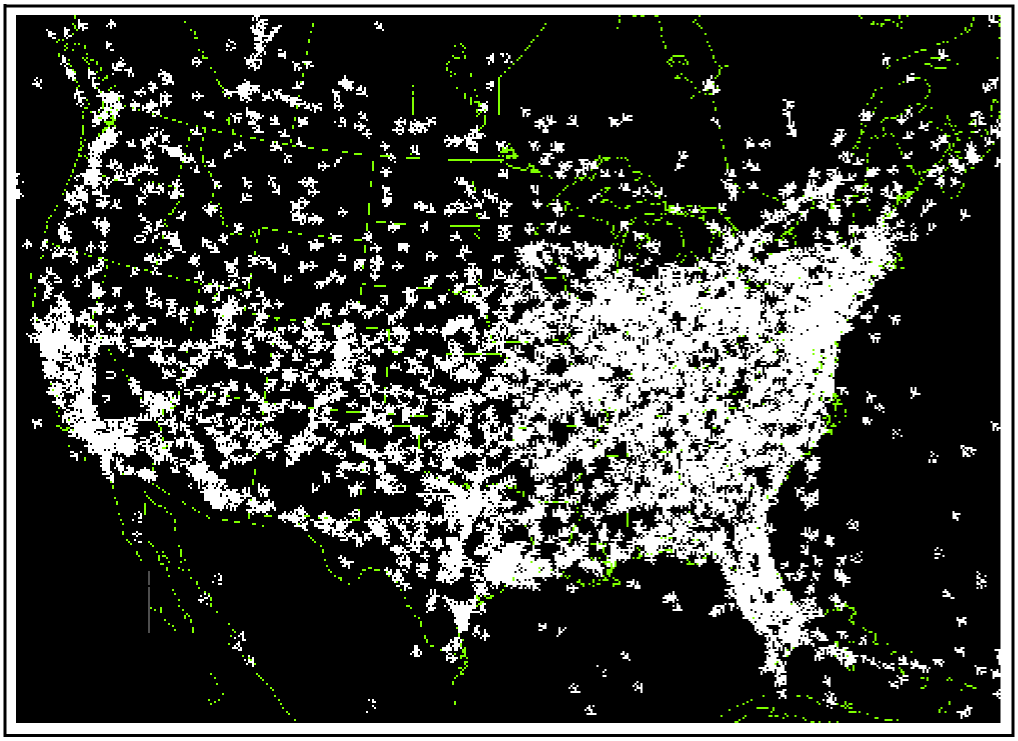


Figure 2.2 Over 5,000 Aircraft Operating in the NAS (Photo obtained from the FAA[102])

There are many varieties of air traffic in the NAS. One way to categorize traffic is by aircraft type. For example, the basic types of air vehicles are helicopters, piston engine aircraft, turboprops, tiltrotors, subsonic jets, and supersonic jets. The types of aircraft are important in Air Traffic Management (ATM), because different types of aircraft can have a wide range of operating performance characteristics. These include: climb, descent rate, cruise speed and altitude. Some of these vehicles operate in specific areas, for example, helicopters operate from small confined metropolitan areas (called heliports), others fly in overlapping regimes.

Air traffic can also be grouped by purpose or affiliation. The FAA is responsible for all commercial, military, and general aviation in the NAS. Commercial aviation includes all air carriers providing scheduled, public air transportation. Military aviation describes the peacetime activities of military aircraft, such as training. GA refers to all other U.S. civil aviation activities, including training, recreational flight, business travel by private aircraft, agricultural crop dusting, etc. These categories of aviation represent a range of activities, involving different types of aircraft and placing various loads on the ATM system.

Not only are there at least six types of vehicles and three categories of aviation, there are also two different systems under which pilots can operate: Visual Flight Rules (VFR) and Instrument Flight Rules (IFR). VFR is a mode in which aircraft are responsible for self-separation (“see-and-avoid”) from other aircraft. As long as they remain clear of clouds by at least 1000 feet and maintain horizontal visibility of at least 3 nautical miles (NM), they are free to fly anywhere in the airspace. VFR aircraft do not receive separation services from controllers, and VFR is only an option in clear weather. Most general aviation (GA) traffic operate under VFR. IFR aircraft, on the other hand, actively participate in the ATC system. IFR traffic is continuously monitored by radar, and IFR pilots must maintain radio contact with controllers, whose clearance must be obtained before changing course or altitude. IFR aircraft may fly under adverse weather conditions. large and high-performance aircraft always operate under IFR, as do nearly all commercial aircraft. In general, the VFR system operates in the lower airspace below 18,000 feet, while the IFR system operates in the upper airspace and around airport.

2.3.2 Existing Air Traffic Flow Models

In air traffic flow management field, a considerable number of models have been developed over the years to study traffic flow phenomena. Indeed, this is the oldest area of model development, with the first significant models dating back to the late 1950s. It is also the area where the most advanced modeling capabilities currently exist. There well-known air traffic flow models are reviewed in the following section.

2.3.2.1 SIMMOD

SIMMOD, the FAA's current airport and airspace simulation model, depicts the dynamic interaction of aircraft movements. This model programmed in the language SIMSCRIPT II.5, simultaneously studies and evaluates en-route traffic, terminal area traffic, and ground operations at one or more airports. SIMMOD produces measures of airport capacity, aircraft travel time, aircraft delay, and aircraft fuel consumption. After a standard scenario has been established with data from existing or proposed operations, the input data may be changed to develop and evaluate different scenarios. This allows the "what-if" questions to be analyzed. The model may be implemented for projects as large as a major route network and as limited as individual terminal gate operations.

SIMMOD provides highly detailed statistics on each aircraft simulated. Outputs can be obtained on: aircraft travel times; traffic flows past specified points; throughput capacity per unit of time; delays by time of day and location on the airfield or in airspace, along with the immediate reason for each delay; and fuel consumption.

One of the main drawbacks of the model is that traffic must move on a pre-specified network of nodes and links according to pre-specified operating strategies or "rules of the road". In terms of conflicts between aircraft paths, SIMMOD is essentially a one-dimensional model, checking for conflicts along the aircraft's longitudinal path only, with no possibility to check for lateral or vertical separation violations.

In the hands of a skilled user, SIMMOD is possibly the most powerful existing tool for "fine granularity" simulation of airport surface operations, allowing for arbitrarily high levels of detail (e.g., simulation of push-back operations, gate occupancies, de-icing procedures, etc.). Several airport studies conducted with SIMMOD to date illustrate this point.

The principal perceived weakness of SIMMOD is that it is a “labor intensive” model whose users must undergo a significant amount of training. Moreover, to avoid several potential pitfalls, SIMMOD users must have a very good understanding of ATM and airport operations. For example, because SIMMOD is essentially a one-dimensional model (i.e., it can check for conflicts between aircraft only along the paths traced by the elements of a network) care must be taken so that the network structure on which the traffic moves is based on sets of nodes and links with sufficient lateral and vertical separations to avoid the presence of undetected conflicts during the simulation. Another difficulty in SIMMOD is the modeling of dynamic rerouting of aircraft to simulate the ATM system's responses to local or regional congestion problems **[SIMMOD User Manual, ATAC, 2000]**.

2.3.2.2 TAAM

The Total Airspace & Airport Modeller (TAAM) developed by Preston Group is an application for the simulation of airspace and airport operations like SIMMOD. TAAM model is a gate-to-gate system that models the entire airside and airspace environment in detail, including pushback, runways, terminals, en-route and oceanic airspace. TAAM can be used as a planning tool or to conduct analysis and feasibility studies of ATM concepts. TAAM can simulate most ATM functions in detail and can provide scenario generation for real-time ATC simulators. The simulations cover the entire gate to gate ATM process, generally in more detail than competing models.

These are in general aggregated metrics and can be reported on system or sector wide basis.

- System delays
- Conflicts: counts by degree of severity, whether successfully resolved or not
- Airport movements, delays, operations on taxiways and runways, runway occupancy
- Airspace operation metrics such as usage of routes, sectors, fixes and coordination
- Noise contours
- Total fuel burnt

- Costs: aggregate, fuel, non-fuel
- Controller workloads
- Individual Aircraft flight profiles
- Scenario generation e.g. for real-time ATC simulators or other playback
- “Show Logic” diagnostics which gives the operator an insight into TAAM's decision making process
- Text messages (extent and content user selectable) which contain further details of TAAM events
- Errors

A 2D or 3D graphical visualization of the simulation can also be generated. The graphical output can be viewed in several windows simultaneously, each window having an independent 2D or 3D view with the scale ranging from 30 m to 40,000 km. Hazardous weather, or special use airspace cannot yet be modeled dynamically. Weather modeling was limited to winds aloft in sectors. Also TAAM is a more expensive software package **[TAAM User Manual, Preston, 1998]**.

2.3.2.3 RAMS

The Reorganized ATC Mathematical Simulator (RAMS) is a fast-time simulation tool developed by the Eurocontrol Experimental Center (EEC) at Bretigny (France). RAMS is a major upgrade of EAM (Eurocontrol Airspace Model), which for the past 15 years has been Eurocontrol's principal simulation tool for evaluating proposed changes to airspace structure and sector configuration in the EEC member states. RAMS deals with all segments of flights starting from take-off until just before landing. However, runway interactions with airborne operations may be modeled, such as for parallel or intersecting runways [RAMS User Manual, **http://www.eurocontrol.fr, 2004]**.

RAMS provides a flexible airspace simulation environment where a broad variety of new concepts may be tested at the desired level of detail. Due to the flexible design of RAMS, the system is capable of carrying out planning, organizational, high-level, or in-depth studies of a wide range of ATC concepts. This design includes 4-dimensional flight profiles, conflict detection and conflict resolution mechanisms, workload models, modern user interfaces and a data preparation environment.

By carrying out comparative analyses between different simulated scenarios, the effects of proposed changes can be expressed in terms of:

- Distribution of workload over centers, sectors, and individual control positions;
- Traffic loads within each sector/center overall and per route, level band, point, classified according to cruise, climb and descent;
- Penalties imposed upon traffic resulting from imposing ATM measures, flight level changes, en-route/ground delays, and arrival holding.
- Frequency distribution based on many iterations of a given scenario (Monte-Carlo simulations).

2.3.2.4 NASPAC

The National Airspace System Performance Capability (NASPAC) is a fast-time simulation model that may encompass large regions of airspace and a large number of airports. The simulation “flies” individual aircraft through daily itineraries (that may include landings and take-offs at a sequence of airports) and provides statistical reports on delays and flow rates observed. The model includes simplified representations of en-route sectors, as well as of airports. Some graphical outputs by airport, sector or region can be provided. NASPAC was originally conceived as a macroscopic-level model that would support studies dealing with issues related to strategies for national airport investments and to policy for national and international ATM. However, much detail has been added to it over the years and it may actually be better suited today to answer questions of a more tactical nature, such as the effects on delays of alternative flow management strategies.

The main outputs of NASPAC consist of estimates of delay and of flows past given points (“throughput”) in the system modeled. Delay is reported in the form of “technical delay” (defined as the local delay incurred at any specific point in the system) and of “effective delay” (defined as the difference between scheduled and actual times of events, such as the arrival or departure from a gate).

Use of the model requires considerable training and significant resources in terms of both costs and personnel. Arrangements must be made with one of the organizations that operate the model. Extensive data are also needed [**http://www.faa.gov, 2005**].

2.3.2.5 AOM

In 1997 - 1999, Virginia Tech carried out research on the "Integration of Reusable Launch Vehicle (RLV) into Air Traffic Management". The main focus of this project was the evaluation of traffic impacts due to closures of airspace during rocket launches, an economic impact model was developed and also an optimal routing model to detour flights around Special Use Airspace (SUA) **[Sherali, et al., 1998]**. In 1999, another project on titled "Use of Next-generation Satellite Systems for Aeronautical Communications" sponsored by NASA was carried out by a joint effect between the University of Maryland and Virginia Tech **[Ball, et al., 2001]**. The primary objective of this research is to further develop these two projects and employ the technologies developed in the projects into NASA Aviation Safety Program.

Aircraft Occupancy Model (AOM) was developed for the project - "Integration of Reusable Launch Vehicle (RLV) into Air Traffic Management" at Virginia Tech. AOM can read ETMS flight data and Sector data and output air traffic workload in each sector or center. In this research, AOM will be modified to use for the case study in Chapter 7.

2.3.2.6 Severe Weather-Modeling Paradigm

McCrea et al. developed a severe weather-modeling paradigm and a new concept of "Probability-nets" in aviation industry. These are used to generate new flight paths around convective weather systems with specified operability threshold levels. This research also developed probabilistic delay assessment methodology for estimating planned paths that might encounter potentially disruptive weather along its trajectory. Finally, an economic benefit analysis for new flight paths is conducted **[McCrea et al. 2006]**.

Weather data is a major component and many current weather forecasts are examined in this research. The Model Output Statistics (MOS) is chosen to use for this research. MOS is developed by the National Weather Service's Meteorological Development Lab (MDL), it produces the necessary information in three-hour or six-hour time intervals using a statistical modeling method. The pertinent aviation MOS text forecasts are available in short-range GFS (6-84 hours), Eta (6-72 hours), and extended-range GFS (12-192 hours) formats. MOS provides specific probability for various weather systems (i.e., convective, ceiling, temperature, etc.) at over 1,500 reporting sites throughout the United States and Puerto Rico **[McCrea et al. 2006]**.

The probabilities at each reporting site are used to build a probability-nets for one region or entire country. After constructing the probability-nets, a flight plan that enters only one probability-net will be assigned an exit probability. The strand intersection probability value is introduced. It means that the discrete representation of the probability data lends itself to a subjective assignment of probability values at the point of intersection between the flight plan and strand of interest. New flight paths that skirts the weather systems are controlled by specified probability threshold. This research also can determine a time-dependent shortest path trajectory.

The probability-nets is a very new and innovative concept for developing new flight paths around weather system. However, most flights are short activity and usually they stay from 1 to 3 hours in the air in the United States. MOS forecasts should provide (1-6 hours) and (2-12 hours) forecasts with interval 1 hour.

2.4 Aviation Weather

2.4.1 Review FAA Weather Requirement Regulations

All pilots need the same basic weather information for safe operation. Aircraft performs in adverse conditions is a function of the type of aircraft, the equipment, and the pilot's training/certification. FAA weather information requirements vary depending upon the category of operation. Similar weather information is needed for each type of operator. There are various civilian categories of aircraft operators identified by the FAA. Each category has its own set of requirements under the Federal Aviation Regulations. The largest segment of operators falls under the following three categories:

- Part 91 – General Operating and Flight Rules
- Part 135 – Air Taxi Operators and Commercial Operators
- Part 121 – Domestic Commercial Operators

The following paragraphs provide a review of FAR requirements for weather information by category of operator.

Part 91 - General Operating and Flight Rules

Part 91 flight operations include personal flights, business and corporate flights, training flights and special operations, (*e.g.*, flight-tests, glider towing, parachuting, *etc*.). Weather information requirements are relatively lenient under Part 91. "Each pilot in command shall, before beginning a flight, become familiar with all available information concerning that flight. This information must include for a flight under IFR or a flight not in the vicinity of an airport, weather reports and forecasts, fuel requirements, alternatives available if the planned flight cannot be completed, and any known traffic delays of which the pilot in command has been advised by air traffic control …other reliable information appropriate to the aircraft, relating to aircraft performance under expected values of airport elevation and runway slope, aircraft gross weight, and wind and temperature" **[FAR 91.103, DOT]**.

However, the FAR does not state what types of weather reports or forecasts are required or information about their timeliness. Since the FARs are not specific on how weather information is to be obtained, many Part 91 pilots obtain weather information from TV, radio, and the Internet.

Part 135 – Air Taxi Operators and Commercial Operators

Generally, Part 135 operations include:

- Commuter (scheduled passenger-carrying operations in airplanes that have passenger-seating configurations of less than 10) or on-demand (charter) operations, and
- Nonstop sightseeing flights for compensation or hire that begin and end at the same airport, and are conducted within a 25 statute mile radius of that airport **[http://www.landings.com/_landings/pages/fars.html]**.

Weather requirements under Part 135 are more stringent than Part 91. FAR 135.213 states: "Whenever a person operating an aircraft under this part is required to use a weather report or forecast, that person shall use that of the U.S. National Weather Service (NWS), a source approved by the U.S. National Weather Service, or a source approved by the Administrator. However, for operations under VFR, the pilot in command may, if such a report is not available, use weather information based on that pilot's own observations or on those of other persons competent to supply appropriate observations…weather observations made and furnished to pilots to conduct IFR operations at an airport must be taken at the airport where those IFR operations are conducted, unless the Administrator issues operations specifications allowing the use of weather observations taken at a location not at the airport where the IFR operations are conducted" [**[FAR 135.213, DOT]**].

Part 121 – Domestic Commercial Operators

Part 121 operations include:

- Passenger and cargo domestic, flag (international), and supplemental operations (*e.g.*, operating aircraft with 10 or more seats or more than 7,500 pounds payload capacity), and
- Nonstop sightseeing flights conducted with airplanes having a passenger-seat configuration of 30 seats or fewer and a maximum payload capacity of 7,500 pounds or less that begin and end at the same airport, and are conducted within a 25 statute mile radius of that airport **[http://www.landings.com/_landings/pages/fars.html]**.

Part 121 operators conducting domestic or flag operations must have sufficient dispatch centers located at points necessary to ensure proper operational control of each flight. Weather service requirements under Part 121 are extensive. FAR 121.101 states in part: "domestic or flag operations must show that enough weather reporting services are available along each route to ensure weather reports and forecasts necessary for the operation. Except as provided in paragraph of this section, no certificate holder conducting domestic or flag operations may use any weather report to control flight **[FAR 121.101, DOT]**.

2.4.2 Aviation Weather Support Systems and Products

2.4.2.1 FAA's Support Systems

Generally, The current system which provides weather information to the aviation community is a partnership between the FAA and the National Oceanic and Atmospheric Administration (NOAA). As mentioned before, an aircraft's flight can be grouped into three regions: en-route, in the terminal area, and on the ground. The national air traffic control system has been designed to support the specific needs of these regions of flight.

En-route

The Air Route Traffic Control Centers (ARTCCs) provide airspace management to aircraft operating under IFR flight plans. A Center Weather Service Unit (CWSU), composed of both National Weather Service meteorologists and FAA support personnel, is associated with each of the ARTCCs. The weather service units provide up-to-date weather information based on analysis of weather products obtained from a number of different sources.

In the Terminal Area and on the Ground

The terminal area and ground are managed by the Airport Traffic Control Tower (ATCT). Weather information is provided to the tower from a number of sources. In turn, the tower serves as one potential source of weather information for arriving and departing aircraft. At some airports, an automated system is in place to provide up-to-date weather information to arriving and departing pilots. This automated system is termed the automatic terminal information service.

Others

Another component of the FAA weather information support system is the FAA Flight Service Stations (FSSs) and the Automated Flight Service Stations (AFSSs). FSSs and AFSSs provide pilots with preflight weather briefings, flight planning assistance, weather and en-route flight information, and airport terminal advisory services.

2.4.2.2 NOAA's Support Systems

Support Centers

The NWS, under the NOAA, measures, analyzes, forecasts, and distributes weather information to the different FAA centers and to pilots as official FAA approved weather products. The NWS is organized into a number of offices and centers which serve the meteorological and hydrological needs of the nation. Four centers of the NWS that provide direct information to the aviation community. They are National Center Operations, Storm Prediction Center, Aviation Weather Center, and Tropical Prediction Center **[NOAA, 2000]**. Another agency under NOAA that provides weather information to the aviation community is the National Environmental Satellite, Data, and Information Service (NESDIS). NESDIS provides satellite images of the atmosphere, which are used in modeling and forecasting.

Weather Forecast Models

The National Centers for Environmental Prediction (NCEP) supports several mesoscale models. A few of the current and future models are described here. The Eta-32 model produces 48 hour forecast twice a day at 0000 and 1200 UTC, a 33 hour forecast at 0300 UTC, and a 30 hour forecast at 1800 UTC **[http://www.comet.ucar.edu/nwplessons/etalesson2/]**. In support of shorter range forecast, the NCEP supports the Rapid Update Cycle (version 2) (RUC-2) model. The RUC forecasts are unique in that they are initialized with very recent data. The RUC-2 produces updated forecast every hour [**http://maps.fsl.noaa.gov/ruc2.tpb.html**]. A third mesoscale model that has found acceptance in the modeling community is the fifth-generation National Center for Atmospheric Research (NCAR)/Penn State Mesoscale Model (MM5). This mesoscale model is a limited-area, nonhydrostatic or hydrostatic terrain-following sigma-coordinate model designed to simulate or predict mesoscale and regional-scale atmospheric circulation [**http://www.mmm.ucar.edu/mm5/overview.html**]. The NCEP is also currently overseeing the development of the next generation in mesoscale modeling termed the Weather Research and Forecast (WRF) model. This collaborative effort is scheduled to produce a product by the end of 2003. The model will provide a common tool for both research and operations [**http://www.emc.ncep.noaa.gov/mmb/wrf/m.ucar.edu/m]**.

The NWS also has Weather Forecast Offices (WFO) located in each state. The NWS WFO provides up-to-date information on weather in its assigned region and route forecast and terminal area forecast.

2.4.2.3 Weather products

Weather products are defined as information (measured data, processed data, forecasts) that have been packaged for interpretation by the recipient to aid in making both strategic and tactical decisions affecting aviation safety. **Table 2-1** contains a listing and brief description of 23 weather products.

For the en-route phases of flight, weather products may provide information on atmospheric events that are affecting a very large area or the weather product may address events on a much smaller scale or along a specific route. For example, the Aviation Routine Weather Report (AIRMETs) and Significant Meteorological Information (SIGMETs) are in-flight advisories provided by the Aviation Weather Center which warn pilots of hazardous conditions that are affecting or will be affecting an area of at least 3,000 square miles at any one instant in time. Route Forecasts (RF), issued by the NWS Weather Forecast Offices (WFO), provide pilots forecast information for more than 200 specific routes over the contiguous United States. Weather products also are designed to provide pilots with information that is very location specific. For example, the pilot reports (PIREPS) are issued by pilots who have experienced adverse weather conditions in flight. This information provides other pilots with a snap shot of potential adverse conditions that may lie along his route

2.4.3 Aviation Weather Product Deficiencies

There are four key areas that contain components that are deficient in some qualitative way. The key areas are data format, support systems, sensors, and forecasting and modeling.

Data Format

The utility of a weather product, in many cases, depends on the delivery system's ability to provide the information in a timely manner and in a format that can be easily interpreted. With the amount of information and the format of some of the information (*e.g.*, radar products) currently available to the pilot, a graphical display is needed to reduce the pilot's workload and to aid in the interpretive process (*e.g.,* a coordinate overlay with hazard areas defined).

Table 2.1 Aviation Weather Products

Number	Names
1	***Aviation Routine Weather Report (METAR)***
2	***Aviation Selected Special Weather Report (SPECI)***
3	***Terminal Area Forecast (or Aerodrome Forecast) (TAF)***
4	***Area Forecasts (AF)***
5	***Airman's Meteorological Advisory (AIRMET)***
6	***Domestic Significant Meteorological Information (Domestic SIGMET)***
7	***Convective Significant Meteorological Information (Convective SIGMET)***
8	***International Significant Meteorological Information (International SIGMET)***
9	***Low Level Significant Weather Charts (LLSWC)***
10	***High Level Significant Weather Charts (HLSWC)***
11	***Winds and Temperatures Aloft (WA and TA)***
12	***Route Forecast (RF)***
13	***Meteorological Impact Statement (MIS)***
14	***Center Weather Advisory (CWA)***
15	***Severe Weather Watch (SWW)***
16	***Pilot Reports (PIREPS)***
17	***Satellite Imagery (SI)***
18	***Radiosonde Additional Data (RAD)***
19	***Convective Outlook (CO)***
20	***Next Generation Weather Surveillance Radar (NEXRAD)***
21	***Terminal Doppler Weather Radar (TDWR)***
22	***Low Level Wind Shear Alert System (LLWAS)***
23	***Weather Systems Processor (WSP)***

Support System

The FAA depends on the NWS to provide weather information that can be tailored to the needs of the aviation community. However, the NWS often provides weather information on a much coarser grid than that required for aviation. The aviation community would like to continue to see weather products that are designed for aviation.

Sensors

Sensors were identified as having deficiencies in a number of areas. The deficiencies have been grouped into five categories: lack of availability, lack of confidence, loss of capability, lack of capability, and required tuning.

Forecasting and Modeling

The fourth area where deficiencies have been identified is the area of forecasted weather products. Mesoscale modeling is required to forecast winds and temperatures aloft. However, the model's forecast products are a function of the model's fidelity and the sensor data input to the model.

2.4.4 Aviation Weather Information and Bandwidth Requirement Model

There are many existing weather forecast models which can produce many aviation weather products as described earlier in this dissertation and some research projects related to the analysis of aviation weather information. However, there is no existing model to examine aviation weather information and bandwidth requirements combining the volume of air traffic at each phase of flight in three flight regions. It is necessary for aviation industry to determine the quantity of aviation weather information transmitted between pilots and the ground service centers so that aviation industry could build a efficient and timely communication system with minimum budget in the future. This is very new area needed to be explored and developed.

2.5 Aviation Weather Communication Systems

Communication systems carry information such as weather information between ground stations and aircraft, and among aircraft themselves. They constitute a very important element in the navigation, ATC and safety aspects of aviation.

2.5.1 Terminal Region

Pilots may receive weather and forecast information from a number of different sources. The Automated Weather Observing System (AWOS) and Automated Surface Observation System (ASOS) broadcast local weather information directly to pilots via discrete very high frequency (VHF) transmissions or as the voice portion of a local navigational aid (NAVAID). The Automatic Terminal Information Service (ATIS) is a continuous broadcast of recorded weather and runway conditions of importance to arriving and departing aircraft. ATIS is also broadcast over discrete VHF radio channels or the voice portion of a local NAVAID. The Aircraft Communications Addressing and Reporting System (ACARS) is a VHF air/ground datalink that relays weather information to the cockpit in a digital format. Both Terminal Weather Information for Pilots (TWIP) and the Digital Automated Terminal Information Service (D-ATIS) are available through ACARS.

2.5.2 En-route Region

Pilots have direct access to weather information and flight planning assistance via the FSSs and AFSSs. If available, an En-route Flight Advisory Service (EFAS) (Flight Watch) provides weather updates and advisories by providing pilots direct access to weather specialists. FSSs, AFSSs and EFASs all transmit data directly over VHF radio. For short or local flights, pilots can use the Transcribed Weather Broadcast (TWEB), which provides continuous, up-to-date, recorded weather information. Pilots can also receive or request weather information directly from their operation centers over VHF radio through ACARS. The ARTCCs are capable of direct communications with IFR air traffic on specific frequencies. If hazardous weather conditions develop, pilots will be advised to tune into the Hazardous In-Flight Weather Advisory Service (HIWAS) for a continuous broadcast of recorded in-flight weather advisories. For oceanic flights, pilots can receive updated weather information via ACARS. The Lockheed Martin report **[Ball, J. W., et al., 1999]** provides additional information into the current set of delivery systems.

A number of systems have been developed to provide pilots with the latest weather information. However, the majority of these systems require the pilot to manually request information. In some cases, the pilot may not know what information to request since conditions may have changed considerably since initiating flight. For all of the delivery systems, except ACARS, voice is the only means of receiving information during flight. For the high-end aircraft, ACARS provides the capability to support both text and voice.

Recently, the FAA seems to be moving in a direction that will support information presentation to the pilot in a graphical format, making it easier to interpret and making possible additional information to aid the pilot in making both strategic and tactical decisions.

2.6 Aviation Weather Economic Impact

All the deleterious effects of weather ultimately affect the operating economy of aviation-based enterprises, especially that of commercial air carriers. The most visible item of financial loss in an air disaster is due to the loss of aircraft and the subsequent cost of replacement which may run into hundreds of millions of dollars in single instances in the case of modern airliners (as also transport aircraft and high-end military aircraft). Other important items of cost associated with airline accidents arise from possible damage to ground facilities and other public and private property, increased cost of insurance, accident investigation, litigation, and compensation to crew and passengers. In addition to these direct and/or closely connected costs, accidents also involve consequential or social costs which may be many times higher. Loss of life in accidents results in social and commercial dislocation, and loss of important cargo can have severe consequential implications. This effect is even more severe in relatively poor economies where the privilege of air travel and transportation is reserved essentially for the most important people and cargo. Passenger discomfort and poor schedule-keeping also result in high levels of direct and consequential costs. Bumpy flights lead to the erosion of passenger confidence and preference for specific airlines or air routes, or for air travel in general. In extreme cases, bumpy flights can cause injury to passengers and damage to their belongings even if the aircraft as a whole may not be damaged.

The economic implications of poor schedule-keeping are even more severe for airlines. Significant delays in takeoffs and landings lead to revenue loss due to the reduced number of operations. They also result in low aircraft utilization factors, necessitating larger capital and recurring expenditures for maintaining a given level of airline operation. Further, unscheduled delays on the part of passengers lead to individual schedule disruption and loss of productivity. In the modern hub-and-spoke model of airline operations, where given pairs of points are often connected through multiple flights, delays in one leg usually get compounded by more missed flights, which further amplifies consequent losses. The ATA estimates that the loss of productivity caused by delayed flights at 6 billion dollars in 2000 alone. As mentioned before, a majority of flight delays are usually caused by weather.

The costs incurred due to loss of aviation system efficiency are equally serious. The most significant ways in which weather affects aviation efficiency are related to aircraft route modification to avoid hazardous weather zones and partial or total shutdown of airports for landing and takeoff operations. Diversion of flight paths to skirt hazardous weather entails consumption of additional fuel and loss of time. Airport or runway closure often necessitates in-flight holding of aircraft for considerable periods, again leading to wastage of fuel and time. The loss is much higher when the closure of airports or runways forces flights to be diverted to different airports altogether.

Indeed, the most significant bottleneck in improving the traffic handling capacity of air traffic control systems is due to the reduction in capacity of airports occurring under instrument flight rule (IFR) conditions. It has been estimated that benefits of 3.5 billion dollars can be obtained through a modest increase of 16% in the IFR terminal capacity in the US **[Evans, 1991]**. A large part of this gain is through savings in petroleum products, which is a nonrenewable resource. A major contribution to these gains can come from proper weather information made available in a timely manner.

CHAPTER 3

Systems Approach and Methodology

“The system approach is the modus operandi of dealing with complex system. It is holistic in scope, creative in manner and rational in execution. Thus, it is based on looking at a total activity, project, design or system, rather than considering the efficiency of the component tasks independently. It is innovative, in that rather than seeking modifications of older solutions to similar problems, new problem definitions are sought, new alternative solutions generated and new measures of evaluation are employed if necessary” **[Drew, 1995]**.

A methodology is a system of rules which guides scientific inquiry. A methodology is usually comprised of procedures (orders of action for defining problems in terms of variables), tools, or elements of communication in the form of verbal, graphical and mathematical constructs, that aid in the execution to “models” representing the problems. A model is an idealized representation of reality developed with the aid of a methodology. Three components of a methodology for creating and utilizing a model are: (1) a substantive component which specifies how the model’s variables and relations are selected (2) a set of criteria that can be used to determine whether the results generated by the model are acceptable; and (3) a scheme for structuring and manipulating the model for performing policy analysis **[Drew, 1995]**.

3.1 Introduction to Modeling and Simulation

3.1.1 Modeling

The term “modeling” spans the spectrum from simple conceptual relationships to highly complicated, parallel, fast-time, constructive, “human-in-the-loop” and discrete-event computer simulations. Modeling is the process of producing a model; a model is a representation of the construction and working of some system of interest. A model is similar to but simpler than the system it represents. One purpose of a model is to enable the analyst to predict the effect of changes to the system. On the one hand, a model should be a close approximation to the real system and incorporate most of its salient features. On the other hand, it should not be so complex that it is impossible to understand and experiment with it. A good model is a judicious trade-off between realism and simplicity. Simulation practitioners recommend increasing the complexity of a model iteratively. An important issue in modeling is model validity. Model validation techniques include simulating the model under known input conditions and comparing model output with system output.

Generally, a model intended for a simulation study is a mathematical model developed with the help of simulation software. Mathematical model classifications include deterministic (input and output variables are fixed values) or stochastic (at least one of the input or output variables is probabilistic); static (time is not taken into account) or dynamic (time-varying interactions among variables are taken into account). Typically, simulation models are stochastic and dynamic.

Both analytical and computer models are critical tools to understand a complex system like the NAS. The reason is that if we wish to conduct tests or deploy new equipment or procedures, we cannot simply halt NAS operations. The NAS operates continuously. Nor can we simply plug in advanced prototype systems for testing during NAS operations because human lives would be at stake should anything go wrong. So we use models.

3.1.2 Simulation

A simulation of a system is the operation of a model of the system. The model can be reconfigured and experimented with; usually, this is impossible, too expensive or impractical to do in the system it represents. The operation of the model can be studied, and hence, properties concerning the behavior of the actual system or its subsystem can be inferred. In its broadest sense, simulation is a tool to evaluate the performance of a system, existing or proposed, under different configurations of interest and over long periods of real time.

Simulation is used before an existing system is altered or a new system built, to reduce the chances of failure to meet specifications, to eliminate unforeseen bottlenecks, to prevent under or over-utilization of resources, and to optimize system performance. For instance, simulation can be used to answer questions like: What is the best design for a new telecommunications network? What are the associated resource requirements? How will a telecommunication network perform when the traffic load increases by 50%? How will a new routing algorithm affect its performance? Which network protocol optimizes network performance? What will be the impact of a link failure?

There are two types of simulation: One is discrete event simulation in which the central assumption is that the system changes instantaneously in response to certain discrete events. For instance, a single server queuing process in which time between arrivals and service time are exponential - an arrival causes the system to change instantaneously. On the other hand, continuous simulators, like flight simulators and weather simulators, attempt to quantify the changes in a system continuously over time in response to control inputs. Discrete event simulation is less detailed (coarser in its smallest time unit) than continuous simulation but it is much simpler to implement, and hence, is used in a wide variety of situations.

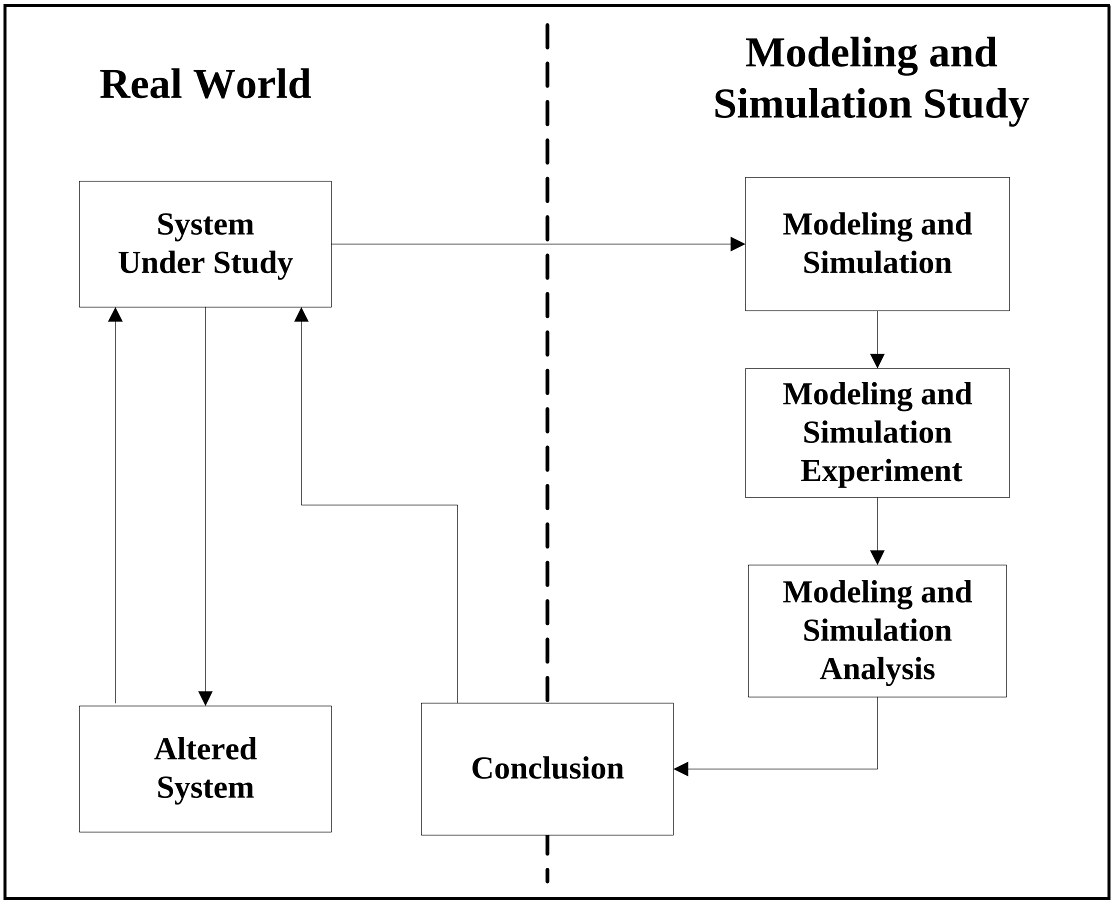


Figure 3.1 Modeling and Simulation Study Schematic.

Figure 3.1 is a schematic of a modeling and simulation study. The iterative nature of the process is indicated by the system under study becoming the altered system which then becomes the system under study and the cycle repeats. In the modeling and simulation study, human decision making is required at all stages, namely, model development, experiment design, output analysis, conclusion formulation, and making decisions to alter the system under study. The only stage where human intervention is not required is the running of the simulations, which most simulation software packages perform efficiently. The important point is that powerful simulation software is merely a hygiene factor - its absence can hurt a simulation study but its presence will not ensure success. Experienced problem formulators and simulation modelers and analysts are indispensable for a successful simulation study

3.2 Tools and Software Package

3.2.1 Systems Dynamics

Systems Dynamics is used for policy modeling. It is based on the foundations of (1) decision making, (2) feedback systems analysis, and (3) simulation. Decision making is stating how action is to be taken. Feedback deals with the way information is to be used for the decision making. Simulation permits decision makers to view the implications of their decisions over the future.

A model of this process can be very complex and can consist of hundreds of variables. The model should have the following characteristics:

- Be able to describe any statement of cause effect relationship that one wishes to include.
- Be simple in mathematical nature.
- Be closely synonymous in nomenclature to industrial, economic and social technology.
- Be extensible to large numbers of variables without exceeding the practical limits of computers.
- Be able to handle continuous interaction in the sense that any artificial discontinuities introduced by solution time intervals will not affect the results.
- Should be able to generate discontinuous changes in decisions when these are needed **[Forrester, J. W., 1961]**.

The three steps in the Systems Dynamics procedure are: (1) the formulation of a mental model of the problem in the form of a verbal description, (2) The verbal description is expressed as a flow diagram, also called a causal diagram. The basic building blocks for drawing a causal diagram is described in **Table 3.1.** The last step is to convert the causal diagram into mathematical form.

TABLE 3.1. Systems Dynamics Variables and Symbols.

Variable	Description
1. Level or Stock or State variables	They are accumulations in a system, such as aircraft, number of runways, and population etc.
2. Rate or Flow Variables	The job of Rate or Flow Variables is to fill and drain accumulations, such as aircraft production rate and population growth rate.
3. Auxiliary or Converters variables	They convert input into outputs. Generally They are used to estimate the rate variables in the simulation of the model.
4. Constants or Converters	They are used to indicate static variables or the boundaries of the model
5. Connectors	The job of the connector is to connect model elements

3.2.2 Software Packages

3.2.2.1 MATLAB

MATLAB 7.0 is a high-performance language for technical computing. It integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. Typical uses of MATLAB include:

- Math and computation
- Algorithm development
- Modeling, simulation, and prototyping
- Data analysis, exploration, and visualization
- Scientific and engineering graphics
- Application development, including graphical user interface building

MATLAB is an interactive system whose basic data element is an array that does not require dimensioning. This allows you to solve many technical computing problems, especially those with matrix and vector formulations, in a fraction of the time it would take to write a program in a scalar noninteractive language such as C or FORTRAN. The name MATLAB stands for matrix laboratory. MATLAB was originally written to provide easy access to matrix software developed by the LINPACK and EISPACK projects, which together represent the state-of-the-art in software for matrix computation.

MATLAB has evolved over a period of years with input from many users. In university environments, it is the standard instructional tool for introductory and advanced courses in mathematics, engineering, and science. In industry, MATLAB is the tool of choice for high-productivity research, development, and analysis.

MATLAB features a family of application-specific solutions called toolboxes. Very important to most users of MATLAB, toolboxes allow you to learn and apply specialized technology. Toolboxes are comprehensive collections of MATLAB functions (M-files) that extend the MATLAB environment to solve particular classes of problems. Areas in which toolboxes are available include signal processing, control systems, neural networks, fuzzy logic, wavelets, simulation, and many others.

3.2.2.2 ITHINK (STELLA)

ITHINK 7.0 is an acronym for “System Think, Experimental Learning Laboratory, with Animation”. The ITHINK 7.0 software is designed to help people build understanding of dynamic systems and processes.

Causal Diagram

Stocks, Flows, Converters, and Connectors are the basic building blocks in ITHINK 7.0. These are the same as the blocks shown in **Table 3.1** and represented by icons depicted in **Figure 3.2**. Stocks or Levels variables represent accumulations and are represented by rectangles. Flows are rate of change variables that regulate the flow in and out of stocks. Flows are represented by a pipe through which the flow takes place. Attached to the pipe is a flow regulator or converter which contains the logic that determines the special flow volume. Converters can represent auxiliary variables, constant parameters, supplementary variables and table functions. They are represented by circles. Converters can represent either information or material quantities. The other basic building block is the connector. Connectors link stocks to converters and converters to other converters. Connectors do not take on numerical values, they represent inputs.

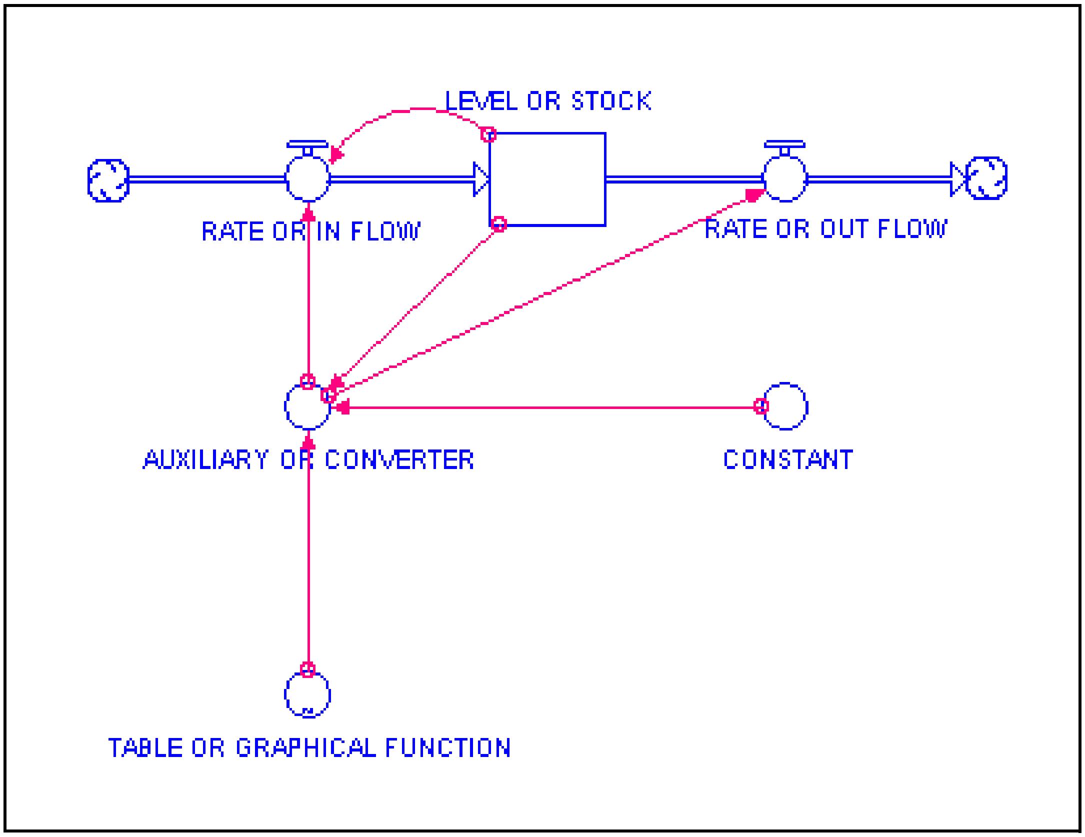


Figure 3.2 Basic Building Blocks in ITHINK 7.0.

Equations

Integration (or Accumulation) is the basis of the level and rate structure used in System Dynamics. A level variable $L(t)$ denotes the accumulation of some physical entity at time t. Let RI and RO represent two rate variables, rate-in (in flow) and rate-out (out flow), denoting the change in the level variable over the interval from $t\text{-}1$ to t. The relationship between the level $L(t)$ and the rate can be expressed mathematically by:

$$L(t) = L(t\text{-}1) + \int_{t-1}^{t} [RI(t)\text{-}RO(t)]dt \tag{3.1}$$

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,

$$L_i(t) = L_i(t\text{-}1) + (dt)\Sigma R_j(t) \quad i = 1,2,......m, j = 1,2,......n \tag{3.2}$$

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

$$R_j(t) = f[L_i(t), E_k(t), A_{ij}(t), A_{kj}(t)] \tag{3.3}$$

where E_k is the set 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 be found from the “level” equation. ITHINK 7.0 is a computer software which can integrate efficiently these finite difference equations.

CHAPTER 3

Systems Approach and Methodology

“The system approach is the modus operandi of dealing with complex system. It is holistic in scope, creative in manner and rational in execution. Thus, it is based on looking at a total activity, project, design or system, rather than considering the efficiency of the component tasks independently. It is innovative, in that rather than seeking modifications of older solutions to similar problems, new problem definitions are sought, new alternative solutions generated and new measures of evaluation are employed if necessary” **[Drew, 1995]**.

A methodology is a system of rules which guides scientific inquiry. A methodology is usually comprised of procedures (orders of action for defining problems in terms of variables), tools, or elements of communication in the form of verbal, graphical and mathematical constructs, that aid in the execution to “models” representing the problems. A model is an idealized representation of reality developed with the aid of a methodology. Three components of a methodology for creating and utilizing a model are: (1) a substantive component which specifies how the model’s variables and relations are selected (2) a set of criteria that can be used to determine whether the results generated by the model are acceptable; and (3) a scheme for structuring and manipulating the model for performing policy analysis **[Drew, 1995]**.

3.1 Introduction to Modeling and Simulation

3.1.1 Modeling

The term “modeling” spans the spectrum from simple conceptual relationships to highly complicated, parallel, fast-time, constructive, “human-in-the-loop” and discrete-event computer simulations. Modeling is the process of producing a model; a model is a representation of the construction and working of some system of interest. A model is similar to but simpler than the system it represents. One purpose of a model is to enable the analyst to predict the effect of changes to the system. On the one hand, a model should be a close approximation to the real system and incorporate most of its salient features. On the other hand, it should not be so complex that it is impossible to understand and experiment with it. A good model is a judicious trade-off between realism and simplicity. Simulation practitioners recommend increasing the complexity of a model iteratively. An important issue in modeling is model validity. Model validation techniques include simulating the model under known input conditions and comparing model output with system output.

Generally, a model intended for a simulation study is a mathematical model developed with the help of simulation software. Mathematical model classifications include deterministic (input and output variables are fixed values) or stochastic (at least one of the input or output variables is probabilistic); static (time is not taken into account) or dynamic (time-varying interactions among variables are taken into account). Typically, simulation models are stochastic and dynamic.

Both analytical and computer models are critical tools to understand a complex system like the NAS. The reason is that if we wish to conduct tests or deploy new equipment or procedures, we cannot simply halt NAS operations. The NAS operates continuously. Nor can we simply plug in advanced prototype systems for testing during NAS operations because human lives would be at stake should anything go wrong. So we use models.

3.1.2 Simulation

A simulation of a system is the operation of a model of the system. The model can be reconfigured and experimented with; usually, this is impossible, too expensive or impractical to do in the system it represents. The operation of the model can be studied, and hence, properties concerning the behavior of the actual system or its subsystem can be inferred. In its broadest sense, simulation is a tool to evaluate the performance of a system, existing or proposed, under different configurations of interest and over long periods of real time.

Simulation is used before an existing system is altered or a new system built, to reduce the chances of failure to meet specifications, to eliminate unforeseen bottlenecks, to prevent under or over-utilization of resources, and to optimize system performance. For instance, simulation can be used to answer questions like: What is the best design for a new telecommunications network? What are the associated resource requirements? How will a telecommunication network perform when the traffic load increases by 50%? How will a new routing algorithm affect its performance? Which network protocol optimizes network performance? What will be the impact of a link failure?

There are two types of simulation: One is discrete event simulation in which the central assumption is that the system changes instantaneously in response to certain discrete events. For instance, a single server queuing process in which time between arrivals and service time are exponential - an arrival causes the system to change instantaneously. On the other hand, continuous simulators, like flight simulators and weather simulators, attempt to quantify the changes in a system continuously over time in response to control inputs. Discrete event simulation is less detailed (coarser in its smallest time unit) than continuous simulation but it is much simpler to implement, and hence, is used in a wide variety of situations.

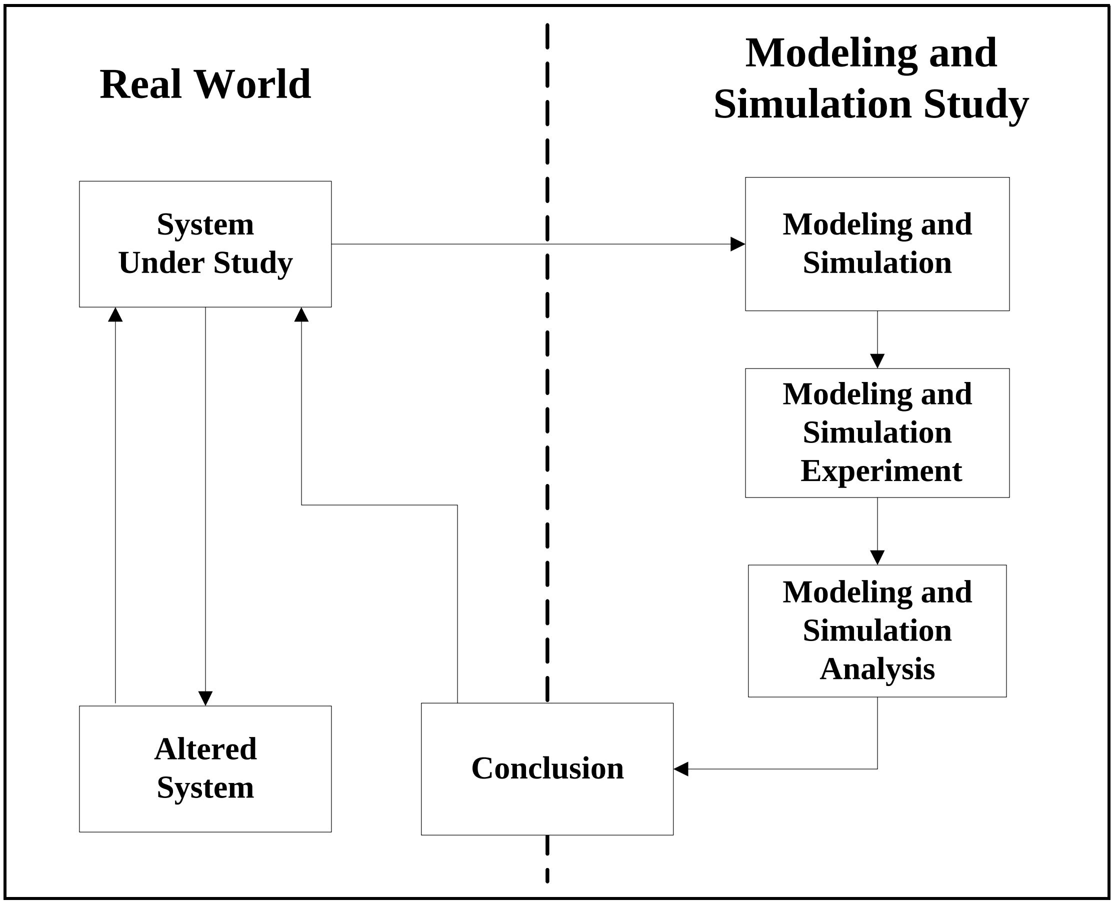


Figure 3.1 Modeling and Simulation Study Schematic.

Figure 3.1 is a schematic of a modeling and simulation study. The iterative nature of the process is indicated by the system under study becoming the altered system which then becomes the system under study and the cycle repeats. In the modeling and simulation study, human decision making is required at all stages, namely, model development, experiment design, output analysis, conclusion formulation, and making decisions to alter the system under study. The only stage where human intervention is not required is the running of the simulations, which most simulation software packages perform efficiently. The important point is that powerful simulation software is merely a hygiene factor - its absence can hurt a simulation study but its presence will not ensure success. Experienced problem formulators and simulation modelers and analysts are indispensable for a successful simulation study

3.2 Tools and Software Package

3.2.1 Systems Dynamics

Systems Dynamics is used for policy modeling. It is based on the foundations of (1) decision making, (2) feedback systems analysis, and (3) simulation. Decision making is stating how action is to be taken. Feedback deals with the way information is to be used for the decision making. Simulation permits decision makers to view the implications of their decisions over the future.

A model of this process can be very complex and can consist of hundreds of variables. The model should have the following characteristics:

- Be able to describe any statement of cause effect relationship that one wishes to include.
- Be simple in mathematical nature.
- Be closely synonymous in nomenclature to industrial, economic and social technology.
- Be extensible to large numbers of variables without exceeding the practical limits of computers.
- Be able to handle continuous interaction in the sense that any artificial discontinuities introduced by solution time intervals will not affect the results.
- Should be able to generate discontinuous changes in decisions when these are needed **[Forrester, J. W., 1961]**.

The three steps in the Systems Dynamics procedure are: (1) the formulation of a mental model of the problem in the form of a verbal description, (2) The verbal description is expressed as a flow diagram, also called a causal diagram. The basic building blocks for drawing a causal diagram is described in **Table 3.1.** The last step is to convert the causal diagram into mathematical form.

TABLE 3.1. Systems Dynamics Variables and Symbols.

Variable	Description
1. Level or Stock or State variables	They are accumulations in a system, such as aircraft, number of runways, and population etc.
2. Rate or Flow Variables	The job of Rate or Flow Variables is to fill and drain accumulations, such as aircraft production rate and population growth rate.
3. Auxiliary or Converters variables	They convert input into outputs. Generally They are used to estimate the rate variables in the simulation of the model.
4. Constants or Converters	They are used to indicate static variables or the boundaries of the model
5. Connectors	The job of the connector is to connect model elements

3.2.2 Software Packages

3.2.2.1 MATLAB

MATLAB 7.0 is a high-performance language for technical computing. It integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. Typical uses of MATLAB include:

- Math and computation
- Algorithm development
- Modeling, simulation, and prototyping
- Data analysis, exploration, and visualization
- Scientific and engineering graphics
- Application development, including graphical user interface building

MATLAB is an interactive system whose basic data element is an array that does not require dimensioning. This allows you to solve many technical computing problems, especially those with matrix and vector formulations, in a fraction of the time it would take to write a program in a scalar noninteractive language such as C or FORTRAN. The name MATLAB stands for matrix laboratory. MATLAB was originally written to provide easy access to matrix software developed by the LINPACK and EISPACK projects, which together represent the state-of-the-art in software for matrix computation.

MATLAB has evolved over a period of years with input from many users. In university environments, it is the standard instructional tool for introductory and advanced courses in mathematics, engineering, and science. In industry, MATLAB is the tool of choice for high-productivity research, development, and analysis.

MATLAB features a family of application-specific solutions called toolboxes. Very important to most users of MATLAB, toolboxes allow you to learn and apply specialized technology. Toolboxes are comprehensive collections of MATLAB functions (M-files) that extend the MATLAB environment to solve particular classes of problems. Areas in which toolboxes are available include signal processing, control systems, neural networks, fuzzy logic, wavelets, simulation, and many others.

3.2.2.2 ITHINK (STELLA)

ITHINK 7.0 is an acronym for “System Think, Experimental Learning Laboratory, with Animation”. The ITHINK 7.0 software is designed to help people build understanding of dynamic systems and processes.

Causal Diagram

Stocks, Flows, Converters, and Connectors are the basic building blocks in ITHINK 7.0. These are the same as the blocks shown in **Table 3.1** and represented by icons depicted in **Figure 3.2**. Stocks or Levels variables represent accumulations and are represented by rectangles. Flows are rate of change variables that regulate the flow in and out of stocks. Flows are represented by a pipe through which the flow takes place. Attached to the pipe is a flow regulator or converter which contains the logic that determines the special flow volume. Converters can represent auxiliary variables, constant parameters, supplementary variables and table functions. They are represented by circles. Converters can represent either information or material quantities. The other basic building block is the connector. Connectors link stocks to converters and converters to other converters. Connectors do not take on numerical values, they represent inputs.

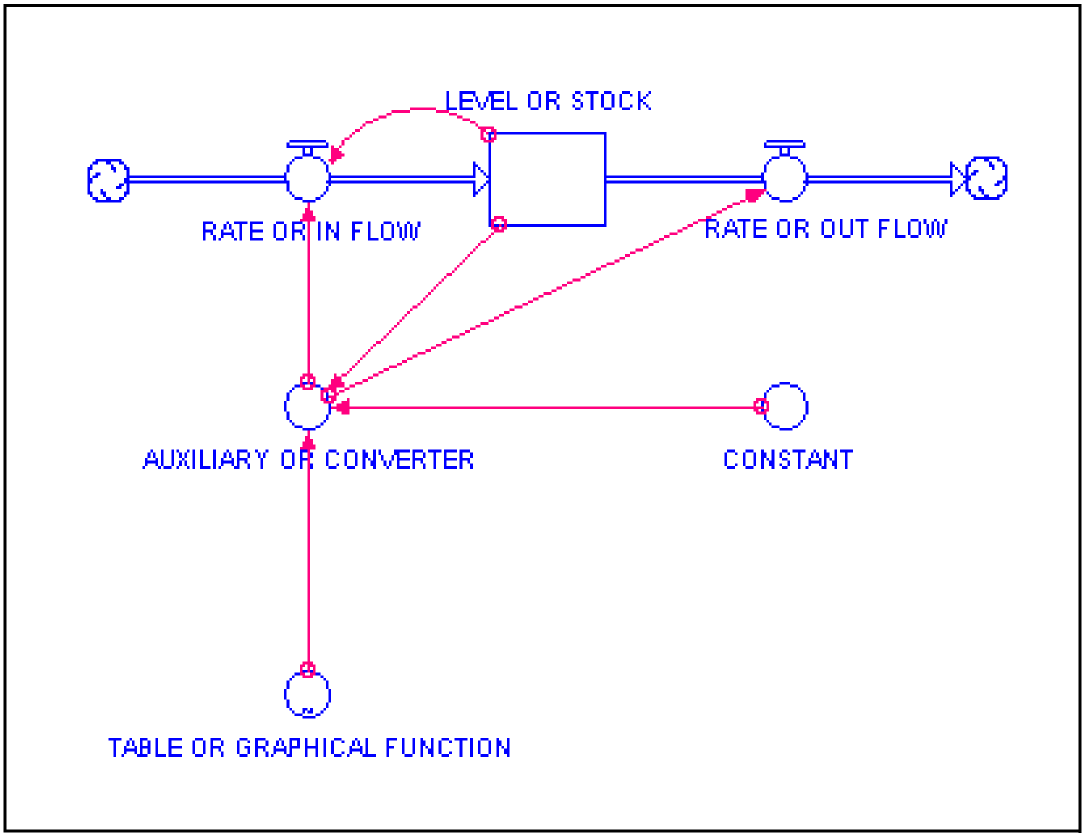


Figure 3.2 Basic Building Blocks in ITHINK 7.0.

Equations

Integration (or Accumulation) is the basis of the level and rate structure used in System Dynamics. A level variable $L(t)$ denotes the accumulation of some physical entity at time t. Let RI and RO represent two rate variables, rate-in (in flow) and rate-out (out flow), denoting the change in the level variable over the interval from t-1 to t. The relationship between the level $L(t)$ and the rate can be expressed mathematically by:

$$L(t) = L(t\text{-}1) + \int_{t-1}^{t} [RI(t)-RO(t)]dt \tag{3.1}$$

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,

$$L_i(t) = L_i(t\text{-}1) + (dt)\Sigma R_j(t) \quad i = 1,2,......m, j = 1,2,......n \tag{3.2}$$

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

$$R_j(t) = f[L_i(t), E_k(t), A_{ij}(t), A_{kj}(t)] \tag{3.3}$$

where E_k is the set 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 be found from the "level" equation. ITHINK 7.0 is a computer software which can integrate efficiently these finite difference equations.

CHAPTER 4 Air Traffic Flow Analysis

This chapter describes the development of an air traffic flow model in National Airspace System (NAS). Three sections related to air traffic flow modeling are discussed: 1) a brief description of the National Airspace System, 2) a description of Flight Operations including Segments and Phases of flight, and 3) an Air Traffic Flow Model. In the first section, the NAS is reviewed including the national airspace system structure, meteorological flight conditions, and flight support centers. The following section analyzes the phases of flight in departure, en-route, and arrival segments. A computer model - Air Traffic Flow Model (ATFM) is developed using ITHINK 7.0 software package and is described in the last section.

4.1 Description of the National Airspace System

The American National Airspace System (NAS) is the largest command, control, and computer system in the world. For the purpose in this research project the National Airspace System can be described in the following three sections:

- National Airspace System Structure
- Meteorological Flight Conditions in the NAS

- Air Traffic Control Support Centers

4.1.1 National Airspace System Structure

To enhance the safety and the efficiency of the air traffic control system, the FAA has divided the airspace above the United States into a number of different en-route traffic control centers and sectors discussed in Chapter 2. All the airspace above the United States is classified into one of two general categories: ***Uncontrolled and Controlled***. One of the primary differences between these two types of airspace is that air traffic control separation services are only offered to pilots operating in controlled airspace. Additional services can be offered to aircraft flying in uncontrolled airspace, but only on a workload permitting basis.

In the early of the twenty century, most of the airspace above the United States was designated as uncontrolled. Only the federal airways and the airspace around very busy airports were designated as controlled airspace. But as air traffic increased, and the technical capabilities of the FAA improved, additional segments of the nation's airspace have been designated as controlled airspace. Today the only uncontrolled airspace in the continental United States is below 1,200 feet above ground level (AGL). The following paragraphs provide a brief description of the regulations and procedures that pilots and controllers must comply with when operating in both controlled and uncontrolled airspace.

4.1.1.1 Uncontrolled Airspace

Uncontrolled airspace is that airspace in which Air Traffic Control (ATC) separation services will not be provided to any aircraft. This includes aircraft operating in Instrument Flight Rules (IFR) or Visual Flight Rules (VFR). The regulations for flight in uncontrolled airspace are quite specific and place the separation burden on the pilot. Most of the uncontrolled airspace in this country is located away from major airports below 1,200 feet AGL.

4.1.1.2 Controlled Airspace

In controlled airspace, the FAA offers both separation and additional ATC services including weather information to pilots. Depending on the type of flight and the category of airspace involved, the pilot may not be required to use these services or even to contact air traffic control facilities. Within controlled airspace, IFR flights are required to receive these services, but VFR flights may not be. In general, as long as VFR pilots can meet the weather minima outlined by the Federal Aviation Regulations Fart 91 and are not entering any special use airspace, no contact with ATC is required.

4.1.2 Meteorological Flight Conditions in the NAS

Weather systems are a critical issue in air transportation because weather phenomena account for 70 percent of the delays in the system. Flights in bad weather conditions require onboard instruments to warrant safety. When pilots fly in inclement weather, so-called Instrument Meteorological Conditions (IMC) or IFR exist. When the weather is good (e.g., more than 3 miles of visibility), Visual Meteorological Conditions (VMC) or VFR prevail.

Aircraft may operate under one of two sets of flight rules: VFR and IFR conditions. Under VFR conditions, the pilot is required to maintain minimum flight visibility conditions and minimum distances from clouds during all phases of flight. These minimums are given in the Federal Aviation Regulation (FAR). VMC implies conditions with observed visibility more than three miles and cloud ceiling more then 1,000 feet. IMC prevails when the visibility or cloud ceiling falls below those minima. The requirements for VFR and IFR operations also consider the airspace in which the aircraft is operating. For example, all VFR flights must occur below 18,000 feet. For the VFR pilot, ceiling and visibility information plays a major role in his ability to remain VFR and to perform safe flight operations during all phases of flight.

IFR conditions permit en-route operations in instrument meteorological conditions. During the approach phase of flight, a pre-defined altitude is reached at which the pilot must be able to make visual contact with the runway or abort the approach. For precision approaches, the minimum altitude is referred to as the decision height (DH), and for non-precision approaches, the minimum altitude is referred to as the minimum descent altitude (MDA). At the decision height, the pilot must be able to see the runway environment. The measure of visibility along the runway is termed the “runway visual range" (RVR). **Table 4.1** contains decision heights and RVR requirements for different approach to landing categories. Weather products, tailored to inform the pilot about visibility conditions before reaching the DH, reduce the number of missed approaches which may jeopardize the safety of the air space around an airport.

TABLE 4.1 Decision Heights and RVR Requirements for IFR Flights.

Landing Type	Decision heights, Feet (not less than)	Runway Visual Range, Feet (not less than)
CAT I	200	1,800
CAT II	100	1,150
CAT IIIA ('see to land')	100	660
CAT IIIB ('see to taxi')	50	160
CAT IIIC ('zero visibility')	0	0

4.1.2.1 Uncontrolled Airspace—IFR Flight

IFR flight may be legally conducted in uncontrolled airspace, although no ATC separation services can be provided by the FAA. A pilot flying in IFR conditions in uncontrolled airspace assumes the entire responsibility for air traffic separation and terrain avoidance. Properly qualified pilots may legally operate under IFR in uncontrolled airspace as long as they adhere to the applicable FARs. Pilots operating in uncontrolled airspace under IFR are not required to file a flight plan, nor will they receive a clearance or separation services from ATC. In fact, air traffic controllers are prohibited from issuing clearances or providing air traffic separations to IFR aircraft operating in uncontrolled airspace. Since controllers are not informed of every aircraft operating in uncontrolled airspace, it is impossible for them to provide separation to these aircraft. In general, pilots wishing to conduct IFR flight in uncontrolled airspace must comply with the following regulations:

- The pilot of the aircraft must be properly rated and the aircraft must be properly equipped for IFR flight as specified in FAR parts.

- The pilot is solely responsible for navigating and avoiding other IFR or VFR aircraft.
- The pilot is responsible for operating the aircraft a safe distance above the ground.
- The pilot is also responsible for getting weather information from various weather service centers.

Pilots operating IFR in uncontrolled airspace should maintain an altitude of at least 1,000 feet above any obstructions located within 5 statute miles of the course to be flown. This rule is not applicable to aircraft landing or taking off, during which it is the pilot's responsibility to operate the aircraft a safe distance above obstacles. In addition, during IFR flight in uncontrolled airspace, the pilot is required to fly at an altitude appropriate for the direction of flight **[FAR Part 91.121]**.

4.1.2.2 Uncontrolled Airspace—VFR Flights

VFR pilots operating in uncontrolled airspace must adhere to the applicable regulations contained in FAR Part 91.105. This regulation specifies the weather conditions that must exist for the pilot to legally operate VFR. The required weather conditions vary depending on the aircraft's cruising altitude and its actual altitude above the ground. To legally fly VFR in uncontrolled airspace, pilots must comply with the following minima **[FAR Part 91.105]** that are listed in **Table 4.2**.

TABLE 4.2 Weather Conditions Under VFR in Uncontrolled Airspace.

Cruising Altitude	Flight Visibility	Distance from Clouds
1,200 ft. or less above the surface, regardless of MSL altitude	1 statute mile	Clear of clouds
More than 1,200 ft. above the surface, but less than 10,000 ft. MSL	1 statute mile	500 ft. below 1,000 ft. above 2,000 ft. horizontal
More than 1,200 ft. above the surface and at or above 10,000 ft. MSL	5 statute mile	1,000 ft. below 1,000 ft. above 1 statute mile horizontal

VFR pilots operating in uncontrolled airspace are not required to file any type of flight plan or to contact any air traffic control facility (unless they are entering a designated area where contact is mandatory). It is the responsibility of VFR pilots to see and avoid any other aircraft that might be within their immediate vicinity, regardless of whether that aircraft is operating under IFR or VFR flight rules.

4.1.2.3 Controlled Airspace—IFR Flights

Within controlled airspace, air traffic controllers are required to separate IFR aircraft and participating VFR aircraft using the procedures specified in the Air Traffic Control Handbook **[FAA Technical Doc. 7110.65]**. Since nonparticipating aircraft may also be operating in controlled airspace, it remains the responsibility of participating pilots to see and avoid these aircraft, regardless of the services being provided by the air traffic controller.

Before beginning an IFR flight in controlled airspace, the pilot is required to file a flight plan with the FAA and receive a clearance from an ATC facility. A general aviation or corporate pilot usually files the IFR flight plan with a flight service station specialist, who forwards the information to the Air Route Traffic Control Center (ARTCC) with jurisdiction over the departure airport. Airline flight plans are normally filed directly with the ARTCC using stored flight plan information. A recent development in computer networking permits private weather-briefing corporations to directly file general aviation or corporate aircraft flight plans into the ARTCC computer.

If a pilot needs to file a flight plan while airborne, the ATC facility in contact with the pilot transmits the flight plan information to the proper ATC facility. The minimum required information that must be received from the pilot when filing a flight plan is specified in the Air Traffic Control Handbook. This includes the following information:

- The aircraft identification number. This is either the aircraft's assigned serial number, if it is a general aviation or corporate flight, or the airline name and flight number.
- The aircraft type and navigation equipment installed on the aircraft. The aircraft type is abbreviated, utilizing the codes found in the Air Traffic Control Handbook.

4.1.2.4 Controlled Airspace—VFR Flights

VFR pilots may fly in controlled airspace as long as they comply with the regulations included in FAR

Part 91. According to these regulations:

- VFR pilots must provide their own separation from other VFR and IFR aircraft and the terrain.
- VFR pilots are not required to file a flight plan or contact ATC unless they are planning to enter an area of special use airspace where contact is mandatory. VFR flight plans are voluntary and are only used by the FAA to assist in locating lost or overdue aircraft.

The weather conditions during flight must meet the criteria specified in FAR Part 91.105. VFR pilots must also maintain the minimum cloud distance stipulated in the FARs. The minimum visibility and distance from the clouds vary with the aircraft's cruising altitude. **Table 4.3** shows these requirements for VFR flight in controlled airspace.

TABLE 4.3 VFR Weather Conditions in Controlled Airspace.

Aircraft Cruising Altitude	Flight Visibility	Distance from Clouds
1,200 ft. or less above the surface, regardless of MSL altitude	3 statute miles	500 ft. below 1,000 ft. above 2,000 ft. horizontal
More than 1,200 ft. above the surface but less than 10,000 ft. MSL	3 statute miles	500 ft. below 1,000 ft. above 2,000 ft. horizontal
More than 1,200 feet above the surface and at or above 10,000 ft. MSL	5 statute miles	1,000 ft. below 1,000 ft. above 1 statute mile horizontal

These minima are designed to maximize the chances of a VFR pilot seeing and avoiding other VFR and IFR aircraft. If the pilot is unable to comply with these minima, a VFR flight cannot legally be conducted in controlled airspace. The pilot must then either land or receive an IFR or a special VFR clearance to legally continue the flight. Special VFR clearances permit VFR pilots to fly in certain weather conditions that do not meet minimum VFR criteria. VFR aircraft operating under special VFR clearances are provided with IFR separation.

4.1.3 Air Traffic Control Support Centers

The primary purpose of the ATC system is to prevent a collision between aircraft operating in the system and to organize and expedite the flow of traffic. In addition to its primary function, the ATC system has the capability to provide (with certain limitations) additional services. The ability to provide additional services is limited by many factors, such as the volume of traffic, frequency congestion, quality of radar, controller workload, higher priority duties, and the pure physical inability to scan and detect those situations that fall in this category. The FAA has developed and managed various air traffic control centers to support flight to takeoff, landing, and en-route operations. These centers also provide aviation weather services. **Figure 4.1** shows flights in the airspace system and various air traffic control centers.

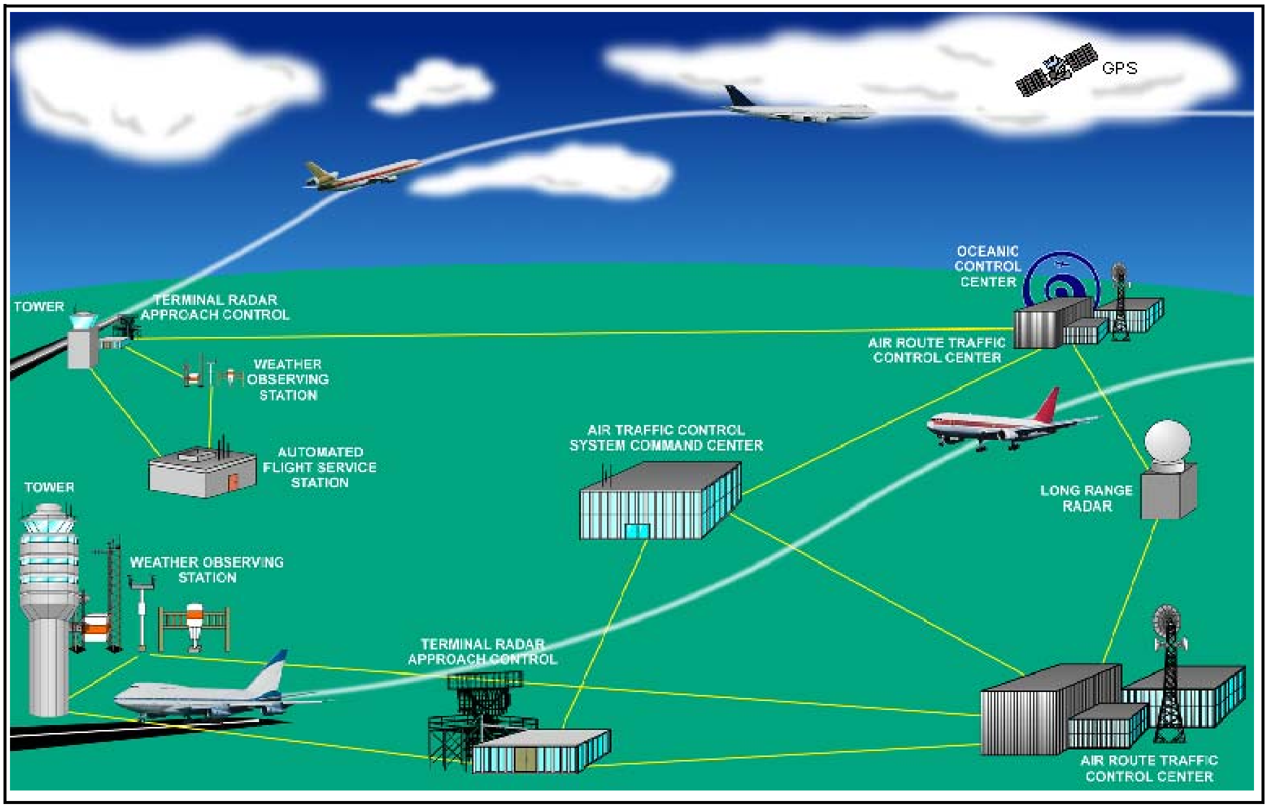


Figure 4.1 Air Traffic Control Centers in the USA (Photo obtained from the FAA[84])

In the United States, there is one Air Traffic Control System Command Center (ATCSCC), 20 Air Route Traffic Control Centers (ARTCC), 61 Automated Flight Service Stations (AFSS), 15 Flight Service Stations (FSS), 14 Alaskan Rotational flight Control Centers (RTCC), 485 Airport Traffic Control Towers (ATCT), 185 Terminal Radar Approach Control (TRACON) facilities, two Radar Approach Control (RAPCON) facilities, and three Combined Center/Radar Approach Control (CERAP) facilities **[NAS 5.0, 2002]**.

The following paragraphs briefly describe various air traffic control support centers.

4.1.3.1 Air Traffic Control System Command Center (ATCSCC)

The FAA's Air Traffic Control System Command Center (ATCSCC) office is located in Herndon, Virginia. The functions of the ATCSCC are to manage civil and military air traffic in the navigable airspace by developing and recommending national policies and establishing national programs, regulations, standards, and procedures for management of the airspace, operation of air navigation and communications systems and facilities, separation and control of, and flight assistance to air traffic. The ATCSCC has other functions:

- Provide for the security control of air traffic to meet the national defense requirements
- Develop and coordinate the U.S. policies, standards, and procedures related to international air traffic
- Operate the FAA national and international flight information and cartographic programs
- Excise operational control and technical direction of the air traffic control system and line authority to the day-to-day operations of the system.

The ATCSCC employs weather unit specialists who provide weather information update to aid local and national traffic management flow and safety.

4.1.3.2 Air Route Traffic Control Centers (ARTCC)

Air Route Traffic Control Centers (ARTCC) are critical information hubs for the NAS and have the responsibility of controlling the movement of en-route aircraft along the airways and jet routes and in other parts of the airspace. Each of the 20 ARTCCs within the continental United States has control of a definite geographical area which may be 100,000 mi^2 in size. At the boundary point, which marks the limits of the control area of the center, control of aircraft may be transferred to an adjacent center or an approach control facility, or radar service may be terminated and aircraft using VFR are free to contact the next center. Air route traffic control centers are not located at airports. Air route traffic control centers can also provide approach control service to non-towered airports and to non-terminal radar-approach control airports. The ARTCC is concerned primarily with the control of aircraft operating under IFR.

Under IFR pilots are required to file a flight plan indicating the route and altitude they desire to fly. The ARTCC will then check to determine whether the flight plan, as filed, can be approved so that a safe separation between aircraft can be ensured. Changes in flight plans en-route are permitted if approved by each ARTCC along the route of the flight.

Each ARTCC geographic area is divided into sectors. The configuration of each sector is based on an attempt to equate the workload of the controllers. Control of aircraft is passed from one sector to another. The geographic area is sectored in both the horizontal plane and the vertical plane. Thus there can be a high-altitude sector above one or more low-altitude sectors. Each sector is staffed by one or more controllers, depending on the volume and complexity of traffic. The average number of aircraft that each sector can handle depends on the number of people assigned to the sector, the complexity of traffic, and the degree of automation provided.

Each sector is normally provided with one or more air route surveillance radar (ARSR) units which cover the entire sector and allow for monitoring of the separation between aircraft. In addition, each sector has data on the identification of the aircraft, destination, flight plan route, estimated speed, and flight altitude, which are posted on pieces of paper called flight progress/strips or may be superimposed on the radarscope adjacent to the blips which specify the position and identity of the aircraft. The strips are continuously updated as the need arises.

At present, communications between the pilot and the controller is done via voice. Therefore each

ARTCC is assigned a number of very high and ultra high radio communication frequencies. The controller in turn assigns a specific frequency to the pilot.

A center weather service unit (CWSU), composed of both National Weather Service (NWS) meteorologists and FAA support personnel, is associated with each of the ARTCCs. The weather service units provide up-to-date weather information based on analysis of weather products obtained from a number of different sources.

4.1.3.3 Terminal Radar Approach Control Facility

The terminal approach control facility monitors the air traffic in the airspace surrounding airports with moderate to high-density traffic. It has jurisdiction in the control and separation of air traffic from the boundary area of the air traffic control tower at an airport to a distance of up to from the airport and to an altitude ranging up to 17,000 ft. This is commonly referred to as the terminal area. Where there are several airports in an urban area, one facility may control traffic to all the airports. In essence, the facility receives aircraft from the ARTCC and guides them to one of several airports. In providing this guidance, the facility performs the important function of metering and sequencing aircraft to provide uniform and orderly flow to airports.

The radar-approach control facility is referred to as TRACON, an abbreviation for Terminal Radar Approach Control. There are various degrees of automation in an approach control facility depending on the volume of traffic normally handled. Various abbreviations are used to designate the type of hardware in an approach control facility. As an example, ARTS III is an acronym for automated radar terminal system. The designation III denotes the highest level of automation, while I is the lowest level of automation. Thus one can have ARTS I, II, III automation capability in a TRACON facility. ARTS IIIA and ARTS HIE are updated enhancements of the ARTS III system capability to accommodate automation data.

The organizational structure of an approach control facility is very similar to that of the ARTCC. Like the ARTCC, the geographic area of the facility is divided into sectors to distribute the workload of the controllers. The approach control facility transfers control of an arriving aircraft to the airport control tower when the aircraft is lined up with the runway about 5 mi from the airport. Likewise control of departing aircraft is transferred to the approach control facility by the airport control tower.

If the flow of aircraft is greater than the capacity of the air traffic facility, traffic manager and command center manipulate aircraft on the ground and en-route to adjust, or meter, the arrival flows to their destination airports. This may result in delays to departing aircraft or delays en-route. In the past such aircraft were delayed by either reducing their speed en-route or detaining them at specified radio fixes within the area of the destination facility. The latter method is referred to as stacking- In a stack, aircraft navigate around a fix in a racetrack pattern, a holding pattern, and are separated vertically by 1000 ft. intervals. There may be as many as 10 aircraft in a stack, and each is directed in turn to a landing by the approach control facility. As a matter of procedure, stacking is no longer performed except when the arrival capacity at an airport is reduced due to unexpected events.

4.1.3.4 Airport Traffic Control Tower (ATCT)

The Airport Traffic Control Tower (ATCT) is the facility which supervises, directs, and monitors the arrival and departure traffic at the airport and in the immediate airspace within about 5 mi from the airport. The tower is responsible for issuing clearances to all departing aircraft; providing pilots with information on wind, temperature, barometric pressure, and operating conditions at the airport; and controlling all aircraft on the ground except in the maneuvering area immediately adjacent to the aircraft parking positions called the ramp area. There are more than 400 air traffic control towers and about half of air traffic control towers operated under contract to the FAA in the United States.

Weather information is provided to the tower from a number of sources. In turn, the tower serves as one potential source of weather information for arriving and departing aircraft. At some airports, an automated system is in place to provide up-to-date weather information to arriving and departing pilots. This automated system is termed the automatic terminal information service (ATIS). ATIS provides weather information as well as other pertinent information related to the airport’s operation.

4.1.3.5 Flight Service Stations (FSS)

Another component of the FAA weather information support system is the FAA Flight Service Stations (FSSs) and the Automated Flight Service Stations (AFSSs) which serve as the primary providers of flight information services throughout the U.S., AFSSs serve a broader area, usually an entire state, and are equipped with more advanced electronic services to allow for more efficient planning of weather and flight information. FSSs and AFSSs provide pilots with pre-flight weather briefings, flight planning assistance, weather and en-route flight information, and airport terminal advisory services.

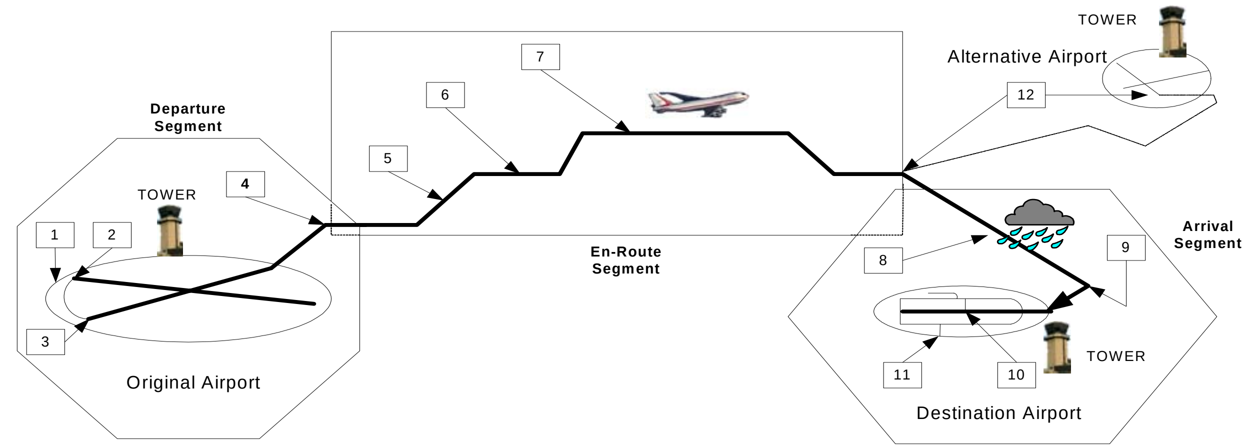
The FSSs are located along the airways and at airports. Flight service stations are not air traffic control facilities but provide essential information to pilots. Their principal function is to accept and close flight plans and to brief pilots, before flight and in flight, on weather, navigational aids, airports and navaids that are out of commission, and changes in procedures and new facilities. A secondary function is to relay traffic control messages between aircraft and the appropriate control facility on the ground. The FAA operated domestic and international flight service stations. Flight service stations are in the process of being converted to AFSS.

4.2 Flight Operation Analysis

As we know, a flight, take-offs from its original airport, cruises in the airspace, and landings to its destination airport, has many flight phases and segments and needs various information including weather information data at each phase. In this research, the totality of a flight operation is divided into three distinct segments - Departure Segment, En-route Segment, and Arrival Segment and twelve phases of flight including an alternative operation. Each segment includes several flight phases.

The departure segment comprises of four phases of flight, which are preflight planning and flight plan filing, preflight operations, taxi out and take off operations, and departure operations. The en-route segment follows the departure segment immediately, it includes three phases of flight, which are initial climb segment operations, initial cruise operations, and cruise operations. The final segment is arrival segment which consists of five phases of flight, they are approach operations, landing operations, taxi in and parking operations, post flight operations, and alternative operations if the destination airport can not accept the flight due to bad weather or other reasons like runway incidents etc.

Figure 4.2 illustrates graphically 12 phases of flight.



Phases of Flight		
Departure Segment	**En-Route Segment**	**Arrival Segment**
1. Preflight Planning, Flight Plan Filing	5. Initial Climb Segment Operations	8. Approach Operations
2. Preflight Operations	6. Initial Cruise Operations	9. Landing Operations
3. Taxi Out and Take Off Operations	7. Cruise Operations	10. Taxi In and Parking Operations
4. Departure Operations		11. Post Flight Operations
		12. Alternative Operations (if required)

Figure 4.2 Twelve Phases of Flight (Data obtained from the FAA[93]).

The time an aircraft spends in each phase of flight is a function of the flight plan (route and purpose of flight). In some cases, there may not be a clear boundary between when an aircraft transitions from one phase of flight to the next. The altitude at which the different phases of flight are performed is a function of the aircraft's and pilot's certification and the flight plan. The 12th phase of flight is included to illustrate the fact that certain conditions may require that an alternative airport be used for landing. In general, Phases 8 to 11 would need to be repeated when diverting to an alternative airport. Weather is an important piece of information collected by users (pilots, airlines, and ATC controllers) in each phase of flight. This information is an integral part of the analysis and is discussed in detail in the next Chapter. The following paragraphs are the analysis of the segments.

4.2.1 Departure Segment

The departure segment has four flight phases (Phases 1-4) including preflight planning and flight plan filing, preflight operations, taxi out and takeoff operations, and departure operations. The departure segment should not be the same as the fourth phase of flight termed "departure operations."

Based on the Airman's Information and before every flight, pilots familiarize themselves with all available information concerning that flight. Therefore, in preflight planning, pilots will collect the following data:

- Airport data - coordinates, elevation, frequencies, runway lengths, navaids, Fixed Base Operator (FBO) information.
- Navaid data - coordinates, names, idents, frequencies, variations and weather frequencies.
- Aircraft data - stored aircraft performance data.
- ATC airway/en-route structure data - airway layout, courses, distances, fix/intersection idents.
- Flight plan data - estimated en-route times, requested altitudes, alternate airports, departure times, weather information like forecast winds and temperatures aloft, headwind/tailwind component, alternate airport course-distance.
- Suggested routes - may not be current, accurate or apply to all types of aircraft.
- Area of coverage - **only the continental U.S.** selected airways and airports outside of the continental U.S. may be included in the database, however, they may not be current or accurate.

Pilots of personal and corporate aircraft usually contact a FSS by telephone (including FAST FILE), in person, or by radio to file a flight plan and receive weather briefings from 30 minutes to several hours before flight time.

Typically, 10 to 20 minutes before departure pilots will contact air traffic control at the departure airport. At that time, air traffic controllers will provide a clearance specifying the departure procedure and airspace route to be followed. Once air traffic controller has cleared the aircraft for flight and provided the flight with a departure plan, pilot will monitor engine start, check equipment, remove passengers' bridge, and contact ground controller who is responsible for issuing a taxi clearance. After power back or push back movement, pilot will take aircraft to taxi out from terminal gate to the departure end of the appropriate runway. After the aircraft has arrived to the runway, the ground controller must advise the local controller that the taxi out operation has been completed.

It is the local controller's responsibility to safely sequence departing aircraft into the local traffic flow. After receiving a clearance for takeoff from a local controller, pilot will take the aircraft to takeoff operation and into the departure area where is usually the shape of a wide fan or a narrow corridor. This wedge of airspace normally extends from the ground up to an altitude of 3,000 - 6,000 feet above the ground.

4.2.2 En-route Segment

The en-route segment is composed of initial climb segment operations, initial cruise operations, and cruise operations (Phases 5-7).

Once the local controller has instructed an aircraft to depart and resolved any conflicts with local traffic, the pilot is directed to contact the departure controller and changes to the departure controller's frequency. At the same time, pilot will continue to climb to the initial cruise operation. If the aircraft transits other sub-sectors within the terminal facility, it is the departure controller's responsibility to either hand off or point out the aircraft to the appropriate controllers. Such hand off is accomplished manually or through the use of automated procedures to an adjacent terminal facility. If the aircraft reaches sufficient high altitude, it is normally handed off to the appropriate ARTCC.

After initial cruise operation, pilot will operate the aircraft at cruise speed and contact the ARTCC. The en-route controllers will separate that aircraft from all others within sector.

4.2.3 Arrival Segment

When an aircraft flies near its destination airport, the pilot will descent the aircraft and enter the arrival segment. The arrival segment consists of approach operations, landing operations, taxi in and parking operations, postflight operations, and alternative operations (Phases 8-12).

The procedure of the aircraft approaching to the destination airport is similar to the departure segment but reversed, The aircraft passes from the last en-route center into a terminal center and finally to a tower facility prior to landing. Each successive controller begins to assign progressively lower altitudes to the aircraft. Pilot will land the aircraft to a runway, taxi on a taxiway, and connect to a passenger bridge. Pilot will do engine rundown and check log book.

During final approach, the required glide slope should be maintained; also, during this procedure, the aircraft follows the runway heading and cannot be vectored. The procedure is set so that the aircraft touches the ground approximately 300 meters form runway threshold.

4.3 Air Traffic Flow Model

Both analytical and computer models are critical tools to do research about the NAS. The reason is that if we wish to conduct tests or deploy new equipment or procedures, we cannot simply halt NAS operations. The NAS operates continuously. Nor can we simply plug in advanced prototype systems for testing during NAS operations. Models are easily justified for these and other reasons.

In order to quantify aircraft traffic flows over large regions of airspace a computer model - Air Traffic Flow Model (ATFM) has been developed. This model is based on the principles of Systems Dynamics (SD) and continuous simulation modeling to model aggregate traffic flows. ATFM uses the premise that aircraft inside a region of airspace (say an Air Route Traffic Control Center - ARTCC) can be in any one of twelve possible states (4 departures, 3 en-routes, and 5 arrivals described in the sequel). These states represent different phases of flight or idle conditions on the ground and each one has specific aviation weather information and communication requirements. The dwell time for each state has been derived from actual flow analyses using FAA Enhanced Traffic Management System (ETMS) data, BADA (Eurocontrol aircraft performance data), Official Airline Guide (OAG), Flight Information Display System (FIDS), Terminal Area Forecast (TAF), simulation case analysis, and observation data at several airports etc. The data used in the model are the representative of traffic flows inside ARTCC for the sake of discussion. However, the model can be tailored to represent any region of airspace desired with minor modifications to some model parameters. So far the model development of this prototype model has been carried out using ITHINK 7- a Systems Dynamics software package developed by High Performance Systems of Nashua, New Hampshire. The model equations using ITHINK nomenclature are presented in Appendix B.

4.3.1 Causal Diagram and Model Equation

4.3.1.1 Causal Diagram

A general causal diagram depicting the possible transition flights inside an ARTCC Center is shown in **Figure 4.3**. The diagram distinguishes between information flows (dashed arrows) and accumulation flows (solid arrows) to showcase fourteen aircraft states (boldfaced names) inside the volume of airspace of interest. Causal diagrams are standard techniques used in Systems Dynamics modeling **[Trani, 1988]**. The polarity of the causal relationships shown in the diagram represent the general trend of the slope relating two immediate variables. For example, the Inbound Aircraft Demand Function (IADF) “causes” an increase in the Number of Inbound Aircraft Entering Cruise Operation (NIAEC) and in the Number of Transient Aircraft Entering the Center Airspace (NTAECA). The left part of the figure describes inbound aircraft operations from entering the center cruise operations (NIAC), following approach operations (NIAA), landing operations (NIAL), taxi-in and parking operations (NIATIP), to post flight operations (NIAP) and aircraft idle condition (IAA). The right part shows outbound aircraft operations beginning preflight and flight plan filing (NOAPP), continue to preflight operations (NOAP), taxi-out and take off operations (NOATOTO), departure operations (NOAD), initial climb segment operations (NOAICS), initial cruise operations (NOAIC), and up to enter cruise operations (NOAC). The plus and minus signs represent air traffic flow changes - increase and decrease, respectively.

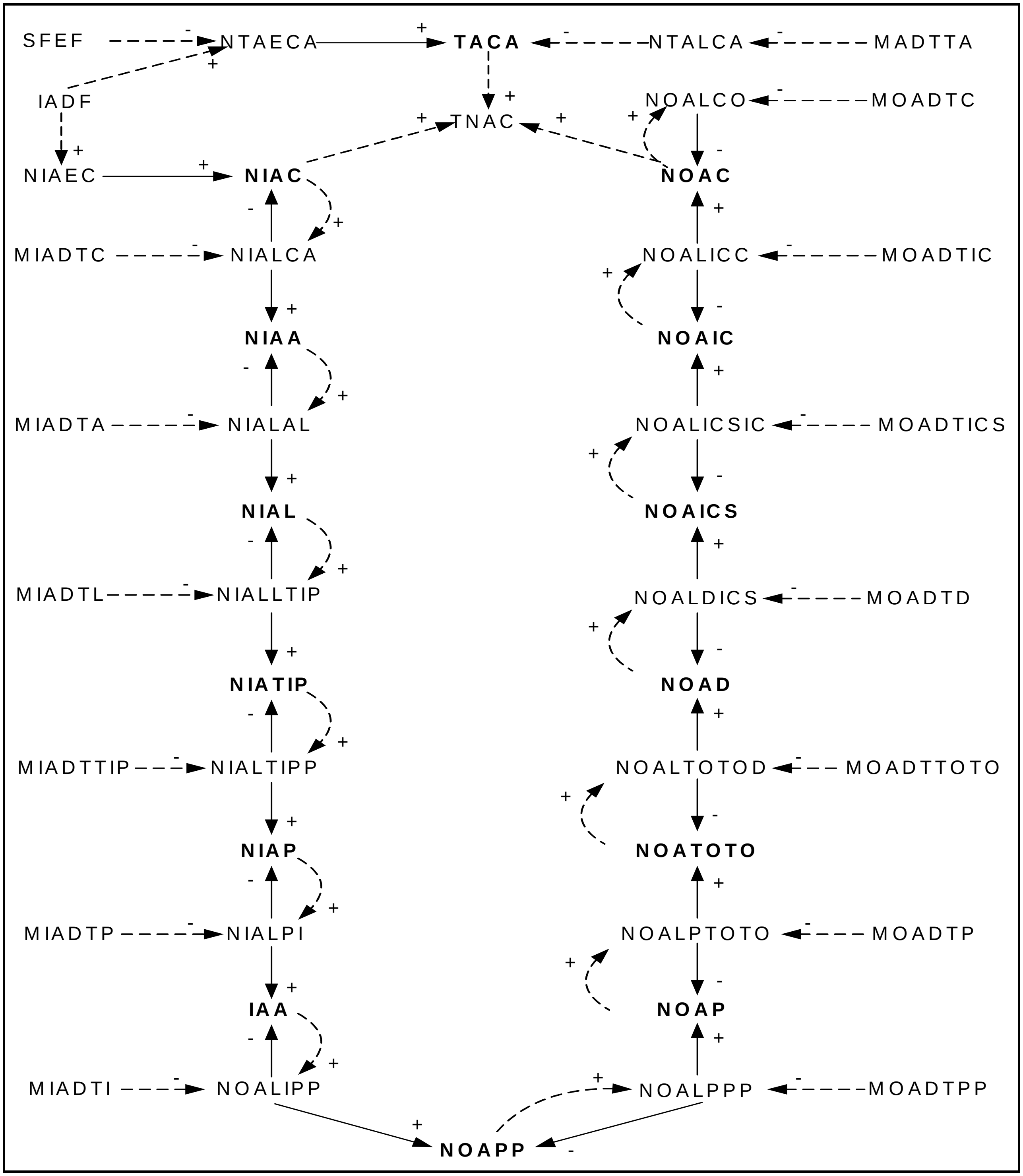


Figure 4.3 General Causal Diagram of Aircraft States Inside ARTCC Region.

The nomenclature used in this diagrams is explained in the following paragraphs as the equations of motion of the model are introduced.

4.3.1.2 Model Equation

The equations described here are used to four aircraft categories. Using the causal diagram as a starting point fourteen state variable equations were defined, Each stock variable requires an initial value. The following are the descriptions of the equations for each state variable in the system.

Transient Aircraft in the ARTCC Center Airspace, TACA

Transient Aircraft in the ARTCC center airspace (TACA) is a state variable representing the number of aircraft. The initial (INIT) values of the TACA for air carrier, air taxi/commuter, general aviation, and military aircraft categories will be assumed in Chapter 7, when the beginning of simulation is at midnight (0:00). TACA is dependent on the value of the TACA in previous time, Number of Transient Aircraft Entering the Center Airspace (NTAECA) rate, and Number of Transient Aircraft Leaving the Center Airspace (NTALCA) rate. Mathematically TACA is expressed as,

$$TACA_t = TACA_{t-1} + \int_{(t-1)}^{t} (TAECA_t - NTALCA_t)dt \tag{4.1}$$

Where:

TACA = Transient Aircraft in this Center Airspace (number)

NTAECA = Number of Transient Aircraft Entering the Center Airspace (aircraft per unit of time)

NTALCA = Number of Transient Aircraft Leaving the Center Airspace (aircraft per unit of time)

INIT TACA= Initial Values of TACA (number)

Number of Inbound Aircraft in Cruise Operation, NIAC

Number of Inbound Aircraft in Cruise Operation (NIAC) is a state variable representing the number of aircraft. The initial (INIT) values of the NIAC for air carrier, air taxi/commuter, general aviation, and military aircraft categories will be assumed in Chapter 7, when the beginning of simulation is at midnight (0:00). NIAC is dependent on the value of the NIAC in previous time, Number of Inbound

Aircraft Entering Cruise Operation (NIAEC) rate, and Number of Inbound Aircraft Leaving Cruise Operation to Approach Operation (NIALCA) rate. The equation of the NICA can be written as,

$$NIAC_t = NIAC_{t-1} + \int_{(t-1)}^{t} (NIAEC_t - NIALCA_t)dt \tag{4.2}$$

Where:

NIAC = Number of Inbound Aircraft in Cruise Operation (number)

NIAEC = Number of Inbound Aircraft Entering Cruise Operation (aircraft per unit of time)

NIALCA = Number of Inbound Aircraft Leaving Cruise Operation to Approach Operation (aircraft per unit of time)

INIT NICA = Initial Values of NICA (number)

Number of Inbound Aircraft in Approach Operation, NIAA

Number of Inbound Aircraft in Approach Operation (NIAA) is a state variable representing the number of aircraft. The initial (INIT) values of the NIAA for air carrier, air taxi/commuter, general aviation, and military aircraft categories will be assumed in Chapter 7, when the beginning of simulation is at midnight (0:00). NIAA is dependent on the value of the NIAA in previous time. The Number of Inbound Aircraft Leaving Cruise Operation to Approach Operation (NIALCA) rate, and Number of Inbound Aircraft Leaving Approach Operation to Landing Operation (NIALAL) rate. The NIAA can be expressed mathematically:

$$NIAA_t = NIAA_{t-1} + \int_{(t-1)}^{t} (NIALCA_t - NIALAL_t)dt \tag{4.3}$$

Where:

NIAA = Number of Inbound Aircraft in Approach Operation (number)

NIALCA = Number of Inbound Aircraft Leaving Cruise Operation to Approach Operation (aircraft per unit of time)

NIALAL = Number of Inbound Aircraft Leaving Approach Operation to Landing Operation (aircraft per unit of time)

INIT NIAA = Initial Values of NIAA (number)

Number of Inbound Aircraft in Landing Operation, NIAL

Number of Inbound Aircraft in Landing Operation (NIAL) is a state variable stating the number of aircraft. The initial (INIT) values of the NIAL for air carrier, air taxi/commuter, general aviation, and military aircraft categories will be assumed in Chapter 7, when the beginning of simulation is at midnight (0:00). NIAL is dependent on the value of the NIAL in previous time, Number of Inbound Aircraft Leaving Approach Operation to Landing Operation (NIALAL) rate, and Number of Inbound Aircraft Leaving Landing Operation to Taxi-In and Parking Operation (NIALLTIP) rate. The equation of the NIAL can be given mathematically:

$$NIAL_t = NIAL_{t-1} + \int_{(t-1)}^{t} (NIALAL_t - NIALLTIP_t)dt \tag{4.4}$$

Where:

NIAL = Number of Inbound Aircraft in Landing Operation (number)

NIALAL = Number of Inbound Aircraft Leaving Approach Operation to Landing Operation (aircraft per unit of time)

NIALLTIP = Number of Inbound Aircraft Leaving Landing Operation to Taxi-In and Parking Operation (aircraft per unit of time)

INIT NIAL = Initial Values of NIAL (number)

Number of Inbound Aircraft in Taxi-In and Parking Operation, NIATIP

The Number of Inbound Aircraft in Taxi-In and Parking Operation (NIATIP) is a state variable in number of aircraft. The initial (INIT) values of the NIATIP for air carrier, air taxi/commuter, general aviation, and military aircraft categories will be assumed in Chapter 7, when the beginning of simulation is at midnight (0:00). NIATIP is dependent on the value of the NIATIP in previous time, Number of Inbound Aircraft Leaving Landing Operation to Taxi-In and Parking Operation (NIALLTIP) rate, and

Number of Inbound Aircraft Leaving Taxi-In and Parking Operation to Post Flight Operation (NIALTIPP) rate. The equation of the NIATIP can be written as follow:

$$NIATIP_t = NIATIP_{t-1} + \int_{(t-1)}^{t} (NIALLTIP_t - NIALTIPP_t)dt \tag{4.5}$$

Where:

NIATIP = Number of Inbound Aircraft in Taxi-In and Parking Operation (number)

NIALLTIP = Number of Inbound Aircraft Leaving Landing Operation to Taxi-In and Parking Operation (aircraft per unit of time)

NIALTIPP = Number of Inbound Aircraft Leaving Taxi-In and Parking Operation to Post Flight Operation (aircraft per unit of time)

INIT NIATIP = Initial Values of NIATIP (number)

Number of Inbound Aircraft in Post Flight Operation, NIAP

The Number of Inbound Aircraft in Post Flight Operation (NIAP) is a state variable representing the number of aircraft. The initial (INIT) values of NIAP for air carrier, air taxi/commuter, general aviation, and military aircraft categories will be assumed in Chapter 7, when the beginning of simulation is at midnight (0:00). NIAP is dependent on the value of the NIAP in previous time, Number of Inbound Aircraft Leaving Taxi-In and Parking Operation to Post Flight Operation (NIALTIPP) rate, and Number of Inbound Aircraft Leaving Post Flight Opeation to Idle Aircraft at Airports (NIALPI) rate. The equation of the NIAP can be written as follow:

$$NIAP_t = NIAP_{t-1} + \int_{(t-1)}^{t} (NIALTIPP_t - NIALPI_t)dt \tag{4.6}$$

Where:

NIAP = Number of Inbound Aircraft in Post Flight Operation (number)

NIALTIPP = Number of Inbound Aircraft Leaving Taxi-In and Parking Operation to Post Flight Operation (aircraft per unit of time)

NIALPI = Number of Inbound Aircraft Leaving Post Flight Operation to Idle Aircraft at Airports (aircraft per unit of time)

INIT NIAP = Initial Values of NIAP (number)

Idle Aircraft at Airports, IAA

Idle Aircraft at Airports (IAA) is a state variable representing the number of aircraft. The initial (INIT) values of IAA for air carrier, air taxi/commuter, general aviation, and military aircraft categories will be assumed in Chapter 7, It is assumed that almost aircraft are parked at airport when the beginning of simulation is at midnight (0:00). IAA is dependent on the value of the IAA in previous time, Number of Inbound Aircraft Leaving Post Flight Operation to Idle Aircraft at Airports (NIALPI) rate, and Number of Leaving Idle Aircraft at Airports to Number of Outbound Aircraft in Preflight Planning and Flight Plan Filing Operation (NOALIPP) rate. The equation of the IAA can be written as follows:

$$IAA_t = IAA_{t-1} + \int_{(t-1)}^{t} (NIALPI_t - NOALIPP_t)dt \tag{4.7}$$

Where:

IAA = Idle Aircraft at Airports (number)

NIALPI = Number of Inbound Aircraft Leaving Post Flight Operation to Idle Aircraft at Airports (aircraft per unit of time)

NOALIPP = Number of Aircraft Leaving Idle Aircraft at Airport to Outbound Aircraft in Preflight Planning and Flight Plan Filing Operation (aircraft per unit of time)

INIT IAA = Initial Values of IAA (number)

Number of Outbound Aircraft in Preflight Planning and Flight Plan Filing Operation, NOAPP

The Number of Outbound Aircraft in Preflight Planning and Flight Plan Filing Operation (NOAPP) is a state variable representing the number of aircraft. The initial (INIT) values of NOAPP for air carrier, air taxi/commuter, general aviation, and military aircraft categories will be assumed in Chapter 7, when the beginning of simulation is at midnight (0:00). NOAPP is dependent on the value of the NOAPP in previous time, Number of Aircraft Leaving Idle Aircraft at Airports to Preflight Planning and Flight Plan Filing Operation (NOALIPP) rate, and Number of Outbound Aircraft Leaving Preflight Planning and Flight Plan Filing Operation to Preflight Operation (NOALPPP) rate. The equation of the NOAPP can be written as follow:

$$NOAPP_t = NOAPP_{t-1} + \int_{(t-1)}^{t} (NOALIPP_t - NOALPPP_t)dt \tag{4.8}$$

Where:

NOAPP = Number of Outbound Aircraft in Preflight Planning and Flight Plan Filing Operation (number)

NOALIPP = Number of Aircraft Leaving Idle Aircraft at Airports to Preflight Planning and Flight Plan Filing Operation (aircraft per unit of time)

NOALPPP = Number of Outbound Aircraft Leaving Preflight Planning and Flight Plan Filing Operation to Preflight Operation (aircraft per unit of time)

INIT NOAPP = Initial Values of NOAPP (number)

Number of Outbound Aircraft in Preflight Operation, NOAP

The Number of Outbound Aircraft in Preflight Operation (NOAP) is a state variable representing the number of aircraft. The initial (INIT) values of NOAP for air carrier, air taxi/commuter, general aviation, and military aircraft categories will be assumed in Chapter 7, when the beginning of simulation is at midnight (0:00). NOAP is dependent on the value of the NOAP in previous time, Number of Outbound Aircraft Leaving Preflight Planning and Flight Plan Filing Operation to Preflight Operation (NOALPPP) rate, and Number of Outbound Aircraft Leaving Preflight Operation to Taxi-Out and Take-Off Operation (NOALPTOTO) rate. The equation of the NOAP can be written as follow:

$$NOAP_t = NOAP_{t-1} + \int_{(t-1)}^{t} (NOALPPP_t - NOALPTOTO_t)dt \tag{4.9}$$

Where:

NOAP = Number of Outbound Aircraft in Preflight Operation (number)

NOALPPP = Number of Outbound Aircraft Leaving Preflight Planning and Flight Plan Filing Operation to Preflight Operation (aircraft per unit of time)

NOALPTOTO = Number of Outbound Aircraft Leaving Preflight Operation to Taxi-Out and Take-Off Operation (aircraft per unit of time)

INIT NOAP = Initial Values of NOAP (number)

Number of Outbound Aircraft in Taxi-Out and Take-Off Operation, NOATOTO

Number of Outbound Aircraft in Taxi-Out and Take-Off Operation (NOATOTO) is a state variable in number of aircraft. The initial (INIT) values of NOATOTO for air carrier, air taxi/commuter, general aviation, and military aircraft categories will be assumed in Chapter 7, when the beginning of simulation is at midnight (0:00). NOATOTO is dependent on the value of the NOATOTO in previous time, Number of Outbound Aircraft Leaving Preflight Operation to Taxi-Out and Take-Off Operation (NOALPTOTO) rate, and Number of Outbound Aircraft Leaving Taxi-Out and Take-Off Operation to Departure Operation (NOALTOTOD) rate. The equation of the NOATOTO can be written as follow:

$$NOATOTO_t = NOATOTO_{t-1} + \int_{(t-1)}^{t} (NOALPTOTO_t - NOALTOTOD_t)dt \qquad (4.10)$$

Where:

NOATOTO = Number of Outbound Aircraft in Taxi-Out and Take-Off Operation (number)

NOALPTOTO = Number of Outbound Aircraft Leaving Preflight Operation to Taxi-Out and Take-Off Operation (aircraft per unit of time)

NOALTOTOD = Number of Outbound Aircraft Leaving Taxi-Out and Take-Off Operation to Departure Operation (aircraft per unit of time)

INIT NOATOTO = Initial Values of NOATOTO (number)

Number of Outbound Aircraft in Departure Operation, NOAD

Number of Outbound Aircraft in Departure Operation (NOAD) is a state variable in number of aircraft. The initial (INIT) values of NOAD for air carrier, air taxi/commuter, general aviation, and military aircraft categories will be assumed in Chapter 7, when the beginning of simulation is at midnight (0:00). NOAD is dependent on the value of the NOAD in previous time, Number of Outbound Aircraft Leaving Taxi-Out and Take-Off Operation to Departure Operation (NOALTOTOD) rate, and Number of Outbound Aircraft Leaving Departure Operation to Initial Climb Segment Operation (NOALDICS) rate. The equation of the NOAD can be written as follow:

$$NOAD_t = NOAD_{t-1} + \int_{(t-1)}^{t} (NOALTOTOD_t - NOALDICS_t)dt \qquad (4.11)$$

Where:

NOAD = Number of Outbound Aircraft in Departure Operation (number)

NOALTOTOD = Number of Outbound Aircraft Leaving Taxi-Out and Take-Off Operation to Departure Operation (aircraft per unit of time)

NOALDICS = Number of Outbound Aircraft Leaving Departure Operation to Initial Climb Segment Operation (aircraft per unit of time)

INIT NOAD = Initial Values of NOAD (number)

Number of Outbound Aircraft in Initial Climb Segment Operation, NOAICS

Number of Outbound Aircraft in Initial Climb Segment Operation (NOAICS) is a state variable with the number of aircraft. The initial (INIT) values of NOAICS for air carrier, air taxi/commuter, general aviation, and military aircraft categories will be assumed in Chapter 7, when the beginning of simulation is at midnight (0:00). NOAICS is dependent on the value of the NOAICS in previous time, Number of Outbound Aircraft Leaving Departure Operation to Initial Climb Segment Operation (NOALDICS) rate, and Number of Outbound Aircraft Leaving Initial Climb Segment Operation to Initial Cruise Operation (NOALICSIC) rate. The equation of the NOAICS can be written as follow:

$$NOAICS_t = NOAICS_{t-1} + \int_{(t-1)}^{t} (NOALDICS_t - NOALICSIC_t)dt \qquad (4.12)$$

Where:

NOAICS = Number of Outbound Aircraft in Initial Climb Segment Operation (number)

NOALDICS = Number of Outbound Aircraft Leaving Departure Operation to Initial Climb Segment Operation (aircraft per unit of time)

NOALICSIC = Number of Outbound Aircraft Leaving Initial Climb Segment Operation to Initial Cruise Operation (aircraft per unit of time)

INIT NOAICS = Initial Values of NOAICS (number)

Number of Outbound Aircraft in Initial Cruise Operation, NOAIC

Number of Outbound Aircraft in Initial Cruise Operation (NOAIC) is a state variable representing the number of aircraft. The initial (INIT) values of NOAIC for air carrier, air taxi/commuter, general aviation, and military aircraft categories will be assumed in Chapter 7, when the beginning of simulation is at midnight (0:00). NOAIC is dependent on the value of the NOAIC in previous time, Number of Outbound Aircraft Leaving Initial Climb Segment Operation to Initial Cruise Operation (NOALICSIC) rate, and Number of Outbound Aircraft Leaving Initial Cruise Operation to Cruise Operation (NOALICC) rate. The equation of the NOAIC can be written as follow:

$$NOAIC_t = NOAIC_{t-1} + \int_{(t-1)}^{t} (NOALICSIC_t - NOALICC_t)dt \tag{4.13}$$

Where:

NOAIC = Number of Outbound Aircraft in Initial Cruise Operation (number)

NOALICSIC = Number of Outbound Aircraft Leaving Initial Climb Segment Operation to Initial Cruise Operation (aircraft per unit of time)

NOALICC = Number of Outbound Aircraft Leaving Initial Cruise Operation to Cruise Operation (aircraft per unit of time)

INIT NOAIC = Initial Values of NOAIC (number)

Number of Outbound Aircraft in Cruise Operation, NOAC

Number of Outbound Aircraft in Cruise Operation (NOAC) is a state variable in number of aircraft. The initial (INIT) values of NOAC for air carrier, air taxi/commuter, general aviation, and military aircraft categories will be assumed in Chapter 7, when the beginning of simulation is at midnight (0:00). NOAC is dependent on the value of the NOAC in previous time, Number of Outbound Aircraft Leaving Initial Cruise Operation to Cruise Operation (NOALICC) rate, and Number of Outbound Aircraft Leaving the Center to Other ARTCC Centers (NOALCO) rate. The equation of the NOAC can be written as follow:

$$NOAC_t = NOAC_{t-1} + \int_{(t-1)}^{t} (NOALICC_t - NOALCO_t)dt \tag{4.14}$$

Where:

NOAC = Number of Outbound Aircraft in Cruise Operation (number)

NOALICC = Number of Outbound Aircraft Leaving Initial Cruise Operation to Cruise Operation (aircraft per unit of time)

NOALCO = Number of Outbound Aircraft the Center to Other ARTCC centers (aircraft per unit of time)

INIT NOAC = Initial Values of NOAC (number)

Total Number of Aircraft in Cruise Operation, TNAC

The Total Number of Aircraft in Cruise Operation (TNAC) in the Atlanta ARTCC center is the sum of the Total Transient Aircraft Entering the center Airspace, the Number Inbound Aircraft in Cruise Operation, and the Number of Outbound Aircraft in Cruise Operation. The equation of the TNAC is expressed as follow:

$$TNAC_t = TAEA_t + NIAC_t + NOAC_t \tag{4.15}$$

Where:

TNAC = Total Number of Aircraft in Cruise Operation (number)

TAEA = Total Number Aircraft Entering the Enroute Center Airspace (number)

NIAC = Total Number of Inbound Aircraft in Cruise Operation (number)

NOAC = Total Number of Outbound Aircraft in Cruise Operation (number)

The rate variables in the model quantity rates of change that regulate the flow in and out of each state variable. The following section describes the rate variables in the model.

Number of Transient Aircraft Entering the Center Airspace, (NTAECA)

The Number of Transient Aircraft Entering the Center Airspace (NAECA) is a rate variable (aircraft per unit of time) and is dependent on the Inbound Air Demand Function (IADF) and the Scaling Factor for En-route Flight (SFEF), the mathematically, NAEEA can be given by:

$$NTAECA_t = IADF_t \times SFEF_t \tag{4.16}$$

Where:

NTAECA = Number of Transient Aircraft Entering this Center Airspace (aircraft per unit of time)

IADF = Inbound Air Demand Function

SFEF = Scaling Factor for En-route Flight

Number of Inbound Aircraft Entering Cruise Operation, NIAEC

The Number of Inbound Aircraft Entering Cruise Operation (NIAEC) is a rate variable (aircraft per unit of time) and is dependent on the Inbound Air Demand Function (IADF), and the Statistical Scaling Factor (SSF), and the Forecast Time Scaling Factor (FTSF). the mathematically, NIAEC can be given by:

$$NIAEC_t = IADF_t \times SSF_t \times FTSF_t \tag{4.17}$$

Where:

NIAEC = Number of Inbound Aircraft Entering En-route Airspace (aircraft per unit of time)

IADF = Inbound Air Demand Function

SSF = Statistical Scaling Factor

FTSF = Forecast Time Scaling Factor

Number of Inbound Aircraft Leaving Cruise Operation to Approach Operation, NIALCA

Number of Inbound Aircraft Leaving Cruise Operation to Approach Operation (NIALCA) is a rate variable (aircraft per unit of time) and is dependent on the state variable of Number of Inbound Aircraft in Cruise Operation (NIAC) and the Mean Inbound Aircraft Dwell Time in Cruise Operation (MIADTC), the mathematically, NIALCA can be given by:

$$NIALCA_t = (NIAC_t)/(MIADTC_t) \tag{4.18}$$

Where:

NIALCA = Number of Inbound Aircraft Leaving Cruise Operation to Approach Operation (aircraft per unit of time)

NIAC = Number of Inbound Aircraft in Cruise Operation (number)

MIADTC = Mean Inbound Aircraft Dwell Time in Cruise Operation (minute)

Number of Inbound Aircraft Leaving Approach Operation to Landing Operation, NIALAL

Number of Inbound Aircraft Leaving Approach Operation to Landing Operation (NIALAL) is a rate variable (aircraft per unit of time) and is dependent on the state variable of Number of Inbound Aircraft in Approach Operation (NIAA) and the Mean Inbound Aircraft Dwell Time in Approach Operation (MIADTA), the mathematically, NIALAL can be given by:

$$NIALAL_t = (NIAA_t)/(MIADTA_t) \tag{4.19}$$

Where:

NIALAL = Number of Inbound Aircraft Leaving Approach Operation to Landing Operation (aircraft per unit of time)

NIAA= Number of Inbound Aircraft in Approach Operation (number)

MIADTA = Mean Inbound Aircraft Dwell Time in Approach Operation (minute)

Number of Inbound Aircraft Leaving Landing Operation to Taxi-In and Parking Operation, NIALLTIP

Number of Inbound Aircraft Leaving Landing Operation to Taxi-In and Parking Operation (NIALLTIP) is a rate variable (aircraft per unit of time) and is dependent on the state variable of Number of Inbound Aircraft in Landing Operation (NIAL) and the Mean Inbound Aircraft Dwell Time in Landing Operation (MIADTL), the mathematically, NIALLTIP can be given by:

$$NIALLTIP_t = (NIAL_t)/(MIADTL_t) \tag{4.20}$$

Where:

NIALLTIP = Number of Inbound Aircraft Leaving Landing Operation to Taxi-In and Parking Operation (aircraft per unit of time)

NIAL= Number of Inbound Aircraft in Landing Operation (number)

MIADTL = Mean Inbound Aircraft Dwell Time in Landing Operation (minute)

Number of Inbound Aircraft Leaving Taxi-In and Parking Operation to Post Flight Operation, NIALTIPP

Number of Inbound Aircraft Leaving Taxi-In and Parking Operation to Post Flight Operation (NIALTIPP) is a rate variable (aircraft per unit of time) and is dependent on the state variable of Number of Inbound Aircraft in Taxi-In and Parking Operation (NIATIP) and the Mean Inbound Aircraft Dwell Time in Taxi-In and Parking Operation (MIADTTIP), the mathematically, NIALTIPP can be given by:

$$NIALTIPP_t = (NIATIP_t)/(MIADTTIP_t) \tag{4.21}$$

Where:

NIALTIPP = Number of Inbound Aircraft Leaving Taxi-In and Parking Operation to Post Flight Operation (aircraft per unit of time)

NIATIP= Number of Inbound Aircraft in Taxi-In and Parking Operation (number)

MIADTTIP = Mean Inbound Aircraft Dwell Time in Taxi-In and Parking Operation (minute)

Number of Inbound Aircraft Leaving Post Flight Operation to Idle Aircraft Condition, NIALPI

Number of Inbound Aircraft Leaving Post Flight Operation to Idle Aircraft Condition (NIALPI) is a rate variable (aircraft per unit of time) and is dependent on the state variable of Number of Inbound Aircraft in Post Flight Operation (NIAP) and the Mean Inbound Aircraft Dwell Time in Post Flight Operation (MIADTP), the mathematically, NIALPI can be given by:

$$NIALPI_t = (NIAP_t)/(MIADTP_t) \tag{4.22}$$

Where:

NIALPI = Number of Inbound Aircraft Leaving Post Flight Operation to Idle Aircraft Condition (aircraft per unit of time)

NIAP= Number of Inbound Aircraft in Post Flight Operation (number)

MIADTP = Mean Inbound Aircraft Dwell Time in Post Flight Operation (minute)

Number of Outbound Aircraft Leaving Idle Aircraft Condition to Preflight Planning and Flight Plan Filing Operation, NOALIPP

Number of Aircraft Leaving Idle Aircraft Condition to Preflight Planning and Flight Plan Filing Operation (NOALIPP) is a rate variable (aircraft per unit of time) and is dependent on the state variable of Number of Aircraft in Idle Aircraft Condition at the Airports (IAA) and the Mean Inbound Aircraft Dwell Time in Idle Aircraft Condition at the Airports (MIADTI), the mathematically, NIALIPP can be given by:

$$NOALIPP_t = (IAA_t)/(MIADTI_t) \tag{4.23}$$

Where:

NOALIPP = Number of Outbound Aircraft Leaving Idle Aircraft Condition to Preflight Planning and Flight Plan Filing Operation (aircraft per unit of time)

IAA = Number of Aircraft in Idle Aircraft Condition at the Airports (number)

MIADTI = Mean Inbound Aircraft Dwell Time in Idle Aircraft Condition at the Airports (minute)

Number of Outbound Aircraft Leaving Preflight Planning and Flight Plan Filing Operation to Preflight Operation, NOALPPP

Number of Outbound Aircraft Leaving Preflight Planning and Flight Plan Filing Operation to Preflight Operation (NOALPPP) is a rate variable (aircraft per unit of time) and is dependent on the state variable of Number of Outbound Aircraft in Preflight Planning and Flight Plan Filing Operation (NOAPP) and the Mean Outbound Aircraft Dwell Time in Preflight Planning and Flight Plan Filing Operation (MOADTPP), the mathematically, NOALPPP can be given by:

$$NOALPPP_t = (NOAPP_t)/(MOADTPP_t) \tag{4.24}$$

Where:

NOALPPP = Number of Outbound Aircraft Leaving Preflight Planning and Flight Plan Filing Operation to Preflight Operation (aircraft per unit of time)

NOAPP = Number of Outbound Aircraft in Preflight Planning and Flight Plan Filing Operation (number)

MOADTPP = Mean Outbound Aircraft Dwell Time in Preflight Planning and Flight Plan Filing Operation (minute)

Number of Outbound Aircraft Leaving Preflight Operation to Taxi-Out and Take-Off Operation, NOALPTOTO

Number of Outbound Aircraft Leaving Preflight Operation to Taxi-Out and Take-Off Operation (NOALPTOTO) is a rate variable (aircraft per unit of time) and is dependent on the state variable of Number of Outbound Aircraft in Preflight Operation (NOAP) and the Mean Outbound Aircraft Dwell Time in Preflight Operation (MOADTP), the mathematically, NOALPTOTO can be given by:

$$NOALPTOTO_t = (NOAP_t)/(MOADTP_t) \tag{4.25}$$

Where:

NOALPTOTO = Number of Outbound Aircraft Leaving Preflight Operation to Taxi-Out and Take-Off Operation (aircraft per unit of time)

NOAP = Number of Outbound Aircraft in Preflight Operation (number)

MOADTP = Mean Outbound Aircraft Dwell Time in Preflight Operation (minute)

Number of Outbound Aircraft Leaving Taxi-Out and Take-Off Operation to Departure Operation, NOALTOTOD

Number of Outbound Aircraft Leaving Taxi-Out and Take-Off Operation to Departure Operation (NOALTOTOD) is a rate variable (aircraft per unit of time) and is dependent on the state variable of Number of Outbound Aircraft in Taxi-Out and Take-Off Operation (NOATOTO) and the Mean Outbound Aircraft Dwell Time in Taxi-Out and Take-Off Operation (MOADTTOTO), the mathematically, NOALTOTOD can be given by:

$$NOALTOTOD_t = (NOATOTO_t)/(MOADTTOTO_t) \tag{4.26}$$

Where:

NOALTOTOD = Number of Outbound Aircraft Leaving Taxi-Out and Take-Off Operation to Departure Operation (aircraft per unit of time)

NOATOTO = Number of Outbound Aircraft in Taxi-Out and Take-Off Operation (number)

MOADTTOTO = Mean Outbound Aircraft Dwell Time in Taxi-Out and Take-Off Operation (minute)

Number of Outbound Aircraft Leaving Departure Operation to Initial Climb Segment Operation, NOALDICS

Number of Outbound Aircraft Leaving Departure Operation to Initial Climb Segment Operation (NOALDICS) is a rate variable (aircraft per unit of time) and is dependent on the state variable of Number of Outbound Aircraft in Departure Operation (NOAD) and the Mean Outbound Aircraft Dwell Time in Departure Operation (MOADTD), the mathematically, NOALDICS can be given by:

$$NOALDICS_t = (NOAD_t)/(MOADTD_t) \tag{4.27}$$

Where:

NOALDICS = Number of Outbound Aircraft Leaving Departure Operation to Initial Climb Segment Operation (aircraft per unit of time)

NOAD = Number of Outbound Aircraft in Departure Operation (number)

MOADTD = Mean Outbound Aircraft Dwell Time in Departure Operation (minute)

Number of Outbound Aircraft Leaving Initial Climb Segment Operation to Initial Cruise Operation, NOALICSIC

Number of Outbound Aircraft Leaving Initial Climb Segment Operation to Initial Cruise Operation (NOALICSIC) is a rate variable (aircraft per unit of time) and is dependent on the state variable of Number of Outbound Aircraft in Initial Climb Segment Operation (NOAICS) and the Mean Outbound Aircraft Dwell Time in Initial Climb Segment Operation (MOADTICS), Mathematically, NOALICSIC can be given by:

$$NOALICSIC_t = (NOAICS_t)/(MOADTICS_t) \tag{4.28}$$

Where:

NOALICSIC = Number of Outbound Aircraft Leaving Initial Climb Segment Operation to Initial Cruise Operation (aircraft per unit of time)

NOAICS = Number of Outbound Aircraft in Initial Climb Segment Operation (number)

MOADTICS = Mean Outbound Aircraft Dwell Time in Initial Climb Segment Operation (minute)

Number of Outbound Aircraft Leaving Initial Cruise Operation to Cruise Operation, NOALICC

Number of Outbound Aircraft Leaving Initial Cruise Operation to Cruise Operation (NOALICC) is a rate variable (aircraft per unit of time) and is dependent on the state variable of Number of Outbound Aircraft in Initial Cruise Operation (NOAIC) and the Mean Outbound Aircraft Dwell Time in Initial Cruise Operation (MOADTIC), the mathematically, NOALICC can be given by:

$$NOALICC_t = (NOAIC_t)/(MOADTIC_t) \tag{4.29}$$

Where:

NOALICC = Number of Outbound Aircraft Leaving Initial Cruise Operation to Cruise Operation (aircraft per unit of time)

NOAIC = Number of Outbound Aircraft in Initial Cruise Operation (number)

MOADTIC = Mean Outbound Aircraft Dwell Time in Initial Cruise Operation (minute)

Number of Outbound Aircraft Leaving the Center to Other Centers, NOALCO

Number of Outbound Aircraft Leaving the Center to Other Centers (NOALCO) is a rate variable (aircraft per unit of time) and is dependent on the state variable of Number of Outbound Aircraft in Cruise Operation (NOAC) and the Mean Outbound Aircraft Dwell Time in the center (MOADTC), the mathematically, NOALCO can be given by:

$$NOALCO_t = (NOAC_t)/(MOADTC_t) \tag{4.30}$$

Where:

NOALCO = Number of Outbound Aircraft Leaving the Center to Other Centers (aircraft per unit of time)

NOAC = Number of Outbound Aircraft in Cruise Operation (number)

MOADTC = Mean Outbound Aircraft Dwell Time in the Center (minute)

Number of Transient Aircraft Leaving the Center Airspace, NTALCA

Number of Transient Aircraft Leaving the Center Airspace (NTALCA) is a rate variable (aircraft per unit of time) and is dependent on the state variable of Transient Aircraft in the Center Airspace (TACA) and the Mean Aircraft Dwell Time for Transient Aircraft (MADTTA). Mathematically, NTALCA can be given by:

$$NTALCA_t = (TACA_t)/(MADTTA_t) \tag{4.31}$$

Where:

NTALCA = Number of Transient Aircraft Leaving the Center Airspace (aircraft per unit of time)

TACA = Transient Aircraft in this Center Airspace (number)

MADTTA = Mean Aircraft Dwell Time for Transient Aircraft (minute)

Other types variables such as auxiliary or converter variables can be expressed using mathematical function or graphics or a table function. The following are the some typical auxiliary or converter variables in the ATFM.

$$InboundDwellTimeApproach = NORMAL(MIADTA, 5) \tag{4.32}$$

Where:

InboundDwellTimeApproach = Inbound Aircraft Dwell Time in Approach Operation (minute)

NORMAL = Normal Distribution Function with Mean and Variance

MIADTA = Mean Inbound Aircraft Dwell Time in Approach Operations (minute)

Variance = 5

The following are the air traffic forecast factors that are expressed in graphic in the model.

Time_Scale_Factor = GRAPH(Year_of_Analysis)

(2005, 0.582), (2007, 0.648), (2009, 0.708), (2011, 0.774), (2014, 0.851), (2016, 0.923), (2018, 0.96), (2020, 1.00), (2023, 1.06), (2025, 1.09)

where: First numbers in each parenthesis are the year and second set of numbers are the forecast factor.

There are some constants that are used to indicate static variables, for example:

$$InitialAircraftatAirport = 537 \tag{4.33}$$

Where:

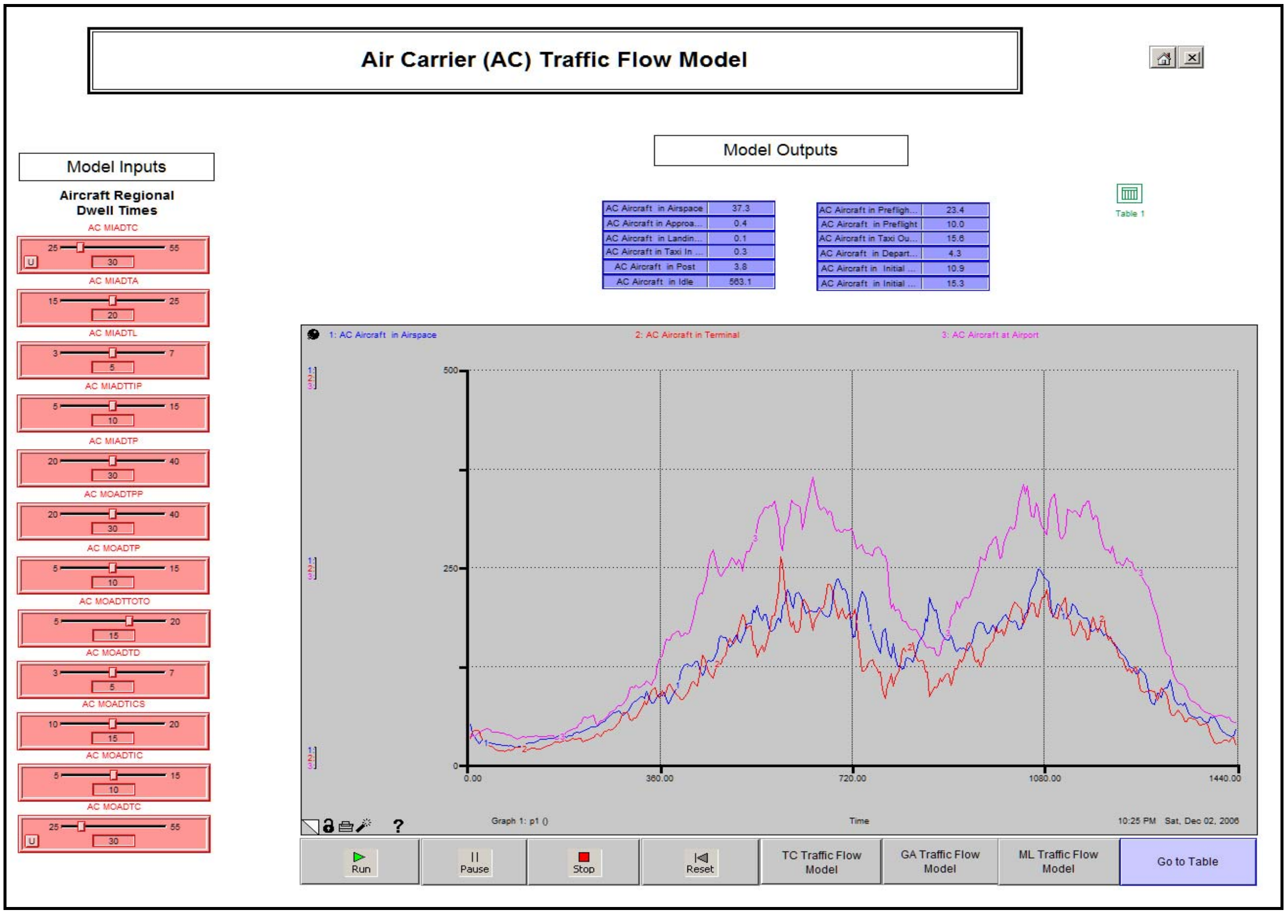
InitialAircraftatAirport = Initial Number of Aircraft at Airport (number)

The equations, variables, and constants discussed above are the typical variables in air traffic flow model. Each aircraft category has its own equations, graphics, and constants. All equations, variables, and constants for air carrier aircraft category in the ATFM are listed in Appendix B - ITHINK Source Code. The equations, variables, and constants for other aircraft categories are similar to the air carrier.

4.3.2 Air Traffic Flow Model Interface

To simplify the interaction between a user and the model a simple Graphic User Interface (GUI) was developed for the ATFM. GUIs are standard features in the modeling approach adopted in ITHINK, the simulation language used to prototype ATFM. **Figure 4.4** illustrates an example of the interface for air carrier traffic flow model.

There are three parts in the interface, which are the model input parameters, model output results, and control buttons. The model input parameters include the air carrier aircraft dwell time at each phase of flight, number of air carrier aircraft at the airports in the Atlanta ARTCC, air carrier inbound aircraft demand function, area size, and the forecast information etc. The users can change the size of input variables, add, or reduce the input parameters. The model output results consist of the numeric display bars, figures, and tables. The numeric display bars list the number of air carrier aircraft at each phase of flight at one time. The output figure graphically depicts the changes of the output variables over a 24-hour period. The users can add or reduce the output variables on the figures. The table lists the detail number of aircraft at each phase of flight in the airspace, in the terminal, and at the airport. The model control buttons such as run, pause, stop and so on can make user to manipulate the model after changing input or output variables or go to other models.



AC MIADTC	25	55	30
AC MIADTA	15	25	20
AC MIADTL	3	7	5
AC MIADTTIP	5	15	10
AC MIADTP	20	40	30
AC MOADTPP	20	40	30
AC MOADTP	5	15	10
AC MOADTTOTO	5	20	15
AC MOADTD	3	7	5
AC MOADTICS	10	20	15
AC MOADTIC	5	15	10
AC MOADTC	25	55	30

AC Aircraft in Airspace	37.3
AC Aircraft in Approa...	0.4
AC Aircraft in Landin...	0.1
AC Aircraft in Taxi In ...	0.3
AC Aircraft in Post	3.8
AC Aircraft in Idle	563.1

AC Aircraft in Prefligh...	23.4
AC Aircraft in Preflight	10.0
AC Aircraft in Taxi Ou...	15.6
AC Aircraft in Depart...	4.3
AC Aircraft in Initial ...	10.9
AC Aircraft in Initial ...	15.3

Figure 4.4 Air Carrier Traffic Flow Model Interface.

Three other similar model interfaces for air taxi/commuter, general aviation, and military aircraft categories are also developed and these have the same functions as the air carrier's interface.

ITHINK also can produce the causal diagram for various level, rate, auxiliary variables as well as constants. The causal diagram for air carrier aircraft category is depicted in **Figure 4.5**. The causal diagrams for air taxi and commuter, general aviation, and military aircraft categories are similar to the air carrier.

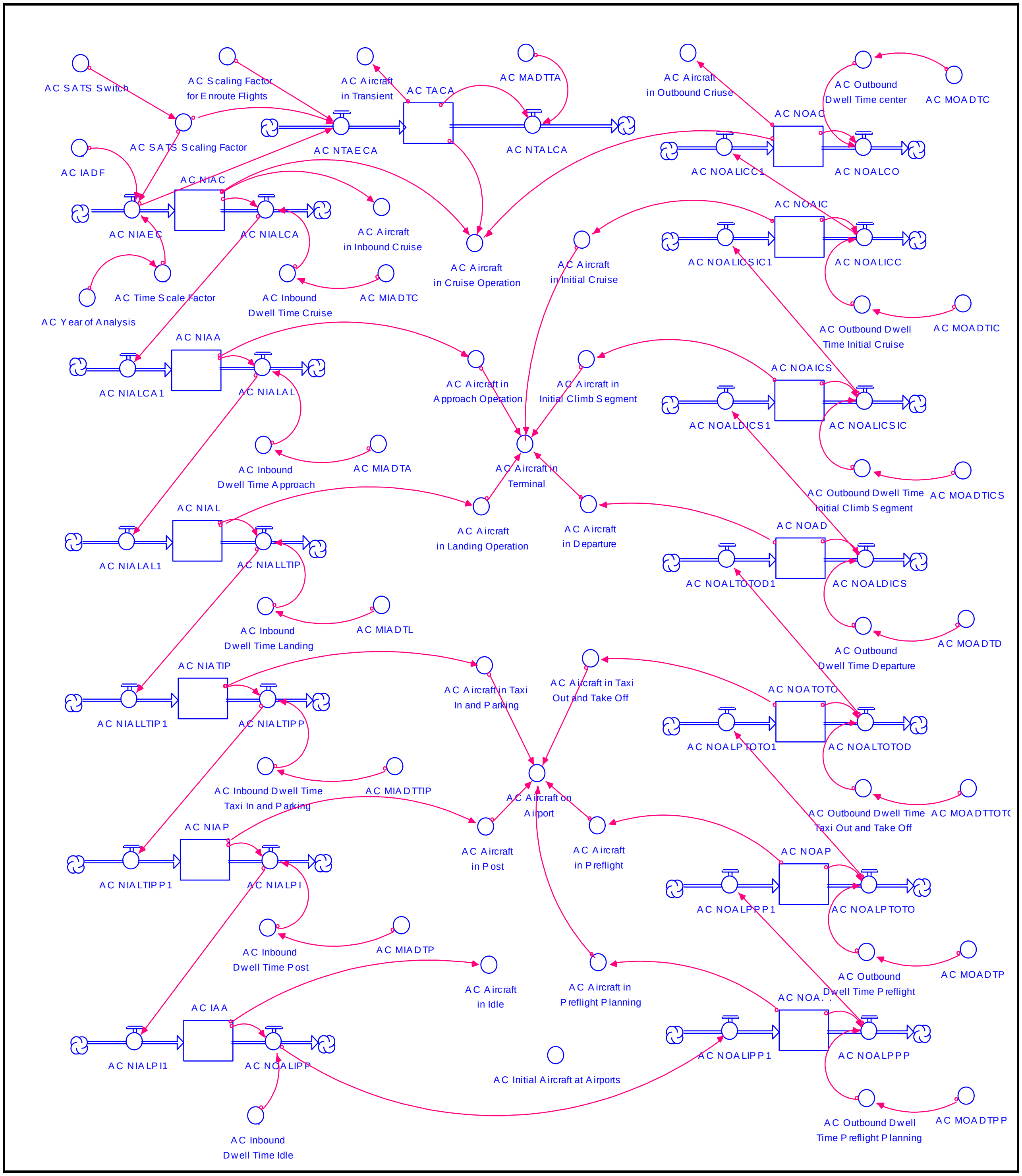


Figure 4.5 Air Carrier Traffic Flow Model Diagram.

Like the general causal diagram discussed in previous section, the left part of the causal diagram is the inbound air carrier traffic flow, the right part is the outbound air carrier traffic flow. The inbound flow describes air carrier aircraft cruise operations, approach operations, landing operations, taxi in and parking operations, post flight operations, and idle condition. The outbound flow shows air carrier aircraft preflight planning and flight plan filing, preflight operations, taxi out and take off operations, departure operations, initial climb segment operations, initial cruise operations, and into the airspace. The transient aircraft in cruise airspace is also included in cruise operations.

The equations for air carrier traffic flow are the same as the general equations discussed in previous section. The differential equations of level variables like the number of inbound air carrier aircraft in cruise operations (AC NIAC), the equations of rate variable such as the number of inbound air carrier aircraft leaving cruise to approach operations (AC NIALCA), and auxiliary variables, for example, the air carrier inbound air demand function (AC IADF) in the ATFM are listed in Appendix B - ITHINK Source Code.

CHAPTER 5

Aviation Weather Information, Products, and Requirements Analysis

In the previous chapter, Air Traffic Flow Model (ATFM) was developed, which can be used to estimated the air traffic flow volume inside an en-route air traffic control center. This chapter describes a companion simulation model - the Aviation Weather Information and Bandwidth Requirements Model (called AWINBRM) to study aviation weather systems, information flow, products, and bandwidth requirements in the NAS to support advanced weather applications in the flight deck. The following materials are covered in Chapter 5:

- Aviation Weather Phenomena
- Aviation Weather Domain Analysis
- Aviation Weather Information Requirements
- Aviation Weather Products
- Aviation Weather Sensors - Aircraft
- Aviation Weather Information and Bandwidth Requirement Model

5.1 Aviation Weather Phenomena

Aviation weather is a series of complex phenomena varying in size from small scale systems like tornados encompassing a few miles to large-scale systems such as hurricanes and winter storms spreading over few hundred or thousands of miles in the airspace. This section describes the fundamentals of weather phenomena and aviation weather systems that are relevant to our modeling task.

5.1.1 Fundamental of Weather Phenomena

This subsection provides a basic overview of weather phenomena, which includes the atmosphere, moisture, air masses, thunderstorms, gust fronts, down busts, wind, and icing which may pose a threat to aviation activities **[Keel, et al., 2000]**. Descriptions of these phenomena are important to put in aviation context as they drive requirements for advanced weather applications in the flight deck. In the end, such applications provide the basis in the development of the AWINBRM model.

5.1.1.1 The Atmosphere

The atmosphere near the earth is divided into three basic layers: the troposphere, the tropopause, and the stratosphere. The troposphere is the layer that extends between 25,000 to 30,000 feet at the poles and 55,000 to 65,000 feet at the equator.The difference of the troposphere altitude between the poles and the equator is because the temperature at the equator is higher than the poles. The troposphere is characterized by a general decrease in temperature with increasing altitude and contains the highest concentration of water vapor of the three layers. The tropopause extends above the troposphere and is characterized by a constant temperature versus elevation profile. The tropopause serves as a boundary layer trapping most of the moisture in the troposphere. The stratosphere exists above the tropopause and is characterized by an inversion in the temperature gradient. Above the stratosphere, the atmosphere has two other layers called mesosphere and ionosphere which are far from the earth. These are not important to aviation because they lie outside the reach of air breathing propulsion vehicles modeled in this research. **Figure 5.1** depicts graphically the atmosphere and its layers.

The earth's atmosphere is a complex system that is composed mostly of oxygen and nitrogen. Temperature around the globe varies as a function of altitude, season, latitude, topography, and time of day. Heating and cooling of the land and sea have a direct impact on the atmosphere. These changes in temperature directly affect atmospheric pressure. Atmospheric pressure is a measure of the weight of the atmosphere at a given altitude. Temperature and pressure differences are a major source of the complex system of winds observed around the globe. Differences in temperature drive circulatory motion (termed convection) as the warmer air ascends and the cool air descends. Pressure gradients result in the movement of air from high to low pressure. The spherical shape and rotation of the earth also plays a major role in the movement of winds as observed by the Coriolis forces [**Gleim, 1998**]. Topography also plays a major role in defining wind patterns. The heating and cooling of mountain surfaces causes temperature gradients between the air near the surface of the mountain and the surrounding air. The result is a flow of air along the mountain's face as the temperature gradients cause warm and cold air to rise and fall. Land and sea interfaces also produce winds because the land is warmer than the sea during the day and the reverse is true during the night. As will be seen, winds have a direct impact on the aerodynamic performance of an aircraft and can present a lethal hazard to aircraft under certain conditions.

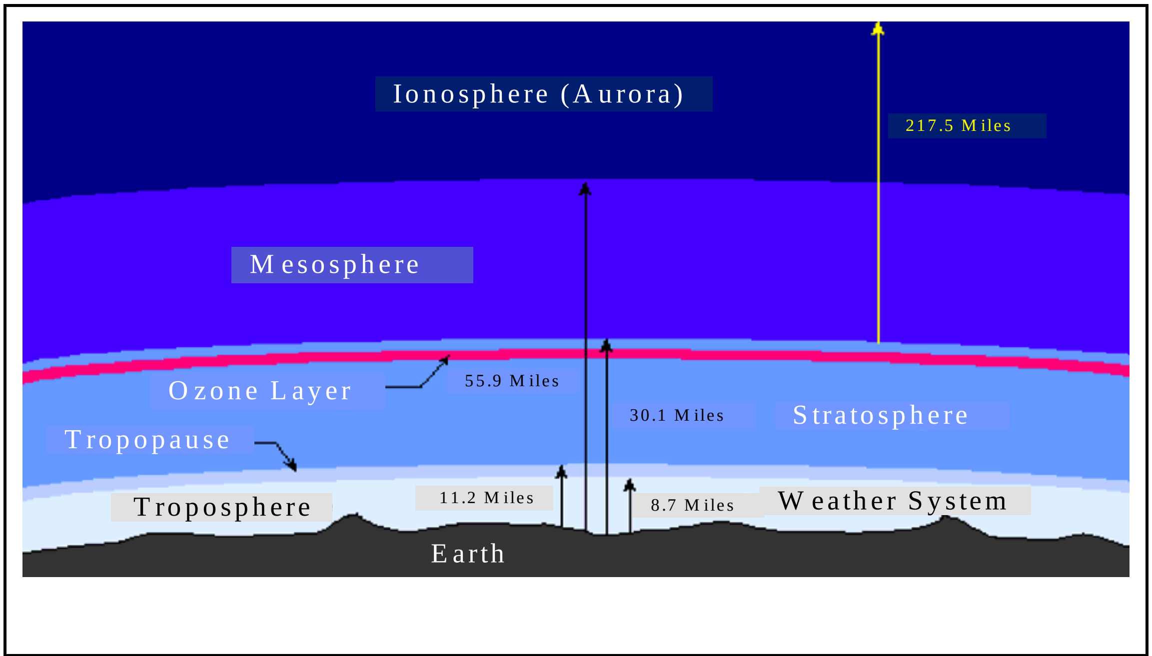


Figure 5.1 Atmosphere Systems

For aviation activity, the different aircraft types have been designed to fly at different altitudes based on the aircraft performance characteristics. **Table 5.1** contains general minimum and maximum cruise altitudes for different types of aircraft considered in the analysis. Note that the majority of commercial and general aviation cruise operations take place in the troposphere. Only supersonic aircraft can fly in the tropopause layer or low in the stratosphere layer.

TABLE 5.1 Minimum and Maximum Cruise Altitudes for Some Types of Aircraft.

Aircraft Type	Aircraft Category	Cruise Altitude (Minimum/Maximum), ft (mile).
Propeller-driven	General Aviation	2000 – 15,000 (0.38 – 2.84)
Subsonic airliners and transport aircraft (turbojet and turbofan engines)	Air Carrier Air Taxi/Commuter	20,000 – 40,000 (3.79 – 7.58)
Supersonic transport	Air Carrier, Military	60,000 – 70,000 (11.36 – 13.26)

Since the troposphere contains the highest concentration of the water vapor, the weather systems form, develop, and vanish in the troposphere layer. There are few very strong weather systems like strong thunderstorms may reach the tropopause layer. The importance of weather phenomena is that aviation activity is heavily influenced by weather. Seventy percent of the aviation delays in the NAS are attributed to weather.

5.1.1.2 Moisture

Water vapor exists in the atmosphere as a gas. Two variables are often used to characterize water vapor in the atmosphere: relative humidity and dew point. *Relative humidity* is defined as the ratio of the amount of water vapor currently in the atmosphere to the amount that would present if the atmosphere were saturated. *Dew point* is the temperature to which the air must be cooled in order for the current level of water vapor in the air to result in saturation. The current temperature and dew point spread near the surface of the earth are an indicator of the potential development of fog. Fog tends to result when the dew point is less than 3° C.

Precipitation requires condensation of water vapor on what are termed condensation nuclei (*e.g.*, small solids in the atmosphere). As the water vapor condenses, the nuclei grow, forming liquid or ice particles. In some cases, “super cooled” water droplets may exist between 0° C and –20° C [**Mahapatra, 1999**]. These super cooled water droplets are a major contributor to in-flight icing. Sublimation defines the direct conversion of water vapor (a gas) to ice (a solid) skipping the water phase entirely. Precipitation results when precipitants (*e.g.*, rain, snow, hail, sleet) are sufficiently heavy that the atmosphere can no longer support them. It should be noted that the precipitants are not stationary during this growth process. Horizontal and vertical winds carry the precipitants aloft, resulting in additional condensation, evaporation, freezing, and melting as the precipitants grow and shrink in size. Precipitation may occur at high altitudes but may never be observed on the ground due to evaporation as the precipitants descend through the atmosphere (*e.g.*, Virga).

5.1.1.3 Air Masses

Air masses are often termed stable or unstable. A stable air mass resists upward or downward displacement, whereas an unstable air mass may permit an upward or downward movement of air or both (*e.g.*, a convective process). The structure of clouds may be used by pilots to sense the presence of certain atmospheric phenomena. Layered or “stratiform clouds” are indicative of a stable air mass whereas unstable air masses exhibit cumuliform clouds that extend upward due to vertical air movement. The structure of clouds may also be an indicator of the presence of ice crystals, water and super cooled liquids, and convection. Pilots may use the structure of a cloud to interpret current atmospheric conditions in the local area.

The term “air mass” is used to describe a body of air that exhibits a fairly uniform temperature and moisture profile. The origins of air masses tend to be stationary or slowing moving air that acquires its properties by association with a particular geographic region (*e.g.*, polar regions or tropical oceans). Fronts define the boundaries between differing air masses. A cold front defines the leading edge of an advancing cold air mass as it overtakes warmer air. At low altitudes, the cold air replaces the warm air. A warm front defines the leading edge of an advancing warm air mass as it moves over the denser cold air. A stationary front is a stalemate between a cold and warm air mass where neither is replacing the other. Air masses may also be influenced by the geographic regions over which they move. A cold air mass moving over a warm region may experience instabilities as the warmer air, near the earth's surface, rises through the air mass. In addition, air masses may add or loss water vapor to due evaporation or precipitation as the air mass moves along. The weather associated with a front is a function of the moisture in the atmosphere and the stability of the air mass.

5.1.1.4 Thunderstorms

Thunderstorms are a primary source of weather-related aviation hazards. Thunderstorm life cycles are characterized by three stages: the cumulus stage, the mature stage, and the dissipating stage. The cumulus stage consists of cumulus clouds that are a result of convective processes. The clouds tend to extend less than a few miles across and have large vertical extents. These clouds may experience stronger convective forces as they pass over warmer regions. The stronger convective forces in combination with the cooler temperatures in the upper atmosphere result in the formation of both updrafts and downdrafts that coexist within the cell. The storm tops are generally between 25,000 feet and 40,000 feet and in extreme cases extend to 65,000 feet (above sea level). The storm top may take on a characteristic anvil shape due to the prevailing winds. Single cell thunderstorms are typically several miles across and have a life cycle between 20 minutes and 1.5 hours. The updrafts in a storm cell may reach 82 ft./s at heights of 25,000 feet. Storm cells may also move at speeds up to 164–230 ft./s in the upper atmosphere. Super cells are a class of severe thunderstorms that exhibit giant hail, strong surface winds, and strong updrafts and downdrafts. Super cells are also known to spawn tornadoes. Super cells may exist for up to 6 hours. A squall line is a linear arrangement of single storm cells that extend over hundreds of miles. Squall lines are associated with violent rain, hail, and strong winds.

All thunderstorms contain moderate turbulence and may also be the source of severe/extreme turbulence in a number of cases. Thunderstorms may also produce mesocyclones which exhibit a circular rotation over a large area. The rotation generally has little impact on aviation since the variation in wind speed changes slowly over a large region; however, mesocyclones are known to produce tornadoes. Tornadoes have an average diameter of 328 feet and typically travel less than 1.2 miles. Maximum wind speeds can reach 360–410 ft/s in extreme cases. Large amounts of rain are also accompanied with thunderstorms. The amount of precipitation varies with altitude with the heaviest amounts of precipitation found in the higher altitudes. Hail is also associated with most thunderstorms since the cells generally extend above the freezing level. Generally, hail size varies between less than 0.2 inches (shot size hail) to greater than 2.4 inches (tennis ball size hail). Hail is generally localized in what are termed hail shafts that may appear offset from the storm cell. The typical cross section of a hail shaft has an area of approximately 0.39 $mile^2$. Hail is most often encountered at altitudes between 10,000 and 25,000 feet. Hail stones have been found to be carried by updrafts and cross winds for distances up to 7.72 $mile^2$ from the center of the storm cell. Thunderstorms are also known to harbor supercold liquids which support icing conditions. In addition, thunderstorms produce electrical discharges known as lightning that are hazardous to aviation. Cloud to cloud and cloud to ground lightning strikes are good indicators of convective activity [**Mahapatra, 1999**]. Hail can result in severe aircraft damage or aircraft accidents depending on its size and intensity.

5.1.1.5 Gust Fronts

Gust fronts are thunderstorm related phenomena that are particularly hazardous to aircraft at low altitudes especially during landing and take-off procedures. Gust fronts are the leading edge of a divergent outflow near the earth’s surface that is generated by strong downdrafts within a thunderstorm. The cold denser air moves out away from the thunderstorm causing the surrounding warm air to rise above it. Gust fronts may move at speeds up to 80 ft/s. Large velocity gradients are observed as the airspeed changes by tens of feet per second over relatively short distances. High levels of turbulence also exist behind the gust front. Gust fronts are known to propagate significant distances. In some cases, gust fronts may be found several tens of miles away from the parent thunderstorm. One problem in detecting gust fronts is the fact that they may be characterized as “dry” or containing little precipitation. The low precipitation levels correspond to low reflective properties in the case of remote sensing.

5.1.1.6 Downbursts

Downbursts are strong downdrafts which cause a divergent flow of wind in all directions. The diverging winds represent a velocity gradient which may be hazardous to aircraft at low altitudes. Macro bursts are defined as downbursts whose maximum radial components of wind velocity are spaced by more than 2.5 miles. Microbursts exhibit a separation, between radial wind velocity maxima, that is less than 2.5 miles and exhibit a differential radial velocity maxima that exceeds 33 ft/s. Radial wind components in a micro burst may exceed 246 ft/s. The maximum wind speeds tend to occur at the lowest altitudes (< 100 feet above ground level (AGL)). This low altitude wind shear is hazardous to aircraft during take-off and landing. Microbursts can be characterized as either wet or dry depending upon the amount of precipitation they contain. For microbursts, the dimensions of the downburst are, on average, approximately 0.6 mile across at the outflow. The outflow tends to start less than 0.6 mi above the ground. Studies have shown that average lifetime for a microburst is approximately 13 minutes with maximum wind speeds lasting 2 to 5 minutes. The short life cycle, small dimension, low altitude, and potentially low reflective properties of the microburst combine to make it a difficult condition to predict and detect.

5.1.1.7 Wind

Wind motion may be characterized in a number of different ways. However, two terms are often used to describe wind motion that may be hazardous to aircraft: turbulence and wind shear. Turbulent air motion (*i.e.*, turbulence) is characterized by variations in wind speed over small spatial extents (*i.e.*, random motion). The term wind shear describes a more systematic variation of wind speed and direction in both spatial and temporal domains. Turbulence tends to excite the dynamics of the aircraft body, resulting in oscillations in the aircraft, which may induce a loss in performance and a bumpy and potentially hazardous ride for passengers. An example of wind shear is a variation in wind speed versus altitude. On landing, if the aircraft experiences head winds which then transition to strong tail winds as the aircraft descends through a shear layer, the aircraft may experience a loss in altitude and deviation from the intended flight path. Turbulence is associated with a number of atmospheric events including thunderstorms, mountain waves, wind shear layers (or boundaries), convection, and topographic features affecting wind flow. Clear air turbulence (CAT) is a term used to describe turbulence that is not associated with clouds or thunderstorms and generally takes place above 15,000 feet. Efforts are under way, under the FAA sponsored Product Development Teams and the Aviation Safety

Program, to develop sensor systems that may aid in the detection of CAT, but none are fielded at this time. Meteorologists do have the ability to forecast turbulence, but the forecasts tend to be issued for a generally large area even though the turbulence may only be present in a smaller sub-region of the forecasted area. Turbulence is characterized as either light, moderate, severe, or extreme. These categories of turbulence can be related to the vertical acceleration experienced by the aircraft. Aircraft should avoid areas of severe or extreme turbulence. Wind gusts are also a hazard to aircraft during landing and take-off and are characterized by a transitory burst of wind.

5.1.1.8 Icing

Icing is a major threat to aviation in that icing increases drag, reduces thrust, reduces lift, and increases the weight of the aircraft. Icing is also known to clog carburetors and pitot tubes. All clouds above the freezing level have the potential to exhibit icing conditions. Icing tends to occur more often in the presence of supercooled water droplets. As an aircraft moves through the supercooled liquids, the water droplets impact the wings of the aircraft and freeze almost instantaneously. There are many aircraft accidents related to icing. Icing is also an issue in the terminal area since icing may occur while an aircraft is waiting for taxi and take-off.

5.1.2 Categories of Weather Hazards

Weather, as described in the previous section, is a complex system driven by winds, temperature, pressure, and moisture. To try and enumerate or describe all of the atmospheric conditions that could eventually lead to a hazardous condition impacting flight safety is a monumental task. However, atmospheric events can be placed into categories based on their impact on aviation. This approach permits one to compartmentalize atmospheric events in a way that an analysis of weather information requirements may be handled.

In this dissertation, weather phenomena are grouped into eight categories that may contribute to hazardous conditions impacting flight safety. These categories extend the five categories proposed by Mahapatra. Mahapatra groups weather phenomena into the following categories: (1) “phenomena involving the physical motion of air," (2) "hydrometeorological phenomena," (3) "phenomena inducing and facilitating ice formation on aircraft surfaces," (4) "phenomena causing low visibility," and (5) "phenomena involving atmospheric electricity." [**Mahapatra, 1999**]. The eight categories of weather applied in this dissertation are: weather systems, air motion, icing, visibility/ceiling, precipitation, volcanic ash, wake vortices, and lightning. The following paragraphs give the detailed information of these weather categories.

5.1.2.1 Weather Systems

Since air masses and convective systems are the main source of the atmospheric hazards, a category, entitled "Weather Systems," is defined in the model. **Table 5.2** contains a list of some of the types of systems included in this category. Weather products that address these systems need to include information about their location, intensity, extent, movement, and life cycle. Specific atmospheric phenomena/conditions that are a product of these weather systems will be included in separate categories based on their impact on aviation.

TABLE 5.2 Weather Systems.

Weather Systems
Thunderstorms
Single Cells
Super Cells
Squall Lines
Snowstorm
Mesoclyclones
Tornadoes
Tropical Storms and Hurricanes
Low and High Pressure Systems
Warm, Cold, and Stationary Fronts

5.1.2.2 Air Motion

As noted in the previous section, air motion has a significant impact on aviation safety. **Table 5.3** represents the significant atmospheric phenomena that are included in the category “air motion.” This category is divided into two sub-categories: en-route airspace level phenomena and terminal region phenomena (including take-off and landing). The phenomena contained in the two sub-categories are not exclusive, but a distinction is made in order to address the differing requirements for the terminal and en-route phases of flight.

In the terminal region, microbursts and gust fronts are significant hazards at low altitudes. At en-route airspace level, clear air turbulence (CAT) is a significant hazard. Currently, the are no fielded systems to detect the presence of CAT with sufficient time for the pilot to react. Aircraft as a dynamic sensor would be a useful tool to detect the CAT in the future. This topic will be discussed in the late part of this chapter. Requirements developed in the later sections of the chapter will focus on a number of the air motion related hazards.

TABLE 5.3 Air Motion Phenomena.

Terminal Region	En-route Airspace Level
Microburst (wet and dry)	Clear Air Turbulence
Gust Fronts	Mountain Waves
Low Level Wind Shear (non-convective)	Convective Turbulence
Sustained Surface Winds	Strong Updrafts
Gusts	Strong Downdrafts
Low Level Turbulence (convective)	Strong Jet Stream
Low Level Jets/Nocturnal Jets	Frontal Shear
Land and Sea Breeze	Winds Aloft
Cross Winds	
Topographically Induced Winds	

5.1.2.3 Precipitation

Since precipitation may impact aircraft performance in a number of different ways, precipitation is assigned a separate weather hazard category. **Table 5.4** contains a list of the types of precipitation phenomena included in this category. Precipitation may impact visibility, but it may also result in other hazardous conditions that impact flight safety. For example, hail is a real threat to aircraft due to the high speeds at which hail impacts the surface of the aircraft during flight. For example, on May 7, 1998, a Douglas DC-9-32 aircraft, operated by Airtran Airlines, as flight 426 from Atlanta, Georgia to Chicago Illinois, encountered hail and turbulence near Calhoun, Georgia. The aircraft received substantial damage **[NTSB, 1998]**.

TABLE 5.4 Precipitation Types.

Precipitation Type
Rain
Freeze Rain
Snow
Ice
Hail
Sleet
Drizzle
Virga

5.1.2.4 Icing

As noted in the previous section, icing may occur near the surface or at altitudes above the freezing level. While in-flight, super cooled liquids are the major contributing factor to the formation of ice on aircraft surfaces. On the ground, precipitation and temperatures at or below 0°C, result in the formation of ice on the surfaces of aircraft. **Table 5.5** provides a summary of some of the factors that contribute to icing both in the terminal area (near or on the ground) and while in flight.

TABLE 5.5 Phenomena Contributing to the Ice on Aircraft Structures.

Terminal Region	En-route Airspace Level
Temperature	Super Cooled Liqids
Precipitation	Temperature/Freezing Level

5.1.2.5 Visibility and Ceiling

Visibility and ceiling conditions are important to pilots under both instrument flight rules (IFR) and visual flight rules (VFR). For the VFR pilot, visibility and ceiling minimums are required during all phases of flight whereas the IFR pilot is concerned with these conditions only in the terminal area during take-off and landing. **Table 5.6** contains a list of some of the atmospheric conditions that impact visibility and ceiling.

TABLE 5.6 Phenomena Contributing to Visibility/Ceiling Conditions.

Terminal Region	En-route Airspace Level
Low Level Clouds	Clouds Ceilings
Fog	Cloud Cover
Rain	Rain
Ice	Snow
Snow	Ice
Dust/Sand Storm	Volcanic Ash
Smoke/Pollution	
Runway Visual Range Conditions	

5.1.2.6 Other Categories

Three other categories in **Table 5.7** have been defined in this analysis: lightning, volcanic ash, and wake vortices. Lightning is an electrical discharge that is generally associated with thunderstorms. The metal surface of the aircraft serves as a conductor, which could result in electrical currents damaging sensitive aircraft components. Volcanic ash is the result of volcanic eruptions which spew large amounts of glass and acidic compounds into the atmosphere which can corrode the surface of aircraft and impact visibility. Wake vortices are “horizontal tornadoes” induced by airflow along the tips of the aircraft wings during take-off and landing. Smaller aircraft are at a particular risk to the effects of wake vortices. For example, American Airlines Flight 587 (Airbus 300-600) crashed in November 2001 in Belle Harbor, New York after the aircraft encountered wake turbulence, which is the second deadliest aviation accident in American history **[NTSB, 2001]**.

TABLE 5.7 Additional Weather Phenomena Impacting Aviation Safety.

Additional Categories
Lighting
Volcanic Ash
Wake Vortices

There are many weather systems in the airspace such as hurricane, tornado, and lighting. The Hurricane is a large scale weather phenomena associated with strong wind and heavy rain and impacts a regional area and causes air traffic delay in multiple states. The flights are difficult to pass, landing, and depart from the area the hurricane covered. Tornado is a small scale weather phenomena with impact on aviation flights due to the local nature of the phenomena. The lighting is dangerous weather phenomena to electronic equipment on board aircraft.

The eight categories of weather phenomena described will be used to define information requirements for each phase of flight in our model.

5.2 Aviation Weather Domain Analysis

The industry generally recognizes two kinds of airborne weather-related decisions, “tactical” and “strategic” **[Ball, et al., 2000]** which mean “now” and “near future”.

5.2.1 Tactical Decisions

“Tactical” decisions are essentially reactive flight trajectory decisions which need to be made quickly with whatever information is at hand. In the tactical environment the pilot tries to decide the safest way to negotiate an immediate weather hazard. For commercial carriers, pilots generally do not have the time or resources to coordinate these decisions with their dispatchers. On rare occasions they might not even coordinate with Air Traffic Control, invoking their emergency authority when extreme situations dictate. These tactical weather decisions are currently made on the basis of on-board sensors: what a pilot sees out the window, feels in the seat of his pants, hears on the radio, or views on the weather radar.

Tactical weather decisions are often safety related and time-critical, typically being forced when a pilot finds him or herself already in a potentially dangerous weather condition. Tactical decisions may include rapidly changing course to escape thunderstorms, wind shear, icing, or turbulence. Time is of the essence as a pilot negotiates a hazard s/he probably wished to avoid to begin with. An arbitrary, but convenient dividing line between “tactical” and “strategic” decisions might be at approximately fifteen minutes ahead of the aircraft’s present position, roughly corresponding to the useful range of on-board weather radar and human vision. **Figure 5.2** shows the weather related decision arenas.

5.2.2 Strategic Decisions

Strategic decisions, on the other hand, tend to be more pro-active, planning for avoidance rather than weather penetration. These decisions are characterized by the ability to identify a hazard early, collaborate on a plan to avoid it, and make relatively small, well-coordinated changes to the flight trajectory.

Strategic weather decisions are typically based on off-board sensor data, and information derived from that data. Pilot Reports (PIREPs), ARTCC advice, satellite imagery, updated forecasts, NEXRAD imagery, etc. are a few sources of the data and information that influence strategic decisions. In contrast to tactical decisions, the strategic decision arena begins beyond on-board sensor range and extends forward to the destination. In this arena, there is more time to collect new information, discuss it with dispatch, flight watch, and/or air traffic, plan a new course of action if needed, and implement that plan in a coordinated fashion.

Though tactical decisions can be critical, strategic decisions might be argued to be even more important. This is because a strong strategic decision process can avoid the need to face tactical decisions to begin with. In fact, this logic is at the core of the thrust to provide strategic weather information to the flight deck.

The strategic arena can be increasingly viewed in two segments, far-term and near-term which are represented in **Figure 5.2**. This is primarily due to new forecasting capabilities and resulting weather products which are beginning to appear. In the near-term segment, these “nowcasts” are short-range forecasts targeted to provide accurate information of greater fidelity than formerly available for up to the next 60 minutes. For the purposes of this discussion, a “nowcast” can be considered to be an automatically generated, computer-produced product, synthesized from multiple sensors. The following sections describe aviation services that relate to these two segments.

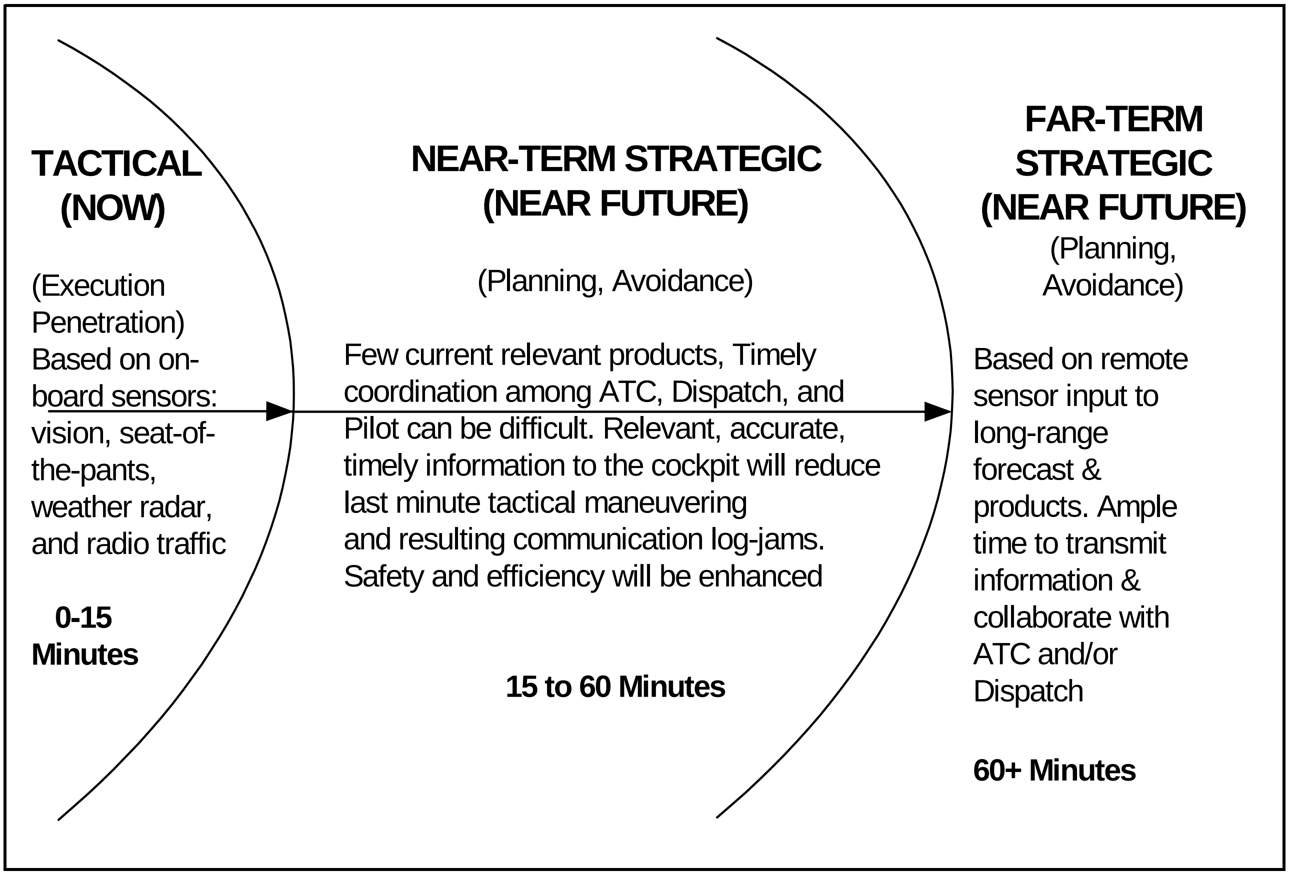


Figure 5.2 Three Weather-Related Decision Arenas.

5.2.2.1 Far-term Strategic

Generally speaking, we currently have minimally adequate data and information to make *far-term* strategic weather decisions in today's commercial and military aviation environments. The extensive ground network designed to flight-follow these aircraft has time and resources dedicated to aid in making far-term strategic weather decisions which are based on long-range forecasts of sometimes volatile weather conditions. The resulting forecasts are understandably not precisely accurate, and therefore often serve as a warning, alerting a pilot that a future decision will have to be made at the appropriate time and location. Cockpit graphical information (if available) greatly enhances a pilot's ability to visualize and avoid these upcoming hazardous situations. Moreover, on-board graphics in any arena will reduce already congested voice radio traffic, especially in the vicinity of bad weather conditions.

The general and business aviation communities, on the other hand, do not always have a similar ground network in place and will benefit even more dramatically from *far-term* strategic graphical weather in the cockpit. Though they, too, can gather textual and/or audio information, it is not nearly as compelling or complete as a picture. Aviation statistics strongly imply that strategic graphical information in GA cockpits will be a compelling force to reduce weather-related accidents. Today satellite services like XM and other provide weather information to GA and corporate aviation with handled devices such as GARMIN 396 and 1000 models.

5.2.2.2 Near-term Strategic

This is perhaps the most promising arena for graphical weather in the cockpit. Its time boundary lies between 15 minutes and 60 minutes ahead of the airplane's current position. This is the time frame when avoidance planning is reaching a crescendo. Pilots request and receive advice from ARTCC controllers while the controllers request and receive PIREPs. At the same time, pilots are also often overwhelming dispatch or flight watch radio frequencies in a search for even more information. In the cockpit, pilots are doing their best to filter the resulting cascade of verbal information and construct a meaningful "picture" in their heads while not missing any flight-critical directions or data. If successful, a pilot can make a relatively small change in planned flight path and avoid an upcoming hazard, altogether.

In this *near-term* strategic arena, there is still time to make strategic avoidance decisions at this stage, the weather hazard in question is becoming mature and predictable enough to base a concrete decision on with a good degree of accuracy. Unfortunately, up to the present, almost no meaningful near-term weather hazard information is easily available to the flight deck, and certainly not in graphical form.

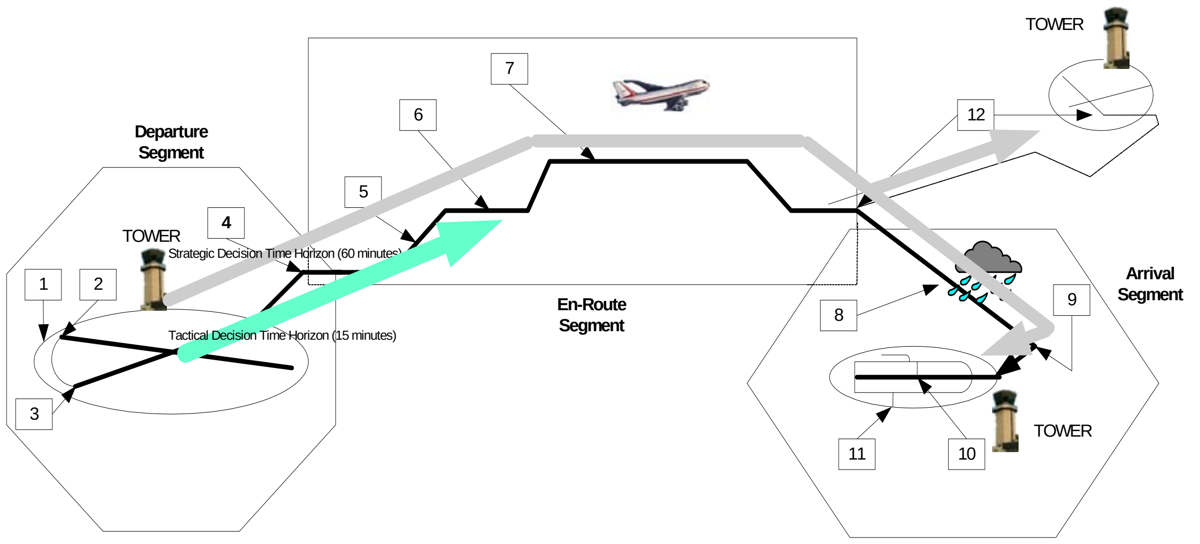
Current weather research promises to fundamentally alter the near-term strategic arena. Improved “nowcasts” promise to help pilots make earlier, smarter, safer decisions in the immediate future: 15 to 60 minutes ahead of the aircraft. As a result, much of the last minute, relatively high-threat tactical maneuvering, and resulting radio traffic, can be avoided in the immediate vicinity of a major “hazard,” such as a rapidly building line of thunderstorms.

With the advent of accurate nowcasts available to the flight deck in graphic form, the *near-term* strategic arena is likely to afford maximum safety and economic benefits. **Figure 5.3** the shows weather domains associated with each phase of flight and the process flow for weather products usage.

This research will seek to define both tactical and strategic weather information requirements to support the goals of the aviation safety program. The description of the various phases of flight includes a concept for near term decision making in the cockpit based the assumptions that 15 minutes is sufficient lead time to respond to most weather hazards. The 15 minute tactical and 60 minute strategic criteria will be applied in this research. These criteria will be used to time step through a representative flight scenario and to ask questions about weather information requirements in the presence of atmospheric hazards encountered in the various phases of flight.

5.3 Aviation Weather Information Requirements

This section seeks to consolidate aviation weather information requirements at each phase of a flight. In reviewing the weather information needs of the aviation community, it was seen that the different Federal Aviation Regulation (FAR) categories (*e.g.*, Parts 121, 135, and 91) require similar weather information to perform safe flight operations. The term “requirements” in this research should be viewed from the standpoint of improving flight safety and should not be viewed as a FAR or regulatory requirement.



Phases of Flight	
1. Preflight Planning, Flight Plan Filing	7. Cruise Operations
2. Preflight operations	8. Approach Operations
3. Taxi Out and Take Off Operations	9. Landing Operations
4. Departure Operations	10. Taxi In and Parking Operations
5. Initial Climb Segment Operations	11. Post Flight Operations
6. Initial Cruise Operations	12. Alternative Operations (if required)

Gereric Process Flow Weather Product Usage	
Weather Source (Sensor/Observer)	Weather Radar, Observer, Pilot, Autodata acquisition
Weather Data	Velocity, Direction, Rate, Height
Weather Information	Ceiling, Visibility, Hazard
Weather Product	TAF, METAR, SIGMET
Weather Dissemination	FSS, ATIS, ACARS
Weather User	Pilot, Dispatch, ATC

Figure 5.3 Flight Phases and Weather Domain (Data obtained from the FAA[93]).

For general consideration of aviation weather information requirement the phases of flight have been combined into ten groups as follows:

1. Preflight Planning, Flight Plan Filing, and Preflight
2. Taxi Out
3. Take Off
4. Departure
5. Initial Climb, Initial Cruise, and Cruise
6. Approach
7. Landing
8. Taxi In and Parking

9. Post Flight
10. Alternative

The aviation weather information requirements at each flight phase are listed in **Table 5.8**. The flights need both surface and aloft weather information except in the of taxi-out, taxi-in, parking, and post flight operations. More surface and aloft weather information are needed in the phases of preflight planning, flight plan filing, and preflight operations.

More detail aviation weather information requirements at each flight phase are described in the following paragraphs **[Keel, et al., 2000]**:

5.3.1 Preflight Planning and Flight Plan Filing

Before getting in an aircraft pilot must do preflight planning, flight plan filing, and preflight operations which involve the collection and assessment of current and forecasted weather conditions at the departure, destination, and alternative airports and along the intended route. This assessment is initially performed to determine if the trip is feasible. The assessment is made by first examining the weather's history over the area encompassing the intended flight. Usually, an assessment of significant weather for the past 3 hours is needed over an area encompassing 150 nautical miles on either side of the route. This assessment should be validated by comparing forecasted information with observed weather reports to identify discrepancies in the forecasted data. This is intended to provide some level of confidence or validity to the forecast data which will be used during the planning stages. As needed, pilot may also talk with weather personnel (e.g., Flight Service Station) to make sure all question issues in a forecast are understood. **Table 5.9** contains the required weather information mapped by flight segment. These include issues in a forecast are understood the departure segment (D), the en-route air

TABLE 5.8 Aviation Weather Information Requirements.

Flight Phase	Surface Weather Information Required	Aloft Weather Information Required
Preflight Planning Flight Plan Filing Preflight	• Summary statement of current and forecast-surface conditions along route • Time phased terminal forecasts along route • Comparisons of terminal forecasts and surface • Observations along route for last 3 hours • Location of acceptable alternate airport	• Summary statement of current and forecast aloft weather conditions along route • Time phased area forecasts along route • Comparison of area forecasts and aloft observations along route for last 3 hours
Taxi-Out	• Current taxiway and runup area conditions and icing area	
Take-Off	• Current runway surface conditions	• Hazardous weather elements aloft in departure terminal area updated since preflight briefing
Departure	• Current surface conditions at departure terminal area airports	• Hazardous weather elements aloft in departure terminal area updated since take-off
Initial Climb Initial Cruise Cruise	• Current and forecast surface conditions at suitable accessible airports along route, including destination and alternates	• Actual and time-phased forecast aloft conditions along the route with emphasis on location and intensity of hazardous weather to be expected
Approach	• Current and forecast surface conditions at destination airport	• Current and forecast aloft conditions in destination terminal area with emphasis on location and intensity of hazardous weather to be expected
Landing	• Current runway surface conditions	• Current aloft conditions in destination terminal area with emphasis on location, intensity, and movement of hazardous weather
Taxi-In and Parking	• Current taxiway and parking area conditions	
Post flight	• Current and forecast surface conditions for the stay time	
Alternative	• Current and forecast surface conditions at alternative airport	• Current and forecast aloft conditions in alternative terminal area with emphasis on location and intensity of hazardous weather to be expected

TABLE 5.9 Weather Information Required During the Planning, Preflight, and Taxi and Take-Off Phases of Flight.

Flight Phase	Preflight Planning/ Flight Plan Filing						Preflight Operations						Taxi-Out and Take-Off					
Flight Segment	D		E		A		D		E		A		D		E		A	
Weather Category	F	C	F	C	F	C	F	C	F	C	F	C	F	C	F	C	F	C
Weather Systems	X	X	X	X	X	X	X	X										
Air Motion																		
En-route Airspace Level	X	X	X	X	X	X												
Terminal Region	X	X	X	X	X	X	X	X						X				
Precipitation	X	X	X	X	X	X	X	X						X				
Icing																		
En-route Airspace Level	X	X	X	X	X	X												
Terminal Region	X	X	X	X	X	X	X	X						X				
Visibility																		
En-route Airspace Level	X	X	X	X	X	X												
Terminal Region	X	X	X	X	X	X	X	X						X				
Lighting	X	X	X	X	X	X	X	X										
Volcanic Ash	X	X	X	X	X	X	X	X						X				
Wake Vortices														X				
Alternate																		
En-route Airspace Level	X	X	X	X	X	X												
Terminal Region	X	X	X	X	X	X												

D = Departure Segment, E = Enroute Segment, A = Arrival Segment, F = Forecasted, C = Current

space segment (E), and the arrival segment (A) for the planning phases and taxi-out and take-off operations. Note that both current (C) and forecasted (F) weather information is required for each segment of flight. The only category of information that is not required during this phase of flight is wake vortex information. Wake vortex information is required in real-time during the taxi and take-off phases and the landing phase because the wake vortex is formed by aircraft following a departure or landing operation and it may last for several minutes and stretch for a few miles behind the aircraft. As discussed in Chapter 4, cloud ceiling and visibility are used to determine VFR and IFR operations, therefore, forecasted ceiling and visibility conditions should be collected for the departure airport, along the route, and for the destination and alternate airports. In order to account for conditions below minimum at the destination airport, The ceiling and visibility forecast should be obtained for the estimated time of arrival (ETA) plus one hour. The ceiling and visibility conditions should also be estimated at the alternate airport taking into account this one hour delay.

Flight planning involves assessing the impact of current and forecasted weather conditions on the different aspects of flight. **Table 5.10** contains a number of the aspects of flight planning that must be assessed in terms of the available weather information.

TABLE 5.10 Flight Plan Components that May be Impacted by Weather.

Flight Plan Considerations	
VMC/IMC	Ground Speeds
Departure Time	Trip Time
Take-off and Climb Performance	Fuel Burn
Route	Arrival Time at Destination
Altitudes	Daylight/Darkness
Airspeeds	Alternate Conditions

5.3.2 Preflight Operations

Preflight operations require a check-out of equipment for proper operation. Past, current, and forecasted weather information is required to assess the need for engine de-icing and carburetor heating. Preflight operation is also a time for validating weather information collected during the planning phase for the departure area. Personal observation of prevailing conditions (*e.g.*, ceiling, visibility, and winds) is the method most often applied. Prevailing conditions may require the pilot to revisit the flight plan. The focus is on conditions at the departure airport at the estimated time of departure (ETD). Table 5.9 contains the categories of weather information required during this phase of operation. The focus is on the current and forecasted conditions in the terminal area at departure airport. In this analysis, the terminal area is included in the departure segment of flight.

5.3.3 Taxi-Out and Take-Off Operation

During taxi-out and take-off operations, the focus of safe aircraft operations is on tactical information. Low altitude air motion information is critical in this phase of flight. Types of low altitude air motion include: microburst, non-convective wind shear, gust fronts, wind gust, surface winds, and turbulence. Section 5.1.2 provides an explanation of these low-level phenomena. Additional types of low altitude air motion are included in Table 5.3. Icing and visibility conditions are also tactical considerations. Of additional concern during this phase of flight is the presence of wake vortices produced by arriving and departing aircraft. Table 5.9 lists the categories of weather information required during this phase of operation. The phase of the Taxi-Out and Take-Off operation just needs the current weather conditions.

5.3.4 Departure, Initial Climb, and Initial Cruise

The departure phase is the last phase in the departure segment. During this phase of flight the pilot focuses on weather information that he will need to make strategic decisions during the en-route segment of flight. During the initial climb and initial cruise phases of flight, the pilot’s weather information requirements are focused on the en-route segment of flight from both a tactical and strategic decision perspective. In all three phases of flight - departure, initial climb, and initial cruise, the required weather information transitions from information about conditions near the surface to flight level condition information. During these phases of flight, weather information and aircraft performance are assessed to determine if the flight plan needs to be updated to account for current and forecasted conditions. **Ta-**

ble 5.11 contains a listing of the weather information required during departure, climb and the initial cruise phase of flight.

5.3.5 Cruise

During the cruise phase, the VFR pilot needs current and forecasted weather information to stay clear of clouds and to maintain visibility requirements. Both the IFR and VFR pilot also require wind information to assess fuel burn rates. The pilot must be updated with current or forecasted hazardous weather conditions (*e.g.*, CAT, hail, thunderstorms, *etc*.) along the intended route. It is during the cruise phase of flight that the pilot needs current and forecasted weather information about the destination and alternate airports in order to make an intelligent decision to continue to the destination airport to attempt a landing or to proceed to the alternate airport. **Table 5.12** contains the categories of weather information required during the cruise phase.

5.3.6 Approach

The approach phase represents the transition between the cruise and landing phases. The current conditions during the final portion of the cruise phase and the current and forecasted conditions for the arrival segment are required by the pilot. During the approach phase, the pilot is correlating current weather conditions with those forecasted for the destination airport. At this point in the flight, the pilot’s options continue to narrow as the aircraft transitions into a more confined air space while flying at lower altitudes. The aircraft may be placed in a holding pattern prior to starting the approach if conditions are below minimums or hazardous weather conditions exist. A possible holding pattern and unexpected winds experienced during flight may result in an in-flight emergency as a result of fuel starvation. Table 5-12 contains the categories of weather information required during the approach phase.

TABLE 5.11 Weather Information Required During the Departure, Initial Climb, and Initial Cruise Phases of Flight.

Flight Phase	Departure						Initial Climb						Initial Cruise					
Flight Segment	D		E		A		D		E		A		D		E		A	
Weather Category	F	C	F	C	F	C	F	C	F	C	F	C	F	C	F	C	F	C
Weather Systems		X	X	X					X	X					X	X		
Air Motion																		
En-route Airspace Level			X	X					X	X					X	X		
Terminal Region		X																
Precipitation		X	X	X					X	X					X	X		
Icing																		
En-route Airspace Level			X	X					X	X					X	X		
Terminal Region		X																
Visibility																		
En-route Airspace Level			X	X					X	X					X	X		
Terminal		X																
Lighting		X	X	X					X	X					X	X		
Volcanic Ash		X	X	X					X	X					X	X		
Wake Vortices																		
Alternate																		
En-route Airspace Level																		
Terminal Region																		

D = Departure Segment, E = Enroute Segment, A = Arrival Segment, F = Forecasted, C = Current

TABLE 5.12 Weather Information Required During the Cruise, Approach, and Landing Phases of Flight.

Flight Phase	Cruise						Approach						Landing					
Flight Segment	D		E		A		D		E		A		D		E		A	
Weather Category	F	C	F	C	F	C	F	C	F	C	F	C	F	C	F	C	F	C
Weather Systems			X	X	X	X					X	X						X
Air Motion																		
En-route Airspace Level			X	X														
Terminal Region					X	X					X	X						X
Precipitation			X	X	X	X					X	X						X
Icing																		
En-route Airspace Level			X	X														
Terminal Region					X	X					X	X						X
Visibility																		
En-route Airspace Level			X	X														
Terminal Region					X	X					X	X						X
Lighting			X	X	X	X					X	X						X
Volcanic Ash			X	X	X	X					X	X						X
Wake Vortices																		X
Alternate																		
En-route Airspace Level					X	X												
Terminal Region					X	X												
D = Departure Segment, E = Enroute Segment, A = Arrival Segment, F = Forecasted, C = Current																		

5.3.7 Landing

During the landing phase, VFR pilots must achieve minimum visibility and ceilings conditions with an uncompromised visual reference of the runway. For the IFR pilot, the approach end of the runway must be visible at the decision height (DH) for precision approaches and at the minimum descent altitude (MDA) for non-precision approaches. In addition, runway visual ranges (RVR) must be met by IFR pilots for the different IFR landing categories (CAT I, II, and III). At the altitudes associated with landing, low-level wind and wind shear information is critical in making a safe landing. The focus of the weather information during the landing phase is on the current weather conditions (*i.e.*, tactical information). As in the take-off phase, information on wake vortex movement and strengths becomes a critical piece of information in an airport environment supporting all aircraft types. In addition, both precipitation and icing change the coefficient of friction of the runway which may impact the aircraft's ability to decelerate or to maintain position in the desired direction along the runway. Table 5-12 contains the categories of weather information required during the landing phase.

5.3.8 Taxi-In and Parking and Post Flight Operations

During taxi-in and parking operations, the pilot needs to be aware of taxiway and ramp conditions. Winds, surface conditions (*e.g.*, snow on the ground), visibility, and other hazardous conditions may impact the aircraft as it moves from the runway to the ramp. Post flight operations should be supported by forecast information covering the remainder of the time the aircraft is in the terminal area. This weather information will be used by the pilot to assess actions to be taken before a continuing flight or to be taken in securing the aircraft. The weather information required during these two phases of flight is given in **Table 5-13**.

TABLE 5.13 Weather Information Required During the Taxi-In, Post, and Alternative Phases of Flight.

Flight Phase	Taxi-In and Parking						Post Flight Operations						Alternative					
Flight Segment	D		E		A		D		E		A		D		E		A	
Weather Category	F	C	F	C	F	C	F	C	F	C	F	C	F	C	F	C	F	C
Weather Systems						X					X				X	X	X	X
Air Motion																		
En-route Airspace Level															X	X		
Terminal Region						X					X				X	X	X	X
Precipitation						X					X				X	X	X	X
Icing																		
En-route Airspace Level															X	X	X	X
Terminal Region											X						X	
Visibility																		
En-route Airspace Level																		
Terminal Region						X											X	X
Lighting																	X	X
Volcanic Ash																	X	X
Wake Vortices																		X
Alternate																		
En-route Airspace Level																		
Terminal Region																		

D = Departure Segment, E = Enroute Segment, A = Arrival Segment, F = Forecasted, C = Current

5.3.9 Alternative

If the flight cannot be permitted to land at its destination airport because of severe weather conditions, the pilot, in consultation with air traffic controllers, will divert to a suitable alternative airport for landing. The aviation weather information requirements are the same as the information needed in the last steps from approach to post flight operation mentioned above. Table 5-13 contains the categories of weather information required during this alternative phase.

5.4 Aviation Weather Products

Aviation weather information available in the U.S. is packaged in various product formats that serve the needs of different planning and decisions involving flights. This section discusses the characteristics of existing aviation weather products which include the type of weather products, information content, product update rates, product life, and product size. Potential improvement to aviation weather products are discussed at the end of this section.

5.4.1 Existing Aviation Weather Product Characteristics

For decision-making purposes, aviation weather products are divided into two categories: tactical and strategic aviation weather products.

5.4.1.1 Aviation Weather Products for Tactical Decision

For making tactical decisions, there are fourteen types aviation weather products which including observation data and forecasts can be used. The following paragraphs describe in the detail each aviation weather products **[NOAA, 2003]** for making tactical decisions.

5.4.1.1.1 Aviation Routine Weather Reports (METAR/SPECI)

Beginning 1 July 1996, the United States transitioned from Surface Aviation Observation (SA) code, and Terminal Forecast (FT) codes to the international standards *Aviation Routine Weather Reports*

(METAR/SPECI) and *Terminal Aerodrome Forecast* (TAF) respectively. The METAR/SPECI reports weather observed at the time of the report and the TAF provides a forecast for weather in the reporting area over the next 24 hours. METAR is the international standard code format for hourly surface weather observations. The acronym roughly translates from the French as Aviation Routine Weather Report. SPECI is merely the code name given to METAR formatted products which are issued on a special non-routine basis as dictated by changing meteorological conditions. The SPECI acronym roughly translates as Aviation Selected Special Weather Report. METAR are taken manually by National Weather Service (NWS) personnel, Federal Aviation Administration (FAA) personnel, contractors, or supplemental observers. METAR reports are also provided by Automated Surface Observation System (ASOS) and Automated Weather Observing System (AWOS) systems. The coverage area of the METAR or SPECI is in the airport terminal area or measurement site.

A METAR report contains the following sequence of elements:

1. Type of report (METAR or SPECI)
2. Station designator (4 LETTER ICAO station identifier)
3. Time of report
4. Wind
5. Visibility
6. Weather and obstructions to visibility
    - Intensity or Proximity (light, moderate, heavy or vicinity)
    - Descriptor (thunderstorm, low drifting, showers, shallow, freezing, patches, blowing, partial)
    - Precipitation (rain, drizzle, snow, hail, small hail, ice pellets, snow grains, ice crystals, unknown)
    - Obstructions to Visibility (fog, haze, smoke, spray, mist, sand, dust, volcanic ash)
    - Other (squall, sandstorm, duststorm, dust/sand whirls, funnel cloud. tornado /waterspout)

7. Sky conditions
   - Amount of clouds (clear, few, scattered, broken, overcast, cumulonimbus, towering cumulus)
   - Height
   - Type or indefinite ceiling height (cumulonimbus, towering cumulus, altocumuluscastellanus, etc. METAR has no explicit ceiling designator; the first broken or overcast layer aloft is inferred to be the ceiling)
8. Temperature and dewpoint
9. Altimeter setting
10. Remarks

5.4.1.1.2 Terminal Aerodrome Forecast (TAF)

A Terminal Aerodrome Forecast (TAF) is a concise statement of the expected meteorological conditions at an airport during a specified the period (usually 24 hours). Each country is allowed to make modifications or exceptions to the code for use in each particular country. The TAF format, as described here, is the one used in the United States (other counties are allowed to make modifications or exceptions to the TAF code). TAF reports use the same weather code found in METAR weather reports. The coverage area of the TAF is located within 5 miles of terminal area.

A TAF report contains the following sequence of elements in the following order:

1. Type of report: (TAF, TAF AMD, TAF COR, TAF RTD)
2. ICAO station identifier: (KSEA, KATL etc.)
3. Date and time of origin: (TAFs are scheduled for issuance four times daily at 0000Z, 0600Z, 1200Z, and 1800Z)
4. Valid period date and time: (Routine TAFs are valid for 24-hours. In the case of an amended forecast, or a forecast which is corrected or delayed, the valid period may be for less than 24 hours)
5. Forecast meteorological conditions:

- Wind (forecast surface wind direction and speed)
- Visibility (forecast of expected prevailing visibility in statute miles and fractions of statute miles)
- Weather
  - Intensity or Proximity (light, moderate, heavy or vicinity)
  - Descriptor (thunderstorm, low drifting, showers, shallow, freezing, patches, blowing, partial)
  - Precipitation (rain, drizzle, snow, hail, small hail, ice pellets, snow grains, ice crystals, unknown)
  - Obstructions to Visibility (fog, haze, smoke, spray, mist, sand, dust, volcanic ash)
  - Other (squall, sandstorm, duststorm, dust/sand whirls, funnel cloud. tornado /waterspout)

6. Sky conditions
   - Amount of clouds (clear, few, scattered, broken, overcast, cumulonimbus, towering cumulus)
   - Height
   - Type or indefinite ceiling height (cumulonimbus only, ceiling layers are not designated in the TAF code. For aviation purposes, the ceiling is the lowest broken or overcast layer or vertical visibility into a complete obstruction)
7. Optional data (Wind Shear is omitted if not expected to occur)

5.4.1.1.3 Route Forecast (RF)

To assist pilots in preflight and en-route planning, the route forecast provides expected conditions along a 25 mile corridor on either side of some 300 routes in the 48 contiguous states. The route forecasts are issued three times daily and are valid for 15 hours. A synopsis may also be issued with the route forecast which describes weather systems affecting the route (pressure systems, fronts, upper air disturbances, and air flow). A route forecast does not address icing or turbulence. A route forecast will not be issued if a TAF has not been issued for that airport.

A route forecast report contains the following weather information:

1. Sustained surface winds
2. Visibility
3. Weather and obstruction to vision
4. Thunderstorms
5. Volcanic ash
6. Sky conditions (coverage and ceiling/cloud heights)
7. Mountain obscuration
8. Non-convective low-level windshear

5.4.1.1.4 Area Forecast (AF)

An area forecast (AF) is a forecast of Visual Flight Rules (VFR) clouds and weather conditions over an area as large as the size of several states. It must be used in conjunction with the AIRMET Sierra bulletin (see In-Flight Advisories below) for the same area in order to get a complete picture of the weather. The area forecast together with the AIRMET Sierra bulletin are used to determine forecast en-route weather and to interpolate conditions at airports which do not have terminal aerodrome forecasts (TAF's) issued. AFs are issued 3 times a day by the Aviation Weather Center in Kansas City for each of 6 areas in the contiguous 48 states. In Alaska, AFs are issued by the Weather Service Forecast Office (WSFO's) in Anchorage, Fairbanks, and Juneau for their respective areas. The WSFO in Honolulu issues AFs for Hawaii. Each AF consists of a 12 hour forecast plus a 6 hour outlook. All distances except visibility are in nautical miles. Visibility is reported in statute miles. The breakdown may be by states, by well known geographical areas, or in reference to location and movement of a pressure system or front. A categorical outlook is included for each area breakdown. Amendments to the AF are issued as needed.

The area forecast report consists of a:

- Synopsis section which is a brief summary of the location and movement of fronts, pressure system, and circulation patterns for an 18 hour period.

- VFR clouds and weather section which is a 12 hour forecast, in broad terms, of clouds and weather significant to flight operations plus a 6 hour categorical outlook. This section is usually several paragraphs. AIRMET Sierra supplies information regarding Instrument Flight Rule (IFR) conditions.

5.4.1.1.5 Airmen's Meteorological Information (AIRMETs)

An AIRMET (AIRman's METeorological Information) advises of weather that may be hazardous, other than convective activity, to light aircraft and Visual Flight Rule (VFR) pilots. However, operators of large aircraft may also be concerned with these phenomena. Three types of bulletins are issued including AIRMET Sierra, AIRMET Tango, and AIRMET Zulu. The items covered are:

In the AIRMET Sierra bulletin the following information is included:

- Ceilings less than 1000 feet and/or visibility less than 3 miles affecting over 50% of the area at one time.
- Extensive mountain obscuration

The AIRMET Tango bulletin includes:

- Moderate turbulence
- Sustained surface winds of 30 knots or more at the surface

The AIRMET Zulu bulletin includes:

- Moderate icing
- Freezing levels

AIRMET items are considered to be *widespread.* They must be affecting or be forecast to affect an area of at least 3000 square miles at any one time. AIRMETs are routinely issued for 6 hour periods. AIRMETs are also amended as necessary due to changing weather conditions or issuance/cancellation of a SIGMET. AIRMET text bulletins are issued from seven different areas of the U.S. including one from Alaska. Other include:

- Boston Area
- Chicago Area

- Ft. Worth Area
- Miami Area
- Salt Lake City Area
- San Francisco Area
- Alaska AIRMETs

5.4.1.1.6 Significant Meteorological Information (SIGMET)

A SIGMET is a weather advisory that covers weather that is potentially hazardous to all aircraft. Three types of SIGMETs are issued in the U.S.: Domestic SIGMETs, Convective SIGMETs and International SIGMETs. SIGMET items are considered to be widespread, they must be affecting or be forecast to affect an area of at least 3000 square miles. However, only a small portion of this total area may be affected at any one time.

Domestic SIGMETs

Domestic SIGMETs are issued for potentially hazardous conditions other than convective activity. Items covered in a domestic SIGMET are:

1. Severe icing
2. Severe or extreme turbulence
3. Duststorms and sandstorms lowering visibilities to less that three (3) miles.
4. Volcanic ash

In Alaska and Hawaii, SIGMETs are also issued for the following events:

1. Tornadoes
2. Line of thunderstorms
3. Embedded thunderstorms
4. Hail greater than or equal to 3/4 inch in diameter

Convective SIGMET

A Convective SIGMET may be issued for any convective situation which the forecaster feels is hazardous to all categories of aircraft. Convective SIGMET bulletins are issued for the Eastern (E), Central (C), and Western (W) United States for regions affecting 40% or more of an area at least 3000 square miles. The boundaries of these regions are at 87 and 107 degrees West longitude. Bulletins are issued hourly and are valid for up to 2 hours. The text of the bulletin consists of either an observation and a forecast or just a forecast. Convective SIGMETs are issued for any of the following conditions:

1. Severe thunderstorm due to
    - surface winds greater than or equal to 50 knots
    - hail at the surface greater than or equal to 3/4 inches in diameter
    - tornadoes
2. Embedded thunderstorms
3. Line of thunderstorms
4. Thunderstorms greater than or equal to VIP level 4 affecting 40% or more of an area at least 3000 square miles.

International SIGMETs

International SIGMETs are issued for oceanic areas adjacent to the United States. Criteria for Domestic and International SIGMETs are similar, however the format, contractions, and wording used are different. International SIGMETs are issued by a Meteorological Watch Office (MWO). The National Weather Service has MWOs at Anchorage, AK, Guam Island in the Pacific Ocean, Honolulu, HI, Kansas City, MO, and the Tropical Prediction Center in Miami, FL. International SIGMET criteria are:

1. Thunderstorms
2. Lines of thunderstorms
3. Embedded thunderstorms
4. Large areas of thunderstorms
5. Tornadoes
6. Large hail

7. Tropical cyclone
8. Severe icing
9. Severe or extreme turbulence
10. Duststorms and sandstorms lowering visibilities to less that three (3) miles.
11. Volcanic Ash

International SIGMETs are issued for 12 hour periods for volcanic ash events, 6 hours for hurricanes and tropical storms and 4 hours for all other criteria. If conditions persist beyond the forecast period, the SIGMET is updated and reissued.

5.4.1.1.7 Severe Weather Forecast Alert (SWFA)

Severe Weather Forecast Alerts define areas of possible severe thunderstorms or tornado activity. The messages are unscheduled and issued as required.

5.4.1.1.8 Center Weather Advisory (CWA)

A CWA is an unscheduled weather advisory issued by Center Weather Service Unit meteorologists for ATC use to alert pilots of existing or anticipated adverse weather conditions within the next 2 hours. Forecast of conditions will impact air traffic flow in the ARTCC area. The conditions are forecast to begin within 2 hours of the advisory. The CWA may refine/tailor the forecast for the ARTCC area of responsibility. CWA may also be issued in advance of an in-flight advisory as conditions warrant. A CWA may even be issued when conditions do not meet CWA in-flight advisory status but may impact the safe flow of traffic in the ARTCC area of responsibility. Also a CWA may modify or redefine a SIGMET. A CWA will covers terminal areas and en-route.

5.4.1.1.9 Winds and Temperature Aloft Forecast (WTAF)

Winds aloft are computer prepared forecast of wind direction and speed as well as forecast temperatures for different flight levels above specific navigation reference points.

Each report contains:

1. The valid time of the forecast (day and valid time range)

2. Forecast location (i.e., MKC - Kansas City, MO)
3. Forecast winds for 3,000 feet
4. Forecast winds (heading and speed) and temperature data at other flight levels (i.e., 6,000; 9,000; 12,000; 18,000; 24,000; 30,000; 34,000; 39,000 feet)

All heights are above Mean Sea Level. Wind directions are true directions. Temperature is in whole degree Celsius for each forecast point. Temperatures are assumed to be negative above 24,000 feet. Wind direction is coded to the nearest 10 degrees. A calm or light and variable wind is indicated by 99. Winds Aloft forecast are provided for 176 locations in the contiguous United States and 21 locations in Alaska (Winds Aloft for Hawaii are prepared locally). Forecast are updated two times each day and include a 6 hour forecast, a 12 hour forecast and a 24 hour forecast.

5.4.1.1.10 Pilot Reports (PIREP)

Pilots that encounter severe weather conditions while in flight will often report them to air traffic controllers. These pilot reports, or "PIREPs", provide valuable information about aircraft encounters with icing, turbulence and other weather phenomena. Data included in the PIREPs include the location and altitude of the icing or turbulence encounter, it's intensity and type, winds, temperature and more.

FAA air traffic facilities are required to solicit PIREPs when the following conditions are reported or forecast: Ceiling at or below 5,000 feet; Visibility at or below 5 miles (surface or aloft); thunderstorms and related phenomena; icing of light degree or greater; turbulence of modest degree or greater; windshear and reported or forecast volcanic ash clouds.

Pilots are urged to cooperate and promptly volunteer reports of these conditions and other atmospheric data such as: cloud base, tops and layers; flight visibility; precipitation; visibility restrictions such as haze, smoke and dust; winds at altitude; and temperature aloft.

PIREPs are given to the ground facility with which communication is established; i.e., En-route Flight Advisory Service (EFAS), AFSS/FSS, ARTCC, or terminal ATC. One of the primary duties of EFAS facilities, radio call FLIGHT WATCH, is to serve as a collection point for exchange of PIREPs with en-route aircraft. In addition to being available to in-flight aircraft through Flight Watch, PIREPs are plotted on maps of the US and made available to over the internet through the Aviation Digital Data Service (ADDS), **Table 5.14** lists the types of information provided by PIREPs and the codes used to record and distribute the information.

The weather elements as well as product message identifiers are coded for distribution to ground based aviation weather service providers to minimize the bandwidth needed for ground communication systems. The service providers decode the weather messages and present descriptions of observations or forecast in verbal messages that can be understood by airborne users. The coded formats used for ground based distribution can be used to estimate the data communication capability that would be required to provide the same information over a digital air/ground network.

TABLE 5.14 PIREP Information and Codes.

	PIREP Elements	PIREP Code	Contents
1	3 letter station ID	XXX	Nearest weather reporting station to the reported phenomenon
2	Report type	UA or UUA	Routine or Urgent PIREP
3	Location	/OV	In relation to VOR
4	Time	/TM	Coordinated universal time
5	Altitude	/FL	Essential for turbulence and icing reports
6	Type Aircraft	/TP	Essential for turbulence and icing reports
7	Sky cover	/SK	Cloud height and coverage (sky clear, few, scattered, broken, or overcast
8	Weather	/WX	Flight visibility, precipitation, restrictions to visibility, etc.
9	Temperature	/TA	Degrees Celsius
10	Wind	/WV	Direction in degrees and true speed in knots
11	Turbulence	/TB	
12	Icing	/IC	
13	Icing	/RM	For reporting elements not included or to clarify previously reported items

Table 5.15 summarizes the amount of data produced and distributed for the weather products

described above. These data provide a high level reference that will be used to determine the size of the weather information requirements in the Aviation Weather Information and Bandwidth Requirement Model (AWINBRM).

TABLE 5.15 Aviation Weather Products Using for Tactical Decision Making.

Products	Application Area	Types	Product Rate (times/day)	Product Life	Estimated Size (byte)
METAR/SPECI	Terminal Area	Current	24	1	500 - 1,000
TAF	Terminal Area	Forecast	4	24	500 - 1,000
Area Forecast	En-route and Terminal Area	Current and Forecast	3	8	3,000 - 10,000
Route Forecast	Air Traffic Routes	Forecast	3	15	500 - 2000
AIRMET - Sierra	En-route and Terminal Area	Current and Forecast	4	6	500 - 1,000
AIRMET - Tango	En-route and Terminal Area	Current and Forecast	4	6	500 - 2,000
AIRMET - Zulu	En-route and Terminal Area	Current and Forecast	4	6	500 - 2,000
Domestic SIGMET	En-route and Terminal Area	Current and Forecast	6	4	500 - 1,000
Convective SIGMET	En-route and Terminal Area	Current and Forecast	6	4	1,000 - 5,000
International SIGMET	En-route	Current and Forecast	6	4	500 - 2,000
Winds and Temperature Aloft	En-route and Terminal Area	Forecast	2	6/12/24	250 - 500
Severe Weather Forecast Alert	En-route and Terminal Area	Forecast	as required	1	250 - 500
Center Weather Advisory	En-route and Terminal Area	Forecast	as required	2	500 - 1000
PIREP Distributed	En-route	Current	as required	1	250 - 500

5.4.1.2 Aviation Weather Product for Strategic Decision

A number of the weather products are designed to support pre-flight planning and strategic decisions. Their applicability to tactical decision making is limited due to the update rates which vary from 1 hour to 12 hours. The following paragraphs provide the descriptions of the strategic aviation weather products **[NOAA, 2003]**.

5.4.1.2.1 Radiosonde Additional Data (RAD)

Radiosonde Additional Data (RAD) is issued every 12 hours by NWS and covers the current conditions in the en-route airspace and terminal region. It contains observed freezing level and relative humidity at the freezing level obtained from radiosonde data.

5.4.1.2.2 Constant Pressure Analysis Charts (CPAC)

Constant Pressure Analysis Charts (CPAC) are issued every 12 hours by NWS and covers the current conditions in the en-route airspace and terminal region. It contains the following information

1. Temperature
2. Temperature – dew point spread
3. Wind (direction and speed)
4. Height about sea level
5. Height change of the pressure surface over the past 12 hours

This information is obtained from radiosonde, aircraft, and satellite date. The charts are produced for the following pressures in millibars/hectoPascal (hPa): 850, 700, 500, 300, 250, and 200. These pressures correspond to pressure altitudes of 1,500; 3,000; 18,000; 30,000; 34,000; and 39,000 feet, respectively. The charts provide contours of constant height, isotherms of equal temperature, and isotachs of equal wind speed.

5.4.1.2.3 Composite Moisture Stability Chart (CMSC)

Composite Moisture Stability Chart (CMSC) is issued every 12 hours by NWS and covers the current conditions in the en-route and terminal area. It consists of four charts containing information on stability, freezing levels, precipitation water, and average relative humidity. Reporting levels include the surface, 1,000 mb/hPa, 850 mb/hPa, 700 mb/hPa, and 500 mb/hPa.

5.4.1.2.4 Low Level Significant Weather Program (LLSWP)

Low Level Significant Weather Program (LLSWP) is distributed four times per day in en-route airspace and terminal region with a life time of 12 or 24 hours. Some of the information provided on the charts includes:

1. Fronts
2. Pressure centers

3. Forecast precipitation and/or thunderstorms
4. IFR, MVFR, turbulence, and freezing levels
5. The significant weather is forecast from the surface to 24,000 feet referenced to MSL

5.4.1.2.5 High Level Significant Weather Program (HLSWP)

High Level Significant Weather Program (HLSWP) is distributed four times per day in en-route airspace and terminal areas and its life is six hours. These charts contain information on the airspace between (25,000 feet and 60,000 feet (in pressure altitude)). Some of the information provided in the charts include:

1. Thunderstorms
2. Tropical cyclones
3. Moderate or severe turbulence
4. Convergence zones
5. Fronts
6. Tropopause heights
7. Jet stream
8. Volcanic activity

5.4.1.2.6 Convective Outlook (CO)

Convective Outlook (CO) is issued two or five times per day by Storms Prediction Center and forecasts to cover in the en-route airspace and terminal area. Its life is 48 hours or 24 hours. A convective outlook defines areas which are at risk of severe thunderstorms over the next 24 and 48 hours.

5.4.1.2.7 Surface Analysis Charts (SAC)

Surface Analysis Charts (SAC) are issued every three hours and covers the current conditions in the en-route airspace and terminal region. Its life is also three hours. A chart showing the pressure systems and isobars across the 48 contiguous states and adjacent areas.

5.4.1.2.8 Weather Depiction Chart (WDC)

Weather Depiction Chart (WDC) is issued every three hours by NWS and covers the current conditions in the en-route airspace and in the terminal airport region. The life of this product is three hours.

A summary of METARs across the U.S. is in a chart format. The chart provides a broad overview of sky conditions based on the METARs including sky cover, cloud height, weather and obstructions to vision, and visibility. The charts are to be used for pre-flight planning purposes only since weather conditions can change considerable in a three-hour period. Specific, up-to-date METARs should be consulted along the planned route.

5.4.1.2.9 Radar Weather Report (RWR)

Radar Weather Report (RWR) is issued every one hours by NWS and covers the current conditions in the en-route airspace and terminal region. The life of this product is one hours.

This report describes general areas of precipitation which includes type (limited to rain, rain shower, snow, snow shower, thunderstorm), intensity, and location of echo top. This report should be used for planning purposes only because the report does not provide information on clouds and fog that impact ceilings and visibility.

5.4.1.2.10 Radar Summary Chart (RSC)

Radar Summary Chart (RSC) is issued every one hours by NWS and covers the current conditions in the en-route airspace and terminal region. The life of this product is one hours. A radar summary charts graphically display areas of precipitation Including information on type, intensity, location, coverage, echo top, and cell movement. These charts are generated from data collected by the WSR-88D network. The charts are to be used for pre-flight planning purposes only.

5.4.1.2.11 Satellite Weather Pictures (SWP)

Satellite Weather Pictures (SWP) are issued every 15 minutes to one hours by NWS and private companies and cover the current conditions in the en-route airspace and terminal region.

Visible Satellite Imagery includes the following information:

1. Presence of clouds
2. Type of cloud infrared imagery
3. Cloud height based on cloud temperature

5.4.1.2.12 Hurricane Advisory (HA)

The hurricane Advisory (HA) provides location of storm center, expected movement, and maximum winds near the center of the hurricane.

5.4.1.2.13 Meteorological Impact Statement (MIS)

Meteorological Impact Statement (MIS) is issued by NWS as condition warrant and forecasts to cover the en-route airspace and terminal region. The life for this product varies from 2 to 12 hours. The conditions are forecast to begin beyond 2 hours of the issuance, but within 12 hours of the issuance.

Meteorological Impact Statements are issued for the following conditions:

1. Convective SIGMET criteria
2. Moderate or greater icing and/or turbulence
3. Heavy or freezing rain
4. Low IFR conditions (ceilings less than 500 ft. and/or visibility less than 1 mile)
5. Surface winds/gusts 30 knots or greater
6. Low-level wind shear within 2000 feet of the surface
7. Volcanic ash, dust, or sand storm

5.4.1.2.14 Volcanic Ash Forecast and Dispersion Chart (VAFDC)

Volcanic Ash Forecast and Dispersion Chart (VASDC) is issued every 6, 12, 24, and 36 hours after a volcanic eruption by NOAA Air Resources Laboratory (ARL) and forecasts the current conditions in the en-route airspace and terminal region. The life of the volcanic ash forecast and dispersion charts is 6 or 12 hours.

A model is used to forecast ash concentrations for three layers of the atmosphere:

1. surface to 20,000 ft (MSL)
2. 20,000 to 35,000 ft (MSL)
3. 35,000 to 55,000 ft (MSL)

The aviation weather products for strategic decision are summarized in **Table 5.16**.

TABLE 5.16 Aviation Weather Products Using in Strategic Decision Making.

Products	Application Area	Types	Product Rate (times/day)	Product Life	Estimated Size (kb)
Radiosonde Additional Data	En-route and Terminal	Current	2	12	2 -50
Constant Pressure Analysis Charts	En-route and Terminal	Current	2	12	50 -500
Composite Moisture Stability Chart	En-route and Terminal	Current	2	12	50 - 500
Low Level Significant Weather Program	En-route and Terminal	Forecast	4	12/24	20 - 200
High Level Significant Weather Program	En-route and Terminal	Forecast	4	6	20 - 200
Convective Outlook	En-route and Terminal	Forecast	5	24/48	5 - 15
Surface Analysis Charts	En-route and Terminal	Current	8	3	100 - 1000
Weather Depiction Chart	En-route and Terminal	Current	8	3	30 - 300
Radar Weather Report	En-route and Terminal	Current	24	1	800 - 2000
Radar Summary Chart	En-route and Terminal	Current	24	1	300 - 3000
Satellite Weather Pictures	En-route and Terminal	Current	72	n/a	1000 - 5000
Hurricane Advisory	En-route and Terminal	Advisory	300 nm offshore	n/a	5 - 50
Meteorological Impact Statement	En-route and Terminal	Forecast	as required	2/12	3 - 30
Volcanic Ash Forecast and Dispersion Chart	En-route and Terminal	Forecast	4	6/12	6 - 60

5.4.2 Potential Improvements of Aviation Weather Product

Text messages and voice are an indispensable part of today’s weather information flow, and will continue to be into the foreseeable future. They are well established, immediate, familiar, and useful, suggesting no reason to believe they will become obsolete. In fact, METAR and TAF text sequences communicate the most fundamental of all weather information—ceiling and visibility—providing the legal (regulatory) basis for filing a flight plan, for designating an alternate airport, and for starting an instrument approach. In the future, graphical weather products will augment and supplant some text and voice usage in the cockpit. It seems likely, therefore, that text and voice exchanges will continue to increase with increasing air traffic volume, though not at the same rates we see today.

A significant safety argument for graphical weather is its immediacy and impact. This is literally a case where “a picture is worth a thousand words.” Studies have shown humans more quickly and completely comprehend a picture than they do written or spoken words. In addition, coded information such as weather data adds yet another level of complexity. Industry statistics indicate that in many weather-related aviation accidents, the appropriate weather was forecast and available, and often actually in the possession of the pilot. Even so, either the pilot did not fully regard the information available, misinterpreted it, or gave it less weight than it deserved.

As technology, communications, and weather prediction algorithms improve, graphical weather information has the power to reduce pilot judgment errors related to weather. It is logical to assume, and individual interviews confirm, that more accurate predictions confined to smaller areas will carry more weight with pilots. If the information is in the form of a picture, especially one quickly and easily available in the cockpit, the information becomes compelling enough to change behavior, thus making airborne decisions both safer and more economical. This process has already started in business aviation and at some commuter airlines.

The industry’s current move toward graphical weather is likely to increase more rapidly than is commonly expected. Experience in the cellular, computer, and internet industries strongly suggest that as information becomes more accurate, accessible, and affordable, volume and demand increase very quickly. Historical increases in the use of Aircraft Communications Addressing and Reporting System (ACARS) data link in the aviation industry serve to reinforce this view.

Figure 5.4 illustrates an example of 24-hour significant weather forecast chart for aviation industry by NOAA. The chart shows various aviation weather phenomena included:

- Stationary, Occluded, warm, and cold fronts
- Low and high pressure centers
- Turbulence area

- Freezing level
- IFR and VFR flight rule area

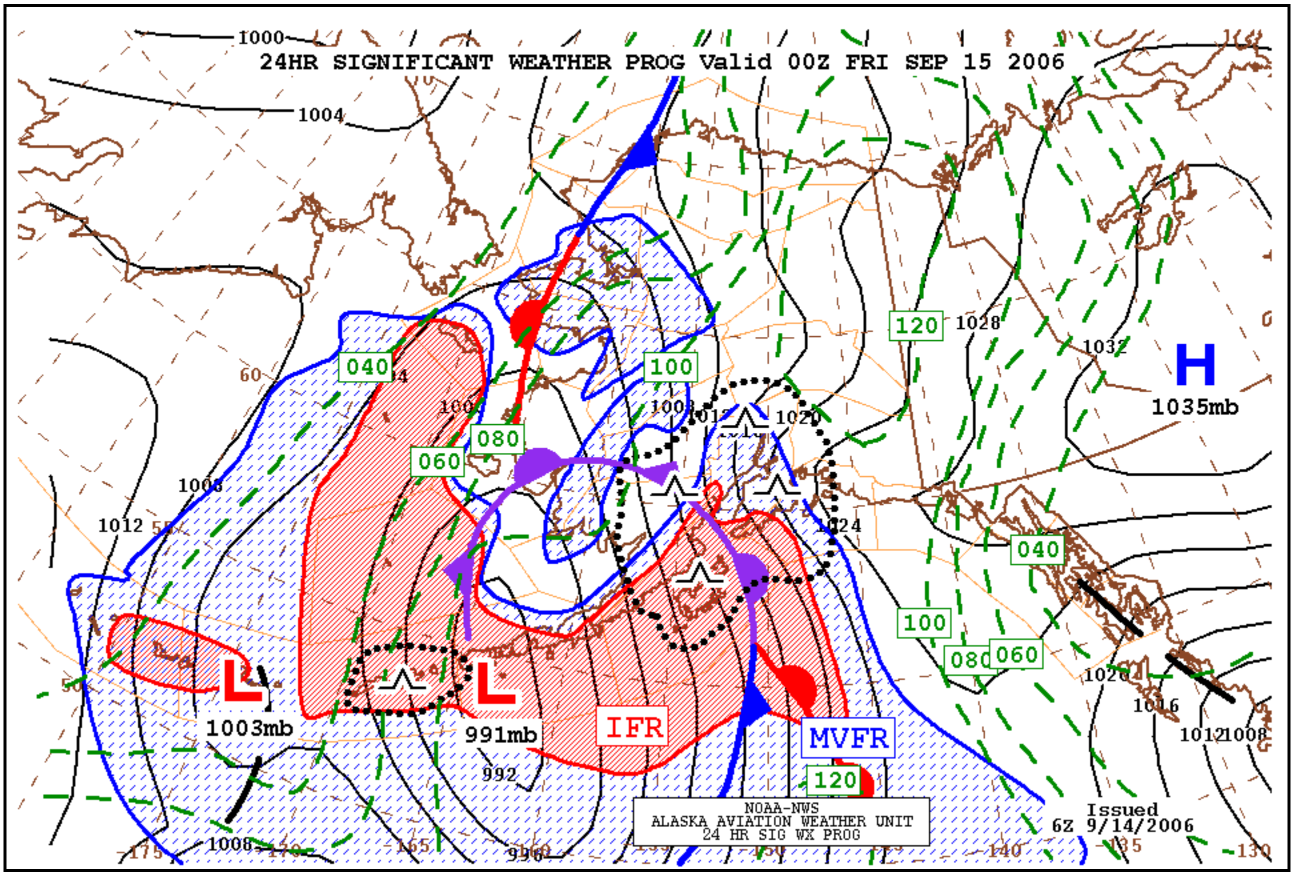


Figure 5.4 Significant Weather Forecast Chart (Photo obtained from the NOAA[107])

5.4.2.1 New Graphical Weather Products

Current thinking seems to group “graphical” weather information presentation into four main categories: text, icons, pictures, and objects. These four, listed according to their relative complexity, have different uses, depending on the phase of flight and decision making arena.

5.4.2.1.1 Colored Text

Better than plain text, “Colored Text” can be used to present visual cues about the severity of a given condition. For instance, red text can describe “bad” conditions; yellow, “marginal”; green, “good.” The colored textual weather forecasts and observations are quite popular with pilots. Since text is far too useful to disappear in the foreseeable future, color coding is a natural enhancement. The file size of color coded text are roughly the same as the white-black text’s, depending on the amount of information encoded and sent.

5.4.2.1.2 Icons

Some weather products reduce a variety of data and information down to a single, coded, “icon.” For weather in the cockpit, those colored icons are used to describe winds, ceiling, and visibility at stations across the country. Icons take up little file size for the amount of information conveyed, but are best at representing conditions at a single point in space and time, such as specific airports, runways, arrival gates, holding patterns, etc.

5.4.2.1.3 Pictures (Bit-Mapped, Gridded, Graphics)

In this context, “Pictures” include, but are not limited to, direct sensor output such as satellite photos or radar returns. A “picture” could also be a computer synthesized product. The defining requirement is that “picture” information is essentially information from a grid, bit-mapped in one of various formats. These files tend to be large, though they can be compressed with a variety of schemes, such as the MIT Lincoln Labs “Huffman” compression algorithm **[Gertz, 1997]**. In its basic form, a “picture” can be difficult to overlay with other information (waypoints, other aircraft, etc.) on a single display since the picture will hide portions of whatever was displayed previously.

5.4.2.1.4 Objects

“Objects” are more easily scalable and “smoother” than “pictures.” In a basic sense, an object can be a “picture” with the relevant material reduced to polygons that exhibit a number of characteristics. One advantage of “objects” is that they can be more easily manipulated in three or four dimensions, allowing the pilot to visualize hazard avoidance by “virtually” examining projected hazards from any angle, altitude, or time desired. Another advantage is that objects are also more easily ranked in importance for merging with other information on a common display. Finally, the raw file size of a hazard described with objects can be smaller than its bit-mapped equivalent, though it may be harder to compress to the same degree.

5.4.2.2 Weather Product Improvement

5.4.2.2.1 Forecast and Observation

In general, forecasted weather information is applied in making strategic decisions; whereas, information on current weather conditions is required to make real-time tactical decisions. The timeliness of the weather information is grouped into two categories: forecast and current.

Aviation weather products can provide both strategic and tactical (for forecasted and current conditions) information as a function of the phase of flight and provide more accurate, localized descriptions of forecasted and current conditions tailored to the need of the aviation community.

5.4.2.2.2 Weather Product Update Rate

Weather products are required which support finer spatial and temporal grids than currently exist if improvements in aviation safety are to be achieved. From a temporal perspective, a number of weather products used in pre-flight planning and strategic analysis are updated at intervals of hours (anywhere from 1 to 12 hours). Some weather products such as microbust and gust front detection are derived from radiosonde measurements that are taken at 00:00 and 12:00 each day. The spatial and temporal spacings of these measurements limit the accuracy of the weather prediction models and the update rates of the corresponding weather products. A requirement exists for updates to the radiosonde measurements on a finer temporal and spatial scale. Other weather products could also be updated on a finer time scale (*e.g.*, a METAR, a weather depiction chart, a radar weather report, and a radar summary chart) in order to better monitor changing conditions that impact aviation.

Aviation weather products need to increase in the update rate associated with a number of weather products used in pre-flight planning and can provide a finer time and spatial spacing between radiosonde measurements

5.5 Aviation Weather Sensor - Aircraft

5.5.1 On-board Sensors

As mentioned in Chapter 2, the weather sensors are the major deficiency in the current set of weather products. There are large number of different sensors used in weather data collection. NASA envisions a future that would allow aircraft to be both a source and user of weather information. Airborne sensors would provide data for weather systems on board of the plane, on the ground, and in other aircraft. Easy-to-read, real-time displays in the cockpit would show weather across the country, not just a limited number of miles ahead. In this way pilots could more easily monitor possible trouble spots and make safer, more cost-efficient routing decisions. This section focuses on the discussion of aircraft as aviation weather sensor.

Many aircraft have multitude onboard sensors that, under current conditions, are not exploited to provide information to others. The availability of aircraft-derived weather information could provide valuable point measurements of weather-related services useful to pilots. Examples of these are: 1) wind data along the flight track derived from wind speed and direction sensors, 2) turbulence levels derived from aircraft accelerator sensors, 3) convective weather information, and 4) icing information along a route. **Table 5.17** contains some possible sensors on-board for inclusion in an electronic pilot report (EPIREP).

Modern sensor systems provide a means of measuring the physical properties of the atmosphere either remotely or *in situ* and of processing the measured quantities to arrive at aviation specific products. The possible candidate sensor packages could be incorporated in an electronic pilot reporting system.

5.5.2 Electronic Pilot Reports (EPIREPS)

The FAA's Aeronautical Information Manual (AIM) **[Gleim, 1998]** states that FAA air traffic facilities (*e.g.*, flight service stations (FSS) and ARTCC) are to solicit pilot reports (PIREPS) when the following conditions are reported or forecast:

- Ceilings at or below 5000 feet
- Visibility at or below 5 miles (surface or aloft)
- Thunderstorms and related phenomena
- Icing of light degree or greater
- Turbulence of moderate or greater degree
- Wind shear
- Volcanic ash clouds

TABLE 5.17 Possible Sensors On-board Aircraft.

EPIREP Reports
Outside Temperature Sensor
Wind Speed and Direction Sensors
Relative Humidity Sensor
Location and Time Stamp
Degree of Turbulence (Accelerometers)
Airborne Weather Radar Summaries
Lightning Detection Sensors
Icing Sensors on the Surface of the Aircraft

Pilots are urged to provide requested information and volunteer information as conditions warrant. The main objective of the PIREP system is to warn other pilots and air traffic facilities of adverse weather conditions experienced in the en-route airspace. The current system requires FSSs and ARTCCs to verbally solicit PIREPs and manually enter the reports into the National Weather Service's communication gateway. However, a number of problems exist with the current system. FSSs can only receive PIREPs on selected frequencies. However, as is often the case, the pilot is using a different set of frequencies to communicate with air traffic control or is monitoring other frequencies. In addition, during FSS peak workloads PIREPS may not get entered into the system. In addition to the warning aspect of a PIREP, there is also a desire to use PIREP data in weather research and forecasting. For example, PIREPs could possibly be used to aid researchers in the development of turbulence and icing forecasts.

In this context aircraft would provide relevant weather information to a centralized National Weather Database System (NWDS) at predetermined intervals. NWDS would collect these data and apply tactical weather models and algorithms to complement ground-based products derived from long-range Doppler radar, terminal doppler radar and other ground sensors. **Figure 5.5** shows the information derived from a proposed NWDS system and sent to pilots (via satellite or other mechanism) at predetermined intervals **[Trani, 2000]**.

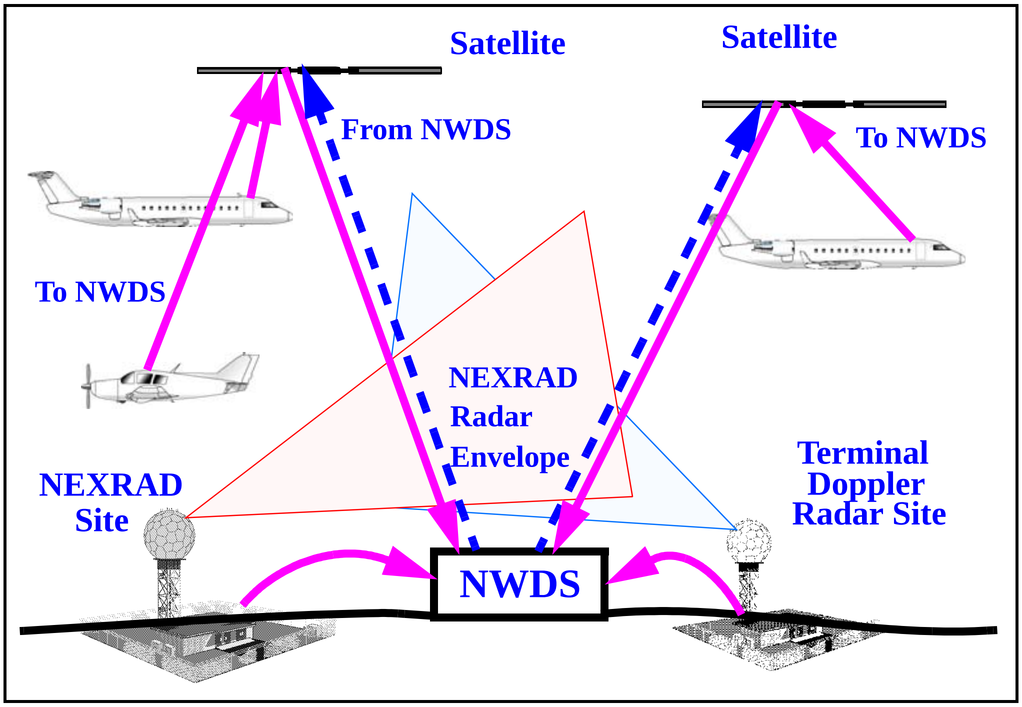


Figure 5.5 EPIREP Dissemination Structure.

The main advantage of this concept is that many of the current voids in weather information would be closed with the presence of aircraft at various flight levels. **Figure 5.6** demonstrates this situation **[Trani, 2000]**.

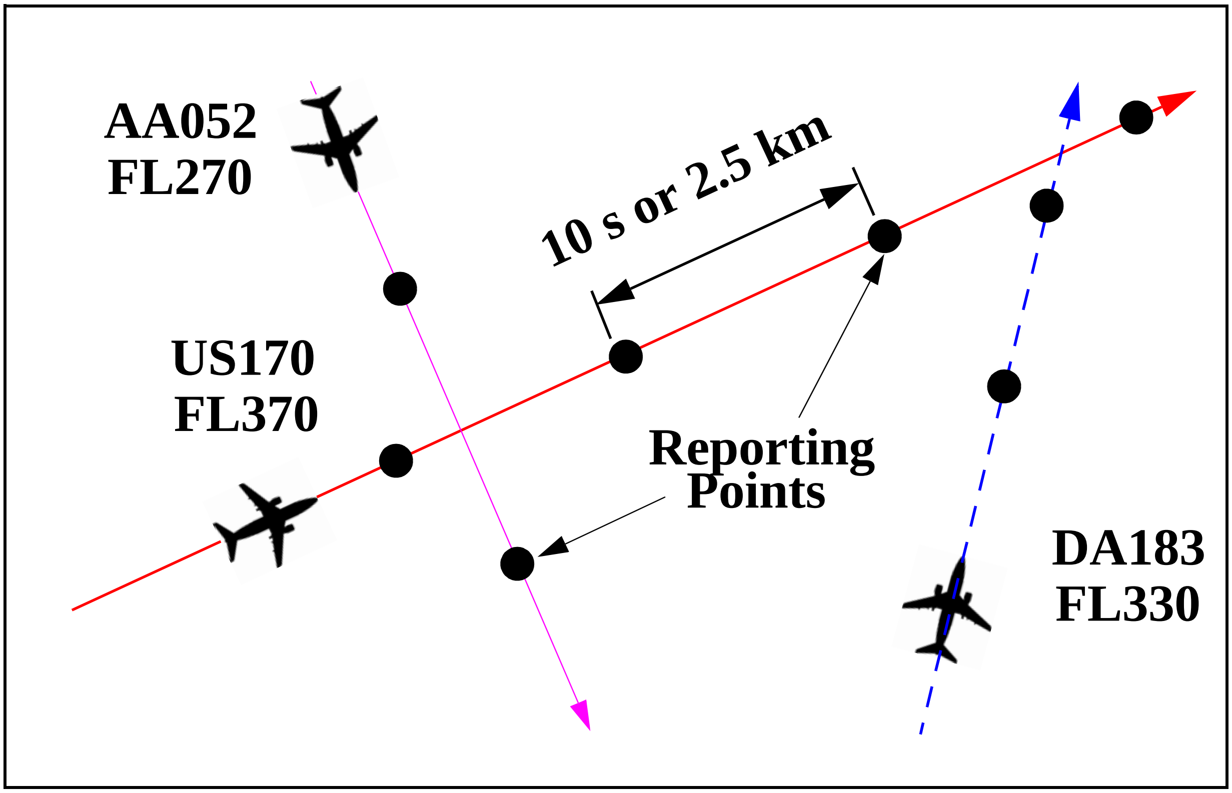


Figure 5.6 Spatial Retrieval Information for Aircraft as a Weather Sensor.

Given the randomness of flight tracks across the NAS the number of data points and the time and spatial distribution of the information will vary substantially. The NWDS will fuse all data collected and provide a common format to all requesting aircraft, The data format assumed for this analysis is a rectangular grid provided to all aircraft. **Table 5.18** contains a description of the aircraft as weather sensor data products prototyped in this research. **Table 5.19** summarizes the data size requirements to make aircraft be collaborative sensors across the NAS. The baseline sampling rate assumed in this analysis is 60 seconds **[Trani, 2000]**.

TABLE 5.18. Aircraft as a Weather Sensor Communication Information Data Sets.

Weather Type	Sources of Data	Sampling Rate	Data Size
Winds and temperature aloft along the flight track	Temperature sensors Wind sensors	Continuous variables reported (direction, magnitude, location, time) every 10 seconds for all aircraft types	512 bytes per aircraft per measurement aircraft ID wind direction wind magnitude 3D location time tag
Icing	Vehicle icing sensors and on-board temperature gradient measurements	every 10 seconds (all types of aircraft) reported as	64 bytes per aircraft per measurement
Turbulence	Vehicle accelerometers, mechanically measured	every 10 seconds (all types of aircraft) reported as	64 bytes per aircraft per measurement
Convective	Moisture contenting struments, Pressure,etc.	every 10 seconds (all types of aircraft) reported as	128 bytes per aircraft per measurement

TABLE 5.19. Aircraft as a Sensor Data Size with Low Sampling Rate.

Domain	Total Weather Data Size (bytes)	Region Size (km^2)	Average Data Set (bytes[a] per sq. km)	Sampling Rate (seconds)
Tactical	1.8×10^5 rectangular 9.0×10^4 triangular	9.0×10^4 rectangular 4.5×10^4 triangular	2.0 in both cases	60
Near Strategic	1.44×10^6 rectangular 7.2×10^5 triangular	7.2×10^5 rectangular 3.6×10^5 triangular	2.0 in both cases	180
Far Strategic	2.48×10^5 rectangular (4 km grid size)	up to 2.7×10^6 rectangular	0.19	600

a. Assumes 8 bit data representation, 8 bit error correction scheme and 1 km grid.

5.6 Aviation Weather Information and Bandwidth Requirement Model

5.6.1 AWINBRM Organization

Aviation Weather Information and Bandwidth Requirement Model (AWINBRM) has two major parts: One is the uplink which means that the aviation weather information is transmitted from ground service centers such as NWAS to the aircraft, This part includes the tactical and strategic aviation weather product sections. In the tactical aviation weather section, aviation weather products are mainly considered the observation data (current condition) and the nowcast weather products that usually are one to three hours forecasts. Four sub-tactical aviation weather product models are developed. They are air carrier, air taxi/commuter, general aviation, and military tactical aviation product models. Similar to the tactical aviation weather product model, the strategic aviation weather product section also has four sub-models for air carrier, air taxi and commuter, general aviation, and military aircraft categories, respectively. The strategic aviation weather products are focused on some nowcasts and the short and longer forecasts aviation weather products.

The second part of the AWINBRM model is the downlink component which means that the aviation weather data observed from the sensors on board are transferred to data processing center on the ground or to the aircraft directly. The structure of the model is illustrated in **Figure 5.7**.

For future development, the AWINBRM also includes the aviation weather improvements such as update weather product sampling rate, coverage area, uncoded, and graphic weather product, etc.

The inputs of the AWINBRM are the demand functions defining aircraft movements inside the region of interest and various aviation weather products and their size. The model computes the size of aviation weather products and data transmitted at each phase of flight in three regions - in the en-route airspace, in the terminal, and at the airport for all aircraft categories.

5.6.2 AWINBRM Causal Diagram and Equation

5.6.2.1 Causal Diagram

The AWINBRM model has been developed using the ITHINK 7.0 software package. Each aviation weather product is analyzed separately at each phase of flight. **Figure 5.8** demonstrates general causal diagram of the AWINBRM model. The causal diagram describes the relationship between various variables. The diagram includes the following data:

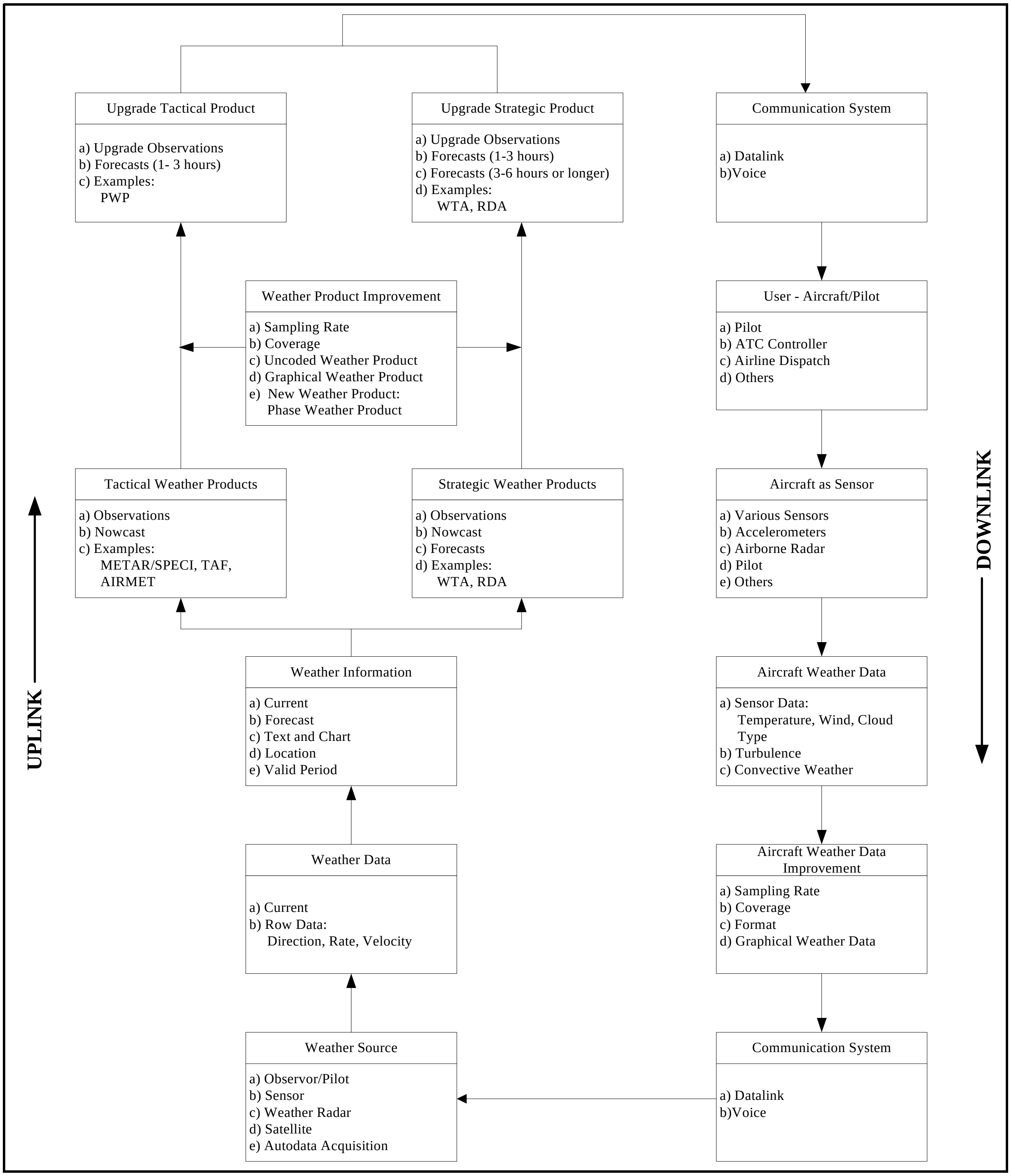


Figure 5.7 AWINBRM Model Flowchart.

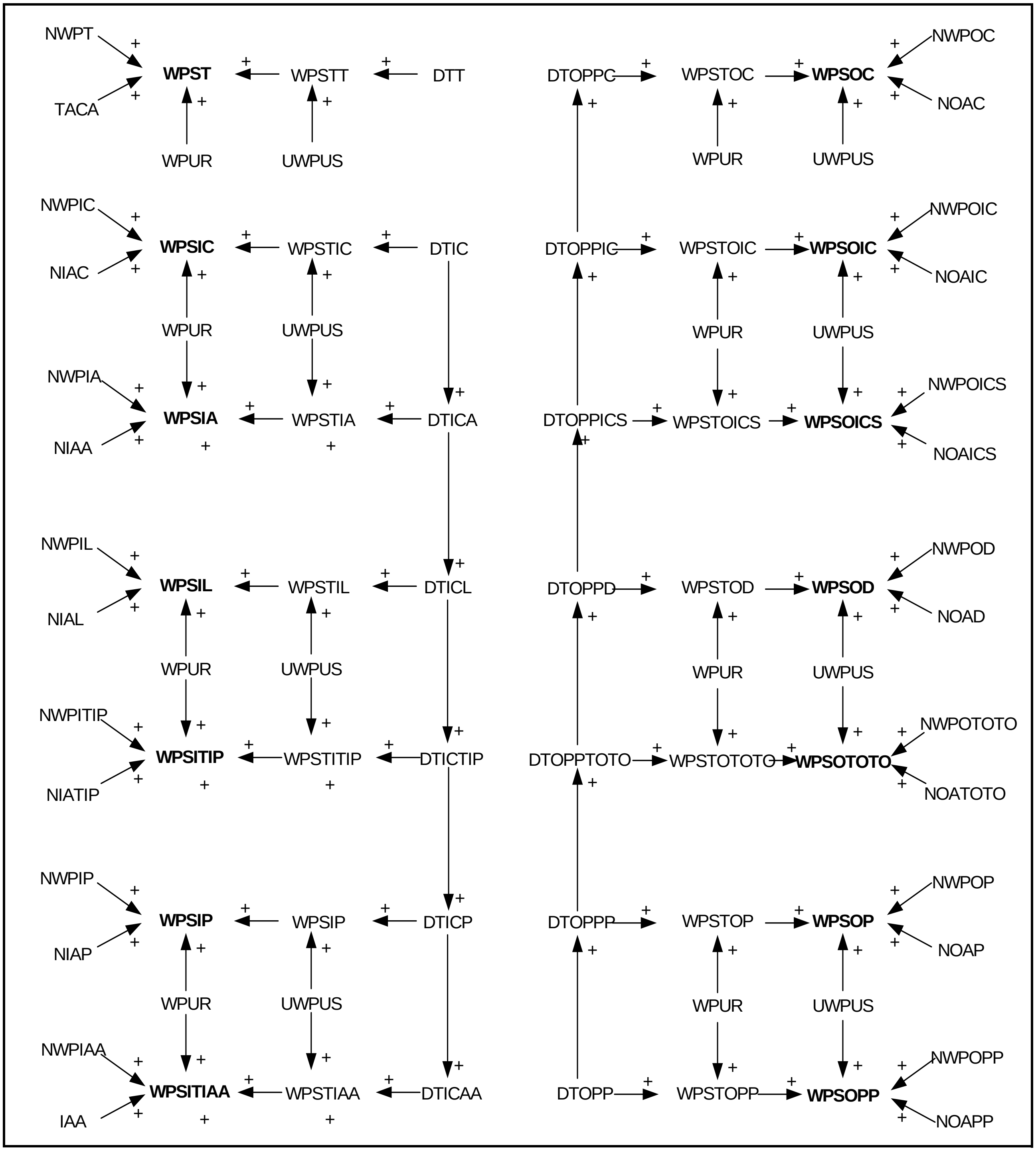


Figure 5.8 AWINBRM Causal Diagram.

The size of weather product requirements at each phase of flight. For example, the size of weather product requirements at inbound approach phase of flight (WPSIA) and the size of weather product requirements at outbound preflight phase of flight (WPSOP) etc.; The weather product sampling times at each phase of flight such as weather product sampling times at inbound approach phase of flight (WPSTIA) and weather product sampling times at outbound preflight phase of flight (WPSTOP); Dwell times from one phase of flight to another phase of flight; DTICA represents the inbound dwell times from cruise phase to approach phase of flight; Number of aircraft at each phase of flight which comes from the ATFM model. Also the diagram shows some other variables such as weather product unit size (WPUS), weather product update rate (WPUR), and number of weather product requirements at each phase of flight.

The nomenclative used in this diagram is explained in the following paragraphs as the equations of motion of the model are introduced.

5.6.2.2 Model Equation

The important factor for determining weather product requirement and bandwidth is that how many times a flight will request for one aviation weather product at each phase of flight. The factor is called the aviation weather product sampling times (WPST) in the AWINRBM. The WSPST is dependent on the dwell time from the outbound initial phase of flight (preflight planning and flight plan filing) or inbound initial phase of flight (cruise operation) to the phase of flight that is determined, weather sampling rate, weather sampling times in the previous phases of flight, and weather product distribution schedules. The following equation is used to determine the weather product sampling times at outbound taxi-out and take-off phase of flight. This is a typical example. Other equations in the AWINBRM model for determining weather product sampling times at different phase of flight are similar this equation.

WPSTOTOTO = IF((INT(DTOPPTOTO/Weather Sampling Rate)- Weather Sampling Times from PP to P)>=1 or METAR Time Factor=1) (5.1)

THEN (1) (5.2)

ELSE (0) (5.3)

Where:

WPSTOTOTO = Weather product sampling times at taxi-out and take off phase (time)

DTOPPTOTO = The total dwell time from Preflight Planning to Taxi Out and Take Off for outbound aircraft (minute)

Weather Sampling Rate = Weather product distribution frequency per day (once/minute)

Weather Sampling Times from PP to P = The total sampling times from Preflight Planning to Preflight for outbound aircraft (time)

Weather Time Factor = Weather product distribution schedule (0 or 1)

INT = Determine integer

The equations of the weather product requirement and bandwidth are similar at each phase of flight. The weather product requirement and bandwidth is dependent on the number of aircraft, weather product sampling times, size of unit of weather product, and number of weather products. The following equation expresses the size of weather product at taxi-out and take-off phase of flight.

$$\text{WPSOTOTO} = \text{WPSTOTOTO} * \text{UWPUS} * \text{NOATOTO} * \text{NWPOTOTO} \quad (5.4)$$

Where:

WPSOTOTO = Total weather product size at taxi out and take off phase (byte)

WPSTOTOTO = The times to transfer weather product to pilot at taxi out and take off phase (time)

UWPUS = Weather product unit size (byte)

NOATOTO = Total number of outbound aircraft at taxi out and take off phases of flight (number)

NWPOTOTO = The number of weather product requirement at taxi out and take off phase (number)

For the future consideration, the factors for updating weather product are included in the AWINRBM model. The equation for updating weather product is written as follows:

$$\text{UWPUS} = \text{UWPS} * \text{WPUF} * \text{WPGF} \quad (5.5)$$

Where:

UWPUS = Update weather product unit size (byte)

UWPS = Original size of unit weather product (byte)

WPUF = Weather product uncode factor

WPGF = Weather product graphical factor

These equations discussed above are the representatives of equations contained in the AWINBRM model. Other equations in the AWINBRM are listed in Appendix B - ITHINK Source Code.

In the AWINBRM model, all aircraft categories (air taxi and commuter, general aviation, and military) share similar aviation weather product but apply to different aircraft flight populations over time. As described in the previous sections, there are nine tactical aviation weather products and fourteen strategic aviation weather products in uplink part and four aviation weather products detected and collected by the sensors on air carrier and air taxi/commuter aircraft board comprising the downlink part of the system.

Each aviation weather product was modeled by each aircraft category. For example, **Figure 5.9** depicts the causal diagram of an aviation weather product (METAR/SPECI) for air carrier category. The causal diagram for METAR/SPECI aviation weather product follows the general causal diagram discussed in previous section.

The sizes of the METAR/SPECI weather product transmitted from ground weather service to the pilots at each phase of flight are determined by the flight time, METAR/SPECI sampling rate, new METAR/SPECI, number of aircraft, number of METAR/SPECI reports, and the unit size of the METAR/SPECI. For outbound aircraft, the model will calculate the size of the METAR/SPECI transmitted from outbound preflight planning operation up to the cruise operation. For the inbound flights it will start from inbound cruise operation to post-flight operations.

Figure 5.9 AWINBRM Model Causal Diagram - AC METAR/SPECI.

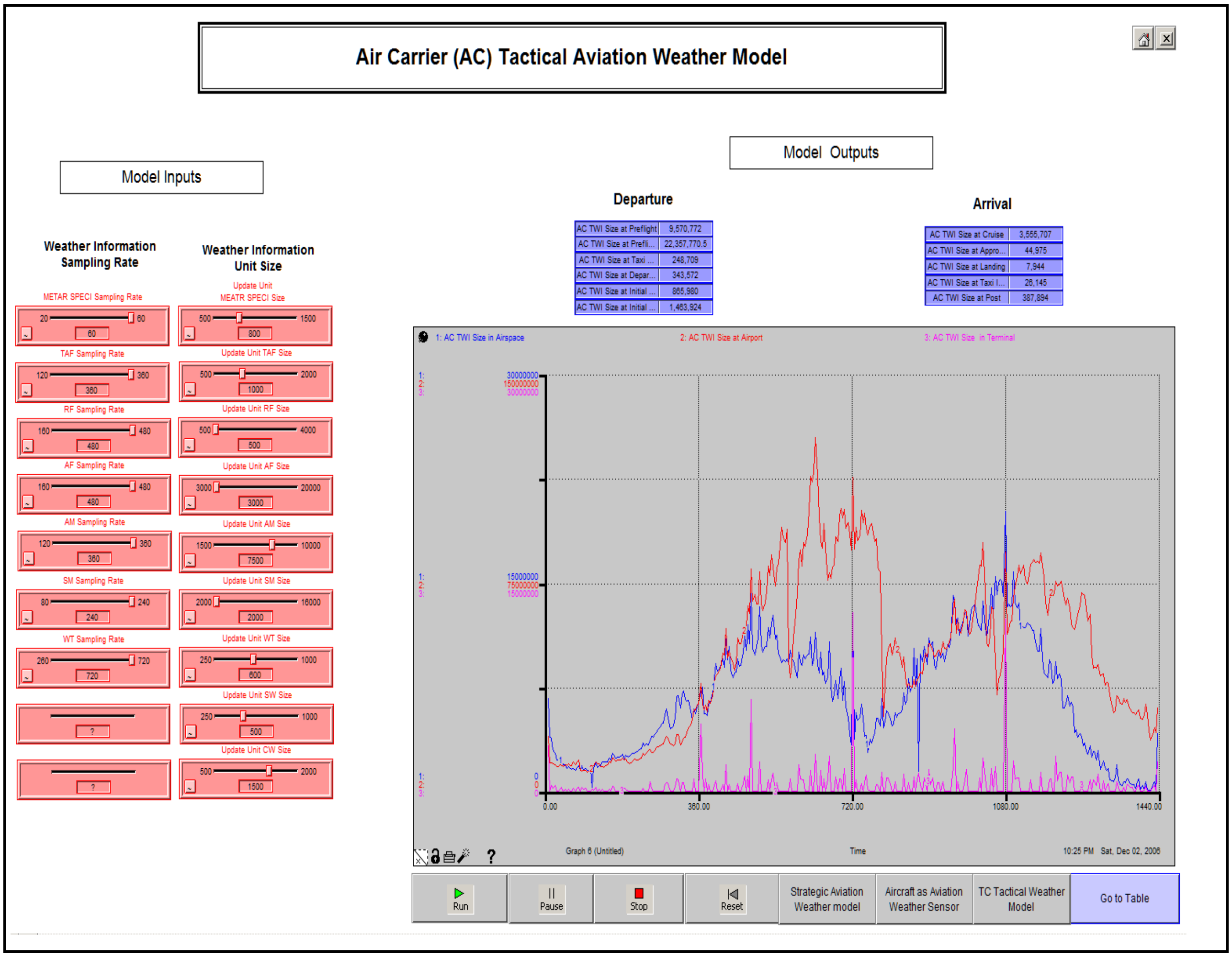
5.6.3 AWINBRM Model Interface

In order to operate and simulate the AWINBRM model at different points easily nine model graphical user interfaces (GUI) are developed using the ITHINK software package. Eight of the them express tactical and strategic weather product for each aircraft category, and one reflects the aircraft as sensor interface. Similar to the interface of the air traffic flow model, each AWINBRM model interface includes input parameters, output results including tables and graphics, and control buttons which can be used to change and modify input parameters, re-run, stop, pause models or go to any other models such as traffic flow model or aircraft as sensor etc.

5.6.3.1 Tactical Aviation Weather product Interface

Figure 5.10 graphically depicts an example of the tactical aviation weather product interface for the air carrier aircraft category. There are three components in the interface corresponding to model input parameters, output bars and graphics, and model control buttons. The input parameters include the sampling rates and sizes for each of nine tactical aviation weather products. The sampling rates are based on the existing condition and would be changed with the technology improvements. For example, the rate of METAR/SPECI aviation weather product is reported once every 60 minutes or 24 times per day, in the future this rate may increase to twice every 60 minutes. In the interface, there are slider input devices for each tactical aviation weather products which can be used to adjust the rate and size.

In the output component, there are numeric display bars, graphics and tables. The numeric display bars are used to show the size of the required tactical aviation weather product at one time. The graphics or tables demonstrate the change and size of the tactical aviation weather product at each flight phase in three regions-in the en-route airspace, in the terminal, and at the airport over a 24 hours time period. Detail output results of the model will be discussed in Chapter 7 - Model Application and Economic Impact of Aviation Weather.



METAR SPECI Sampling Rate: 20–60, 60
TAF Sampling Rate: 120–360, 360
RF Sampling Rate: 160–480, 480
AF Sampling Rate: 160–480, 480
AM Sampling Rate: 120–360, 360
SM Sampling Rate: 80–240, 240
WT Sampling Rate: 260–720, 720
?
?

Update Unit MEATR SPECI Size: 500–1500, 800
Update Unit TAF Size: 500–2000, 1000
Update Unit RF Size: 500–4000, 500
Update Unit AF Size: 3000–20000, 3000
Update Unit AM Size: 1500–10000, 7500
Update Unit SM Size: 2000–16000, 2000
Update Unit WT Size: 250–1000, 600
Update Unit SW Size: 250–1000, 500
Update Unit CW Size: 500–2000, 1500

Departure

AC TWI Size at Preflight	9,570,772
AC TWI Size at Prefli...	22,357,770.5
AC TWI Size at Taxi ...	248,709
AC TWI Size at Depar...	343,572
AC TWI Size at Initial ...	865,980
AC TWI Size at Initial ...	1,463,924

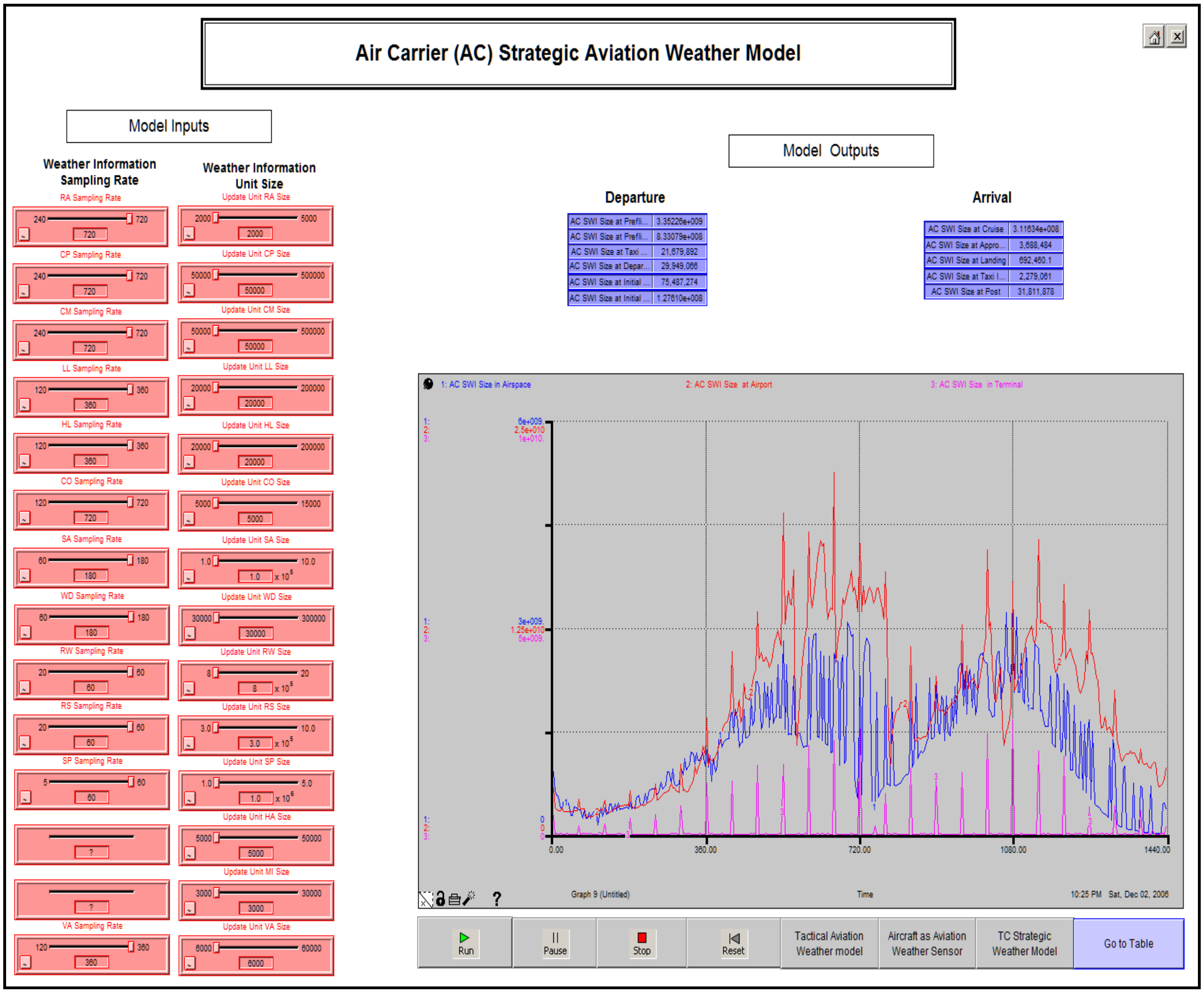
Arrival

AC TWI Size at Cruise	3,555,707
AC TWI Size at Appro...	44,975
AC TWI Size at Landing	7,944
AC TWI Size at Taxi I...	26,145
AC TWI Size at Post	387,894

Figure 5.10 AC Tactical Aviation Weather Product Model Interface.

5.6.3.2 Strategic Aviation Weather Product Interface

Figure 5.11 shows the interface of the strategic aviation weather product model for the air carrier category. As stated, the input parameters in the left of the figure have the sampling rates and sizes of fourteen strategic aviation weather products. In the right hand side of the figure, output results include the numeric display bars and figures showing the bandwidth requirements of the strategic aviation weather product over time. Other aircraft categories have the similar interfaces of the AC tactical and strategic aviation weather products.



Air Carrier (AC) Strategic Aviation Weather Model

Model Inputs

Weather Information Sampling Rate

RA Sampling Rate	240	720	720
CP Sampling Rate	240	720	720
CM Sampling Rate	240	720	720
LL Sampling Rate	120	360	360
HL Sampling Rate	120	360	360
CO Sampling Rate	120	720	720
SA Sampling Rate	60	180	180
WD Sampling Rate	60	180	180
RW Sampling Rate	20	60	60
RS Sampling Rate	20	60	60
SP Sampling Rate	5	60	60
			?
			?
VA Sampling Rate	120	360	360

Weather Information Unit Size

Update Unit RA Size	2000	5000	2000
Update Unit CP Size	50000	500000	50000
Update Unit CM Size	50000	500000	50000
Update Unit LL Size	20000	200000	20000
Update Unit HL Size	20000	200000	20000
Update Unit CO Size	5000	15000	5000
Update Unit SA Size	1.0	10.0	1.0 x 10^5
Update Unit WD Size	30000	300000	30000
Update Unit RW Size	8	20	8 x 10^5
Update Unit RS Size	3.0	10.0	3.0 x 10^5
Update Unit SP Size	1.0	5.0	1.0 x 10^6
Update Unit HA Size	5000	50000	5000
Update Unit MI Size	3000	30000	3000
Update Unit VA Size	6000	60000	6000

Model Outputs

Departure

AC SWI Size at Prefli...	3.35226e+009
AC SWI Size at Prefli...	8.33079e+008
AC SWI Size at Taxi ...	21,679,892
AC SWI Size at Depar...	29,949,066
AC SWI Size at Initial ...	75,487,274
AC SWI Size at Initial ...	1.27610e+008

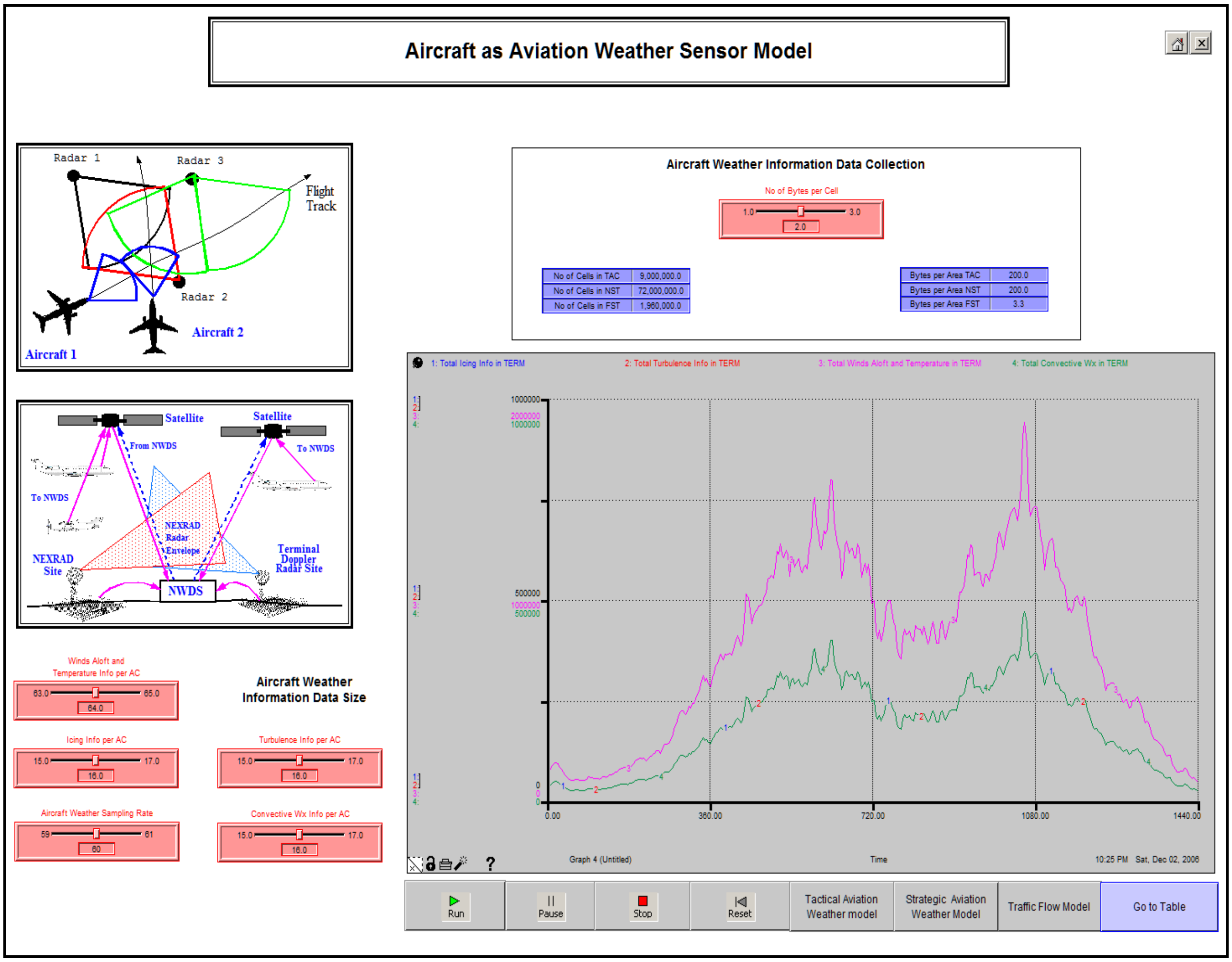
Arrival

AC SWI Size at Cruise	3.11634e+008
AC SWI Size at Appro...	3,688,484
AC SWI Size at Landing	692,460.1
AC SWI Size at Taxi I...	2,279,061
AC SWI Size at Post	31,811,878

Figure 5.11 AC Strategic Aviation Weather Product Model Interface.

5.6.3.3 Aircraft as Aviation Weather Sensor Interface

The interface of the aircraft as aviation weather sensor is depicted in **Figure 5.12**. In existing condition, there are four types of aviation weather data collected by the sensors on board.



No of Bytes per Cell
1.0 3.0
2.0

No of Cells in TAC	9,000,000.0
No of Cells in NST	72,000,000.0
No of Cells in FST	1,960,000.0

Bytes per Area TAC	200.0
Bytes per Area NST	200.0
Bytes per Area FST	3.3

Winds Aloft and Temperature Info per AC
63.0 65.0
64.0

Icing Info per AC
15.0 17.0
16.0

Turbulence Info per AC
15.0 17.0
16.0

Aircraft Weather Sampling Rate
59 61
60

Convective Wx Info per AC
15.0 17.0
16.0

Figure 5.12 Aircraft as Weather Sensor Model Interface.

In the input part, five slider input devices present the sizes of icing, turbulence, wind aloft and temperature, and convective weather data and their sampling rates. In the output part shown on the left hand-side of the figure, the numeric display bars and the figure show the size of total aviation weather data in the en-route airspace and in the terminal areas.

CHAPTER 6

Aviation Weather Communication Systems Analysis

Weather Information Communication (WINCOMM) is an element of the National Aeronautics and Space Administration's (NASA's) Aviation Safety Program (AvSP). Weather data dissemination was considered the most critical and highest ranked item related to aviation safety **[NASA, 2000]**. It is realized that many of the new weather tools could present severe demands and challenges to existing ground-to-air communications channels. This is due to the anticipated increase in the amount of weather data being transported over various channels to warrant the safety and regularity of flight. Aeronautical communications will thus need to accommodate the increased traffic associated with the dissemination of tactical and strategic weather information to the cockpit. This chapter reviews the current and planned aviation weather communication systems and explores potential communication systems and technologies that are available from non-aviation communication systems. Chapter 6 has three sections:

- General Communication Requirements,
- Current and Planned Aviation Weather Communication Systems, and
- Potential Solution from Non-Aviation Communications.

6.1 General Aviation Communication Considerations

It is useful to analyze communications requirements to support future aviation weather products in two dimensions: 1) Decision Arena (i.e., tactical, near-term strategic, and far-term strategic decisions), and 2) phases of flight (i.e., ground, terminal, and en-route). These two dimensions are represented graphically in **Figure 6.1**.

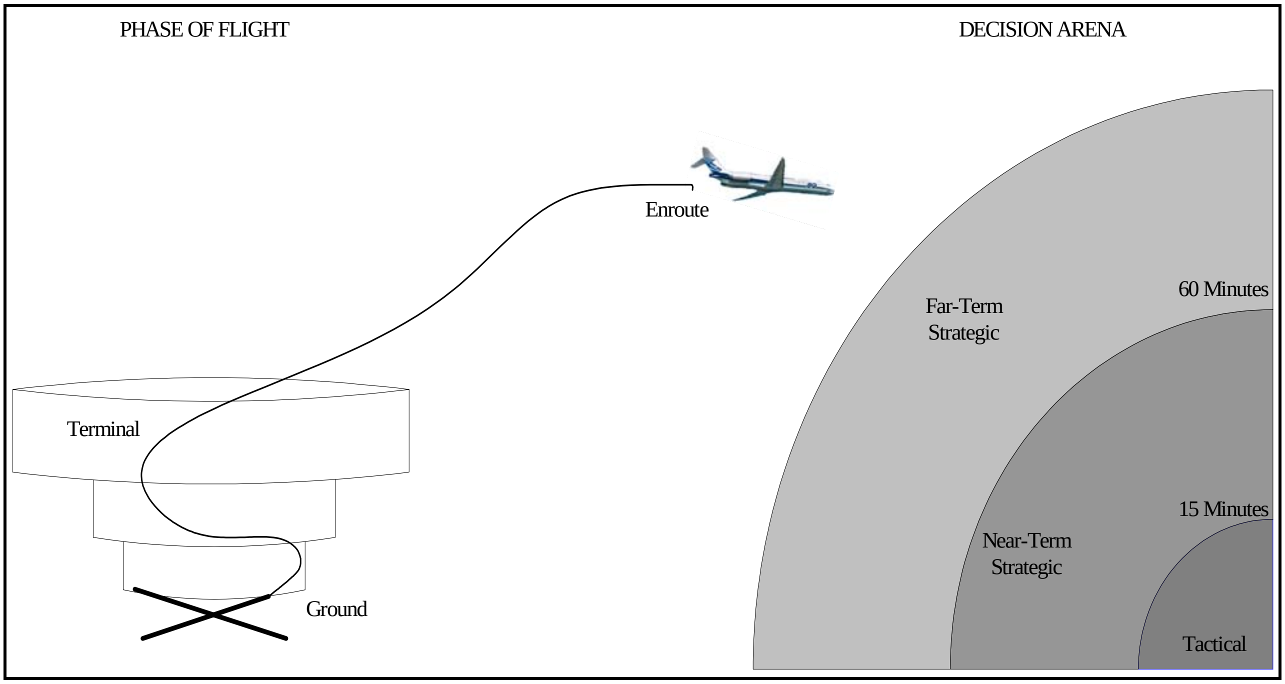


Figure 6.1 Decision Arenas and Phases of Flight.

These two dimensions can be further related to one another according to bandwidth required to support the decision arena and bandwidth available in each phase of flight.

Bandwidth requirements are shown in **Figure 6.2**. Cross-referencing each phase of flight and each decision arena yields nine specific areas that can be discussed in terms of requirements levied on communications to support future weather products. Many of these nine areas share similar restrictions and requirements, while some of the nine have very specific requirements.

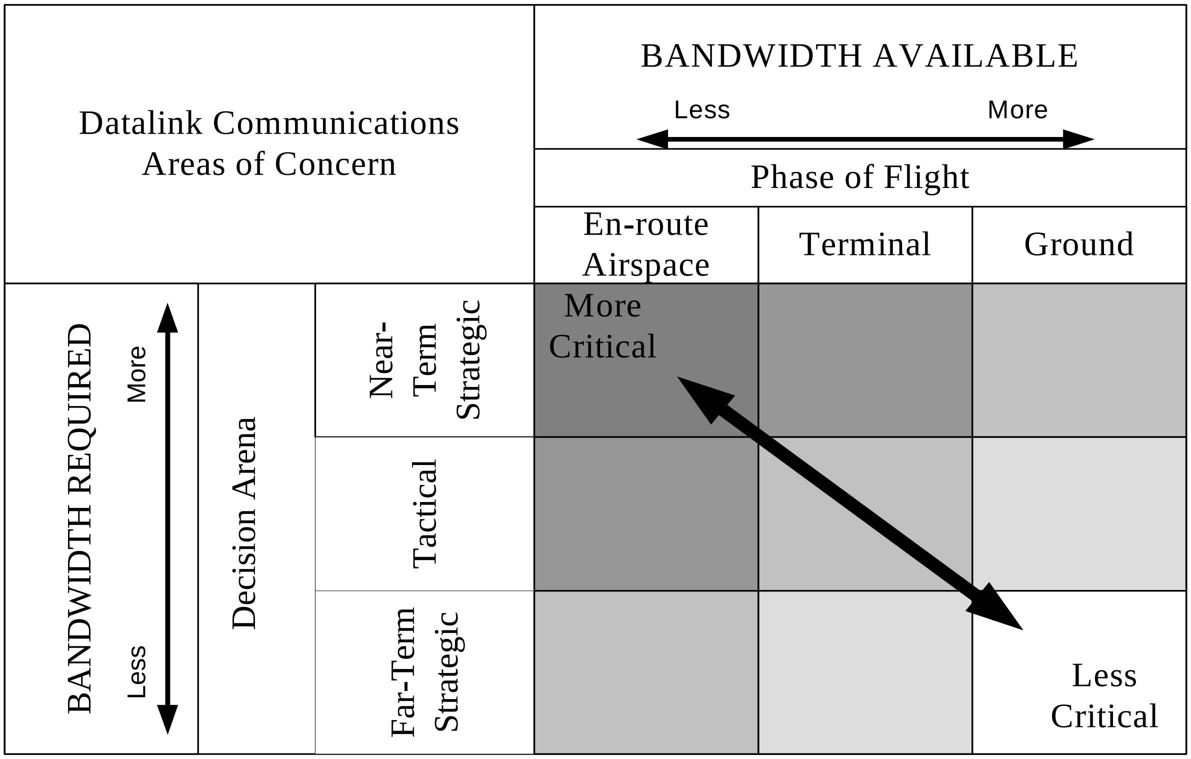


Figure 6.2 Datalink Areas of Concern in Aviation.

The bandwidth available on the ground will generally not be restrictive. Most of the time an aircraft is on the ground, the crew will have access to either wired weather outlets, or high-bandwidth wireless outlets. Terminal operations are primarily tactical in nature. This is because both “far-term” and “near-term” strategic planning would usually accompany a departure, a situation in which the crew had just completed extensive ground planning. Consequently, neither of the strategic situations adds to the terminal case and are not considered separately. The operations in the en-route airspace are primarily strategic in nature. This is because en-route tactical planning will continue to be done via on-board sensors, including PIREPs, visual cues, on-board radar and satellite linked weather. In the en-route airspace, Far-term Strategic area is currently served by a mixture of voice, paper products carried on board, Aircraft Communications Addressing and Reporting System (ACARS), and a growing population of basic, datalinked, graphic and textual weather products. Future weather products will complicate the current situation in a number of ways, creating some unique requirements.

6.2 Current and Planned Aviation Weather Communication Systems

This section will review the current and planned aviation weather information communications systems and their functions. Current aviation weather products are delivered to the cockpit using a combination of broadcasts, voice request/reply using aviation radios, and text request/reply using the ACARS. Current aviation weather communication systems include discrete very high frequency transmissions or as the voice portion of a local navigational aid and the ACARS in the terminal area. In the domestic en-route flight phase, all data is directly transmitted over Very High Frequency (VHF) radio. For short or local flights, pilots can use the Transcribed Weather Broadcast (TWB), which provides continuous, up-to-date, recorded weather information. Pilots can also receive or request weather information directly from their operation centers over VHF radio through ACARS. **Figure 6.3** shows the delivery systems available for different communication infrastructures.

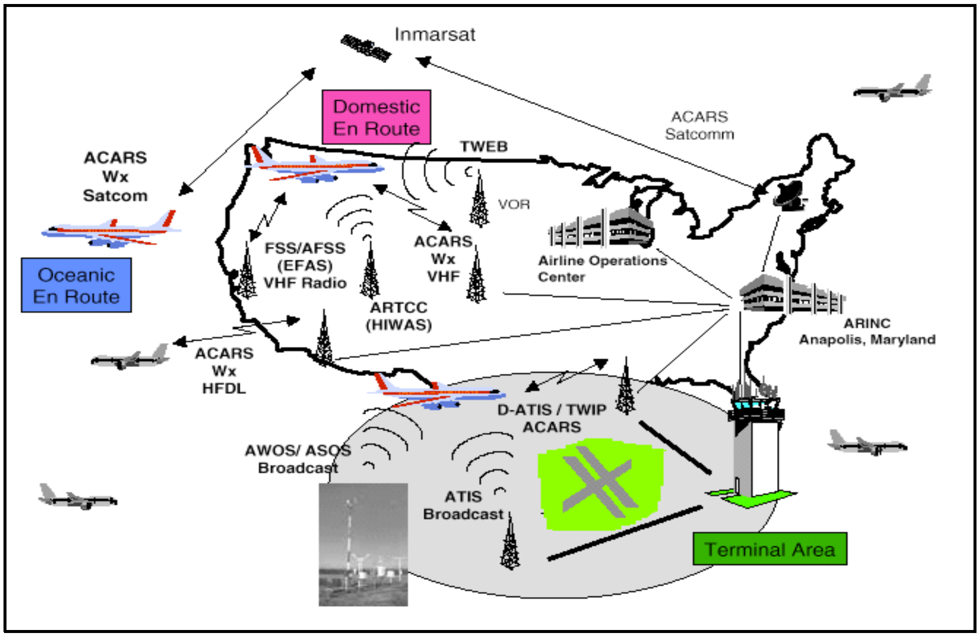


Figure 6.3 Existing Aviation Communication Systems Architecture

(Photo obtained from the FAA[23]).

Generally, there are two types of aviation weather information communication systems which are aviation datalink and voice communication systems. Each communication system includes several aviation weather information transmitted method. **Figure 6.4** graphically depicts the aviation datalink and voice communication systems **[NASA, 2000]**.

6.2.1 Aviation Datalink Communication Systems

National Airspace System version 5.0 (NAS 5.0) and the Compliance Activity Tracking System (CATS) tool indicate the following “aviation specific” datalink associated frequencies, technologies, and protocols that should be considered in this section of the research. The term “datalink” is often used to mean a variety of different wireless communications concepts within the industry. As shown in **Figure 6.4**, the aviation datalink has been divided into five groups:

1. VHF Datalink
2. Inmarsat Satellite Data ACARS
3. HF Datalink
4. UHF Datalink
5. ADS-B Datalink

6.2.1.1 VHF Datalink

In the US domestic, civil world, Very High Frequency is the predominant frequency band for aviation communications. There are various schemes proposed and currently in use for transmitting data in this spectrum. In the NAS 5.0, the following schemes are included:

6.2.1.1.1 VHF ACARS

The ACARS is an existing VHF air/ground data link that uses nearly 600 VHF locations throughout North and Central America, Hawaii, the Caribbean, and several U.S. territories. Although begun as a VHF datalink, ACARS messages can now be transmitted by High Frequency (HF) or Satellite Communication (SATCOM) as well.

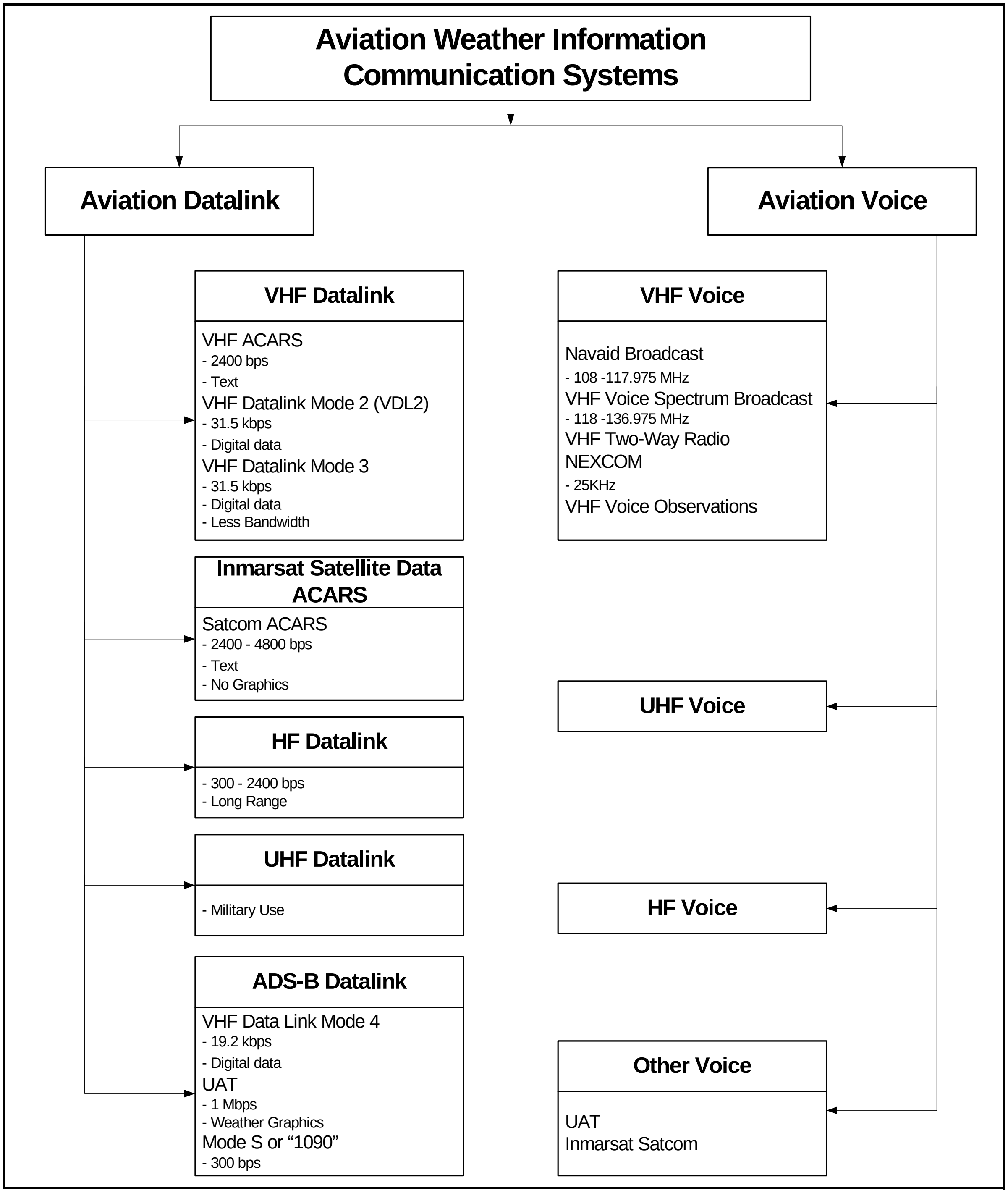


Figure 6.4 Aviation Weather Datalink and Voice Communication Systems.

Initially used to transmit only Out/Off/On/In (OOOI) events for scheduled air carriers, ACARS today supports over 50 applications, including relaying Aircraft Operational Control (AOC), Airline Administrative Control (AAC), and Air Traffic Control (ATC) messages between ground-based organizations and the cockpit. It has also been pressed into service for weather in the cockpit, including pseudo-graphical representations of detected microburst activities at selected airports under the "Terminal Weather Information Program (TWIP).

VHF ACARS datalink, as currently used, is a character-based system which has a maximum speed of roughly 2400 bps, but its effective throughput is usually much lower – sometimes on the order of 300 bps.

Although there are upgrade plans to transition ACARS from a character to a digital transmission system, it still has limited potential to provide graphical weather in the cockpit. Existing cockpit ACARS displays are generally small, monochromatic, and character based. Additionally, the limited VHF frequency allocations are already overcrowded in major terminal areas. Retrofit costs associated with upgrading future versions of ACARS to a meaningful graphical weather depiction system will probably be prohibitive.

ACARS is useful, and will remain useful, for limited, addressed, text-based, products to high-end customers. It may provide an eventual growth path for flightdeck weather if the digitized, character-based, transmission, interim standard for VHF Data Link Mode 2 (VDL2) is dropped and the system migrates to a truly pure digital mode. ACARS and its use will probably remain closely tied to airline operations which will limit its usefulness.

6.2.1.1.2 VHF Datalink Mode 2 (VDLM2, or VLD2)

VDL2, as it is often abbreviated in the industry, transmits digitized data over current VHF 25kHz channels via a Carrier Sense Multiple Access (CSMA) scheme. Good for data only, there are some VDL2 radios already in existence, and more slated for installation in future production transport aircraft.

Designed as a sub-network for the ICAO Aeronautical Telecommunications Network (ATN), VDL2 represents a transition step from analog to digital radios that will eventually support both voice and data. VDL2 supports a connection-mode, addressable datalink with an ISO 8208 network interface, can operate at a 31.5kbps maximum data rate, and is expected to be used for AOC type functions for airlines. Besides AOC functions, VDL2 is expected to support other datalink applications, including AAC and eventually ATC via Controller Pilot Data Link Control (CPDLC). It is the first step into an ATN capable datalink. ARINC also plans to use VDL2 for ACARS transmissions as described previously.

VDL Mode 2 is useful for delivering current and future weather products to the flightdeck. It is appearing now, has good speed, supports broadcast, and supports multiple protocols. It does need some frequency planning, however, due to the need for a clear guard channel on either side of a high speed datalink connection. Additionally, weather uses for VDL2 are in competition for other uses of this link, such as ATM messaging, ACARS, etc.

6.2.1.1.3 VHF Datalink Mode 3 / NEXCOM (VDLM3 or VDL3)

The Next-Generation Air/Ground Communications (“NEXCOM”) is the generic term used in NAS 5.0 plan to describe a future, digital radio capable of both voice and data transmission and reception. In current, common usage, NEXCOM and VDL3 are considered to be the same thing, although officially, that has yet to be declared. VDL3 plans to use the entire current VHF spectrum (112-136.975 MHz), split into four separate time slots for each 25kHz channel.

The NEXCOM concept was intended to use as much of the allocated aviation spectrum as efficiently as possible. Thus – it supports both voice and data, and is poised to take advantage of spectrum that is released by the decommissioning of VOR Navaids. Like VDL2, it can support up to a 31.5Kbps.

VDL3 was designed for supporting digital voice and data communications while using available, assigned, aeronautical bandwidth efficiently. It has a generally agreed technical specification that Aircraft Owners and Pilots Association (AOPA) tentatively supports, and thus seems well positioned both technically and politically. It is ATN compatible and would be able to carry all manner of communications from weather information to flight critical applications.

VDL Mode 3 could be useful for future weather product delivery to the flightdeck, with major caveats.

6.2.1.2 Inmarsat Satellite Data ACARS

Satcom datalinks are essentially telephone calls that put ACARS units in contact with an airline's operations center, using addressed communications over primarily geosynchronous satellites. There are a variety of current and planned implementations, including Aero H, H+, I, C, and mini-M – all with slightly differing schemes and target audiences that include other industries besides aviation. Typically relatively expensive, Satcom ACARS links usually need steerable airborne antennae and have been used primarily for oceanic/remote airspace.

As all current ACARS implementations are, Satcom ACARS is a character-based system that cannot support graphics. Most systems are limited to 2400 bps or less, though some upgrades will boost this to 4800 bps under certain conditions. Even with these limitations of ACARS, the requirement for addressed communications, and the relative expense of the link relegate Inmarsat to proving occasional, text-based products in remote/oceanic areas.

6.2.1.3 HF Datalink

High Frequency (HF) datalinks are currently operated by ARINC from eight stations throughout the world. They are long range, low speed links aimed at serving remote and oceanic aviation users. Like all current ACARS, HF ACARS datalink is a character based system. It typically operates at 300 bps or less, although 2400 bps is theoretically the highest speed available under perfect conditions.

There are currently no HF datalinks used or planned within the US civil aviation community, other than through ACARS. It is satisfactory for addressed, slow speed, character-based information delivery through ARINC, but not much more. Due to the nature of HF communications, an aircraft will hardly ever know in advance which HF station it might listen to, consequently, geographically-tailored broadcasts would be difficult to implement.

6.2.1.4 UHF Datalink

Ultra High Frequency (UHF) datalink will continue to play a role for US armed forces. Since the aviation portion of UHF datalink is currently reserved for the military, however, little civilian use is likely. On the other hand, there is an identifiable, but remote possibility that the military might negotiate the use of other more desirable frequencies, using their current UHF assignments as a bargaining chip. If this unlikely scenario came to pass, civil aviation, at least here in the Continental United States, could make very good use of the UHF band for datalink for all manner of information, including Universal Access Transceiver (UAT) and weather. If Instrument Landing Systems (ILS) transmitters are decommissioned with the advent of Global Position System (GPS) Local Area Augmentation System (LAAS), the UHF portion of the ILS that broadcasts glideslope information could conceivably be used for a weather datalink.

6.2.1.5 ADS-B Datalink

6.2.1.5.1 VHF Datalink Mode 4 (VDLM4 or VDL4)

VDL4 is a proposed ICAO standard, most popular in Europe, that includes a hybrid ground controlled Time Division Multiple Access (TDMA) scheme with a self-organizing capability designed primarily to enable Automatic Dependent Surveillance - Broadcast (ADS-B). It is one of the datalink candidates for ADS-B currently under consideration, along with UAT and Mode S, in the Safe Flight 21 activities. Although it is looked upon primarily as an ADS-B link, it has the potential to be used as a weather datalink, even if selected as the primary ADS-B link.

VDL4 is designed to be a multi-channel ADS-B link, providing ground-to-air and air-to-air connections via ATN. It is capable of data sharing (no voice) up to a limit of approximately 19.2 Kbps per channel, and has demonstrated limited Flight Information Service Broadcast (FIS-B) functionality in various pre-production testing. It follows a cellular paradigm and can handle nearly unlimited message traffic by managing the size of the appropriate cells. Message transfer and broadcast uplink services will be provided on supplemental channels.

6.2.1.5.2 UAT

The Universal Access Transceiver (UAT) is a MITRE Corporation developed system that features an extremely wide bandwidth broadcast system that has been proposed as an ADS-B link. UAT has been demonstrated, and has the capacity to provide both ADS-B and FIS-B, but does not currently have an official set of Incorporated (RTCA), RTCA supporting documentation or an official frequency allocation.

UAT is not planned as a voice radio and is designed exclusively to be an ADS-B link, while allowing for other broadcast applications as well. It is broadcast only, and cannot carry addressed messages such as ATN or ACARS. Due to the digital nature of the radio, however, it could conceivably carry voice signals.

UAT is currently working in the 960 MHz spectrum, and will occupying a bandwidth of approximately 2 MHz to obtain 1 Mbps raw throughput. Unlike many of the VHF datalink solutions, it will not be “tuned” to different frequencies, but would have access to various time slots within the operating frequency assignment by use of GPS-derived UTC. It uses a TDMA slotted scheme to manage various broadcasts, but also relies heavily on the high capacity of the link to allow for multiple collisions while still getting the message through to the intended receiver.

UAT offers the greatest single-channel throughput, by far, of all the currently planned civil aviation datalinks. It has ample bandwidth to provide ADS-B messages as well as complex weather graphics.

6.2.1.5.3 Mode S or “1090”:

Mode S, or “1090” as it is sometimes referred to, uses the 1090 MHz “squitter” signal associated with the Mode S transponder to transfer other information. It is the third of the three proposed ADS-B links currently under consideration in the Safe Flight 21 link evaluation.

Mode S is not planned as a voice radio and is designed to be an ADS-B link utilizing current antennae and wiring on board many of today’s airplanes. It is broadcast only, and cannot carry addressed messages such as ATN or ACARS.

Mode S operates at 1090 MHz. Although the higher frequency used would indicate a much higher throughput. Mode S, as planned, will continue to be tied to the sweep of the surveillance radar. The dwell time of about 5 seconds for each 12 second sweep leaves a throughput of only 300bps. Although adequate for ADS-B, this is not really enough for delivering graphical weather to the flight-deck.

While Mode S has adequate bandwidth to serve ADS-B purposes, it does not have the available bandwidth to also provide FIS services if it remains tied to the sweep of the radar. General Aviation (GA) does not favor Mode S as the ADS-B link due to its high cost and high power requirements. Additionally, Mode S's high frequency range gives it multi-path problems on the airport which would limit its usefulness for ground traffic management and preventing critical runway incursions.

6.2.2 Voice Communication Systems

As mentioned previously, data is the primary focus of this research. Nevertheless, both digital and analog voice communications will continue to play a vital role in delivering weather to the cockpit. How voice communications are handled as the NAS is upgraded will impact both the frequencies and bandwidth available for data.

6.2.2.1 VHF Voice

VHF is by far the most widely used portion of the spectrum for voice broadcast. It is predicted to remain so in the foreseeable future.

6.2.2.1.1 Navaid Broadcast

Currently, many VHF Omnidirectional Ranges (VORs) broadcast weather information via the Hazardous In-flight Weather Advisory Service (HIWAS) program, however, the current NAS calls for decommissioning many VORs over the next 15 years. As this occurs, the HIWAS outlet for Severe Weather Forecast Alerts (AWW), SIGMET, convective SIGMET, CWA, urgent PIREP, etc. information will be replaced. Currently, this information is transmitted on the navigational portion (108-117.975 MHz) of the VHF spectrum.

6.2.2.1.2 VHF Voice Spectrum Broadcast:

Some broadcasts, such as the Automated Terminal Information Service (ATIS), Automated Weather Observing Systems (AWOS), etc. are transmitted on regular voice frequencies (118-136.975 MHz). While many of these products are being digitized, synthetic voice broadcast of the digitized information seems likely to be required beyond the 15 year horizon described in NAS plan due to projected aircraft equipage, especially among GA.

6.2.2.1.3 VHF Two-Way Radio

PIREPs, controller-provided information, contact with airline operations centers, requests to Flight Service Stations, etc. will also continue into the foreseeable future. In many areas the frequencies are already overloaded with such radio traffic which is part of the justification for sending future information via datalink.

6.2.2.1.4 NEXCOM

NAS 5.0 indicates that VDL3/NEXCOM is programmed to occupy the bandwidth made available as VORs are decommissioned. The combination of splitting each 25KHz frequency into two voice and two data channels, combined with using more of the VHF spectrum for voice could nearly, effectively double the available voice channels over the next 15 years, however the effect of co-channel interference is problematic and may severely limit that theoretical maximum.

6.2.2.1.5 VHF Voice Observations

VOR navaids are scheduled to be decommissioned, although they currently serve a vital voice broadcast need. If voice broadcast is continued as a means to disseminate aeronautical information such as ATIS, and SIGMETs, the current VHF voice spectrum will continue to be heavily taxed.

6.2.2.2 UHF Voice

UHF voice is primarily a military issue, and it will likely remain so. Generally the military is likely to face the same congestion and allocation issues with UHF as the civilian world faces with VHF

6.2.2.3 HF Voice

Because HF voice is so widespread and relatively inexpensive, it will likely remain in use for some time. As satellite communications become less expensive, and more common, it appears HF voice will go through a protracted, but steady decline. HF datalink has usefulness, but is slow and will probably not grow in the future. Consequently, there appears to be no significant forced tradeoff between voice and data in the HF spectrum in the future.

6.2.2.4 Other Voice

There are a variety of other voice communications available to the cockpit in the future. At present, only UAT and Inmarsat Satcom are generally recognized as aviation-specific in that they are mentioned in NAS 5.0.

6.2.2.4.1 UAT

If UAT becomes a viable radio choice, as noted above, conceivably there could be enough bandwidth for voice and data to co-exist, although UAT has been designed specifically for data transmission. As in the VDL3 case, if enough aircraft, especially general aviation users, equip with UAT radios, datalink will likely become the leading method of broadcasting information. UAT could technically be forced into supporting only broadcast voice, but interactive voice conversations will still be required and performed.

UAT is potentially very useful for delivering future weather products to the flightdeck, with major caveats. Since UAT was designed from scratch to support ADS-B and other broadcast applications, it has the theoretical bandwidth to support the future products. However, it does not yet have an officially assigned frequency and is far behind in the technical development for standards as compared to VLD4 or Mode S. If UAT can overcome these significant hurdles, it would be an attractive source for delivering future weather products to the flightdeck.

6.2.2.4.2 Inmarsat Satcom

Inmarsat enjoys a unique place in the world of aviation. With an aviation certified system, they provide a critical link in remote areas of the globe. Even so, the directional nature and relatively higher costs of these established Geosynchronous Earth Orbit (GEO) systems will likely minimize their impact on future voice weather dissemination.

Inmarsat's remote connectivity is useful, and will continue to be so; however, its usefulness is limited to that which can be supported by a telephone-type connection. This holds true for both voice and data. The low data rate and non-support of broadcast capability will limit it in delivering future weather products to the flightdeck. It will remain useful for oceanic/remote areas and continue to serve both AOC and ATM functions. Although it is subject to growing competition, Inmarsat's planned speed increases and installed base should keep it viable for this limited aviation use for the foreseeable future.

6.2.3 Summary

According to the weather information requirements analyzed in Chapter 5 the existing aviation weather communication systems discussed above do not have enough capabilities to transmit all weather information, especially for graphical weather information, between ground service centers and pilots. The next section will explore non-aviation communication systems for potential use in aviation weather formation transmission.

6.3 Potential Solution from Non-Aviation Communication

Current aviation communication and those planned for the future offer a variety of methods for getting weather information to the cockpits. It is also apparent that there is no one-size-fits-all solution. Some products are well served by current and emerging communication systems but other products that are needed now and are likely to result from on-going weather research will overload even the most capable aviation communication systems, especially the increase in air traffic in the future. The solution may be to look outside the aviation industry for technologies to augment aviation communications in supporting weather information distribution. This section identifies and evaluates specific existing communications technologies, techniques and services which are not currently applied to aviation but could offer potential technical solutions enabling the efficient delivery and use of tactical and strategic weather information.

Figure 6.5 shows some specific systems and technologies **[NASA, 2000]** which will be discussed and these include:

- Cellular / PCS Telephone Technology
- Microwave Distribution System - MMDS / LMDS
- Satellite - Digital Audio Radio Services (S-DARS)
- Internet In/From the Sky
- Software Defined Radios

6.3.1 Cellular / PCS Telephone Technology

The cell phone industry has grown significantly since the introduction of mobile hand held telephone systems in the late eighties. Initially, these systems were analog voice modulated carriers but are rapidly transitioning to digitized voice systems that utilize complete digital processing and routing techniques. Two distinguishing characteristics of a cellular telephone system that are different from earlier mobile radio phones are the Cell and Tracking / Hand-off techniques. These two concepts allow mobile users to move beyond the basic range of the radio link without interruption of service.

The basic cell arrangement is a seven cell pattern which allows frequencies to be re-used without interference between adjacent cells. This basic pattern is repeated as often as necessary to cover the defined area using the frequency spectrum allocated for the type of telephone service.

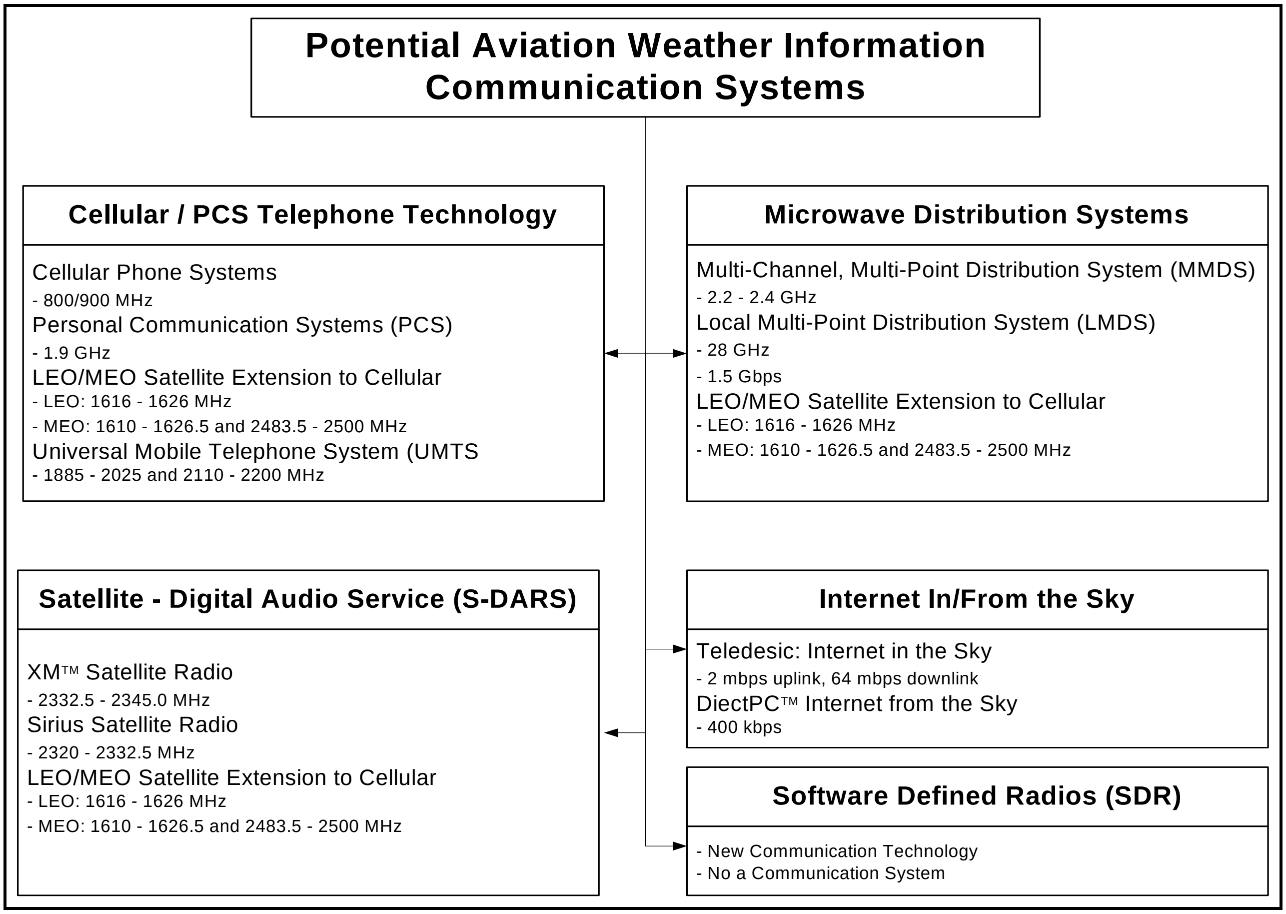


Figure 6.5 Potential Aviation Weather Information Communication Systems.

The Tracking / Hand-off functions allow mobile users to be identified and served throughout the service area. These essential functions include: the Mobile Unit (cell phone), the Antenna and Base Station (at least one per cell); the Mobile Switching Center and the Call Processing Center. The Antenna and Base Station provide the radio link to mobile units within the cell and route information to the Mobile Switching Center. The Mobile Switching Center routes call initiation information to the Call Processing Center for user identification, billing, etc. then to the called party either through the public telephone switching system (PSTN) of another mobile switching center.

6.3.1.1 Cellular or PCS?

The original allocation of frequency bands for Personal Communication Systems (PCS) was distinct from the cell phone industry and intended to create new technology to support personal communications of all types. The distinction between the terms Cellular Phones and Personal Communication Systems is becoming somewhat blurred however. Generally, mobile phone system operating in the 800/900 MHz band are considered cellular phone systems while Personal Communication Systems are mobile phone systems operating in the 1.9 GHz band. The distinction between the two terms is more than just semantics since the Federal Communication Commission (FCC) has restricted the sale of spectrum and service areas based on a complicated set of rules designed to foster competition. Cellular and PCS services areas cover overlapping geographical regions.

6.3.1.2 Cellular Phone Systems

The Cell phone industry began in the United States in 1981 when the FCC adopted rules creating a commercial cellular radio telephone service. Geographical regions were identified and two 25 MHz bands for each region were allocated for cell phone service. One 25 MHz band was allocated for wireline (phone companies), and one for nonwireline to stimulate competition.

6.3.1.3 Personal Communication Systems (PCS)

The FCC allocated PCS Radio Frequency (RF) spectrum and began auctioning space in the band on December 5, 1994 - *to foster creation of new radio communication services that allow individuals to communicate anywhere at anytime*. Two PCS types were defined: narrowband and broadband. Three one MHz bands were allocated at 901-902, 930-931, and 940-941 for PCS narrowband to support advanced paging services. Six broadband PCS bands in the 1850 - 1990 GHz range were allocated for voice, data, and video services. The allocation consisted of three 120 MHz blocks and three 10 MHz blocks.

The type of communication service was not specified in the FCC ruling in an attempt to stimulate new technology. Winning bidders were free to decide how to use the spectrum in the regions they had purchased. The spectrum has been used primarily for higher performance voice phone system, however. Some of the cell phone like systems that have been established using the new spectrum allocation include, PCS1900, a U.S. version of Global System for Mobile Communications (GSM) operating in 1.9 GHz band as well as upbanded Advanced Mobile Phone System (AMPS), Narrowband-AMPS, Digital-AMPS, and Code Division Multiple Access (CDMA).

6.3.1.4 LEO/MEO Satellite Extension to Cellular

The emerging voice telephone satellite systems such as Iridium and GlobalStar offer services very similar to cell phone. In fact they are becoming extensions to the cell phone communication systems that allow world wide roaming.

Iridium is a Low Earth Orbit (LEO) system of 66 satellites providing digital voice as well as fax and pager communication services. Handheld mobile units communicate directly to satellites using the 1616 - 1626 MHz band. In Iridium, the frequency reuse function of the cell is replaced by spot-beams and switching and handoff is performed by processing on-board the satellite. Some Iridium mobile units allow GSM customers to use their Subscriber Identification Module (SIM) modules in Iridium handsets to gain access to the Iridium system. The SIM provides for authentication and billing through the user’s GSM account.

GlobalStar is a constellation of 48 LEO bent-pipe satellites that operate in the 1610- 1626.5 MHz band for uplink and 2483.5-2500 MHz band for downlink. GlobalStar is a CDMA system. User-terminals for the GlobalStar system are dual or multi-mode, allowing interoperability between satellites and terrestrial systems such as AMPS, GSM and PCS1900. Mobile units first try to connect through existing cellular networks and, failing that, connect through the satellite system.

6.3.1.5 Future Cell Phone Systems - Universal Mobile Telephone System (UMTS)

A future cell phone technology system called the Universal Mobile Telephone System (UMTS) aims to expand the capabilities of mobile telephony into high speed data and video media as well as voice.

UMTS is a European led initiative to define the next (third) generation of global cellular. The UMTS forum was created in 1996 for defining standards and procedures and to encourage industrial cooperation. The forum has over 190 members representing “who’s-who” in mobile communications.

UMTS will employ multi-mode/multi-band audio/visual terminals with voice and packet data communication. Wide band-CDMA will be used for multiple access. A family of cell types are being defined to support different data rates as allowed by available spectrum and technology. These include: Home-cell, Pico-cell (in-building), Micro-cell (urban), Macro-cell (suburban), and Satellite (global). The transmission rate that will be supported based on the type of communication cell is: 2,048 Mbit/s (home/pico/micro), 384 Kbit/s (micro/macro), 144 Kbit/s (full mobility).

Based on the list of members of the UMTS Forum, there seems to be very little interest from the aviation community in UMTS for air-ground communications. The performance anticipated for the system would provide for weather information to the cockpit and an effort should be made to assure that aviation is included in the development and planning of the system.

6.3.1.6 Aviation Weather Applications for Cell / PCS Phone Technology

If cell phone technology is available in the cockpit a number of sources of weather information would be made available. These include all the sources that a pilot currently has for getting information over the terrestrial telephones such as FSS/AFSS and some ASOS installations. In addition, those sources of weather graphics currently available via FAX would be accessible. With a lap top and a modem attached to a cell phone, a wide variety of internet sites that provide aviation weather would be available to pilots. Having available computer/modem/cell phone combination opens up many possibilities for enhancing weather information for pilots. An example might be a software system aware of the flight plan that periodically retrieves weather information along the route.

The process could be automated to get weather updates much like most e-mail systems are designed to contact the mail server for new e-mail on a regular basis. Such a system could check for changes to forecast weather in the flight plan and alert the crew if there is potential danger ahead. Weather databases could be designed to update a revision code if there are major changes so airborne systems would not have to download new weather files if the forecast revision has not changed since the last download.

Automated dialing and canned messages have been used in telephone advertising for years. Weather warning systems could be designed to automatically call each plane in a danger zone to provide weather condition alerts.

6.3.1.7 Cell Phones in the Cockpit

Cellular phone systems are already finding their way into the cockpit. The Allied Signal AIRSAT™ system is a low cost cell-like system for accessing the Iridium network of satellites from the cockpit. Another cockpit telephone system that is actually a cell phone in the cockpit is the AirCell system.

6.3.2 Microwave Distribution Systems

Several systems have been used to distribute television and provide interactive services to business and residences using microwave links rather that cable or fiber optics. Two of these evaluated for their potential for aviation weather applications are the Multi-channel, Multi-point Distribution System (MMDS) and the Local Multi-point Distribution System (LMDS).

6.3.2.1 Multi-channel, Multi-point Distribution System (MMDS)

Multi-Channel, Multi-point Distribution Service (MMDS) is a digital wireless communication system designed primarily as a distribution system for cable television. It operates in the 2.2 - 2.4 GHz band. At this frequency, line-of-sight between antennas is required and repeaters are implemented to work around obstructions such as buildings and terrain. Antennas are usually about 15 miles apart. MMDS was a predecessor to Direct Broadcast Satellite (DBS).

6.3.2.2 Local Multi-point Distribution System (LMDS)

Local Multi-point Distribution System (LMDS) is a broadband fixed wireless point-to-multipoint communication system that operates in the 28 GHz band. It uses a cellular like implementation to provide line-of-sight internet access, videophone, video conferencing and Pay-Per-View cable television. It uses cells sizes with a 2-4 mile radius. It offers potential data rates of up to 1.5 Gbps.

6.3.2.3 Potential for Using MMDS/LMDS for Aviation Weather Distribution

The technology used for MMDS and LMDS have several characteristics that would limit their use for ground-to-air communication. These include:

- Current systems are for fixed services only
- No tracking and handoff capability is implemented
- Sectorized polarization favors fixed rather than mobile service
- Short distances - 2 to 4 miles
- Systems are not likely to be widely distributed - they are most useful where fiber and cable systems are expensive to implement
- Airborne systems would require tracking systems that would be very expensive and limited in application

The conclusions are that MMDS and LMDS are not likely candidate systems for distributing aviation weather.

6.3.3 Satellite - Digital Audio Radio Service (S-DARS)

Digital Audio Radio Service (DARS) is a revolutionary update to the existing AM/FM radio bands. The idea is to broadcast digitized audio rather than modulating the carrier with analog audio signals. The resulting signals received and processed have potentially much higher quality audio. S-DARS is Digital Audio Radio Service broadcast from satellites.

In 1991, the FCC awarded Worldspace Management Corp. experimental licenses to launch a S-DARS satellites over Africa. In 1992, the FCC allocated spectrum in “S” band (2.3 GHz) for nationwide broadcasting of satellite-based Digital Audio Radio Service. Licenses were awarded to American

Mobile Radio Corp. (AMRC) and CD Radio in 1997 to build and operate S-DARS in the United States.

6.3.3.1 XM™ Satellite Radio

American Mobile Radio Corp. (AMRC) was renamed XM™ Satellite Radio in 1998. XM™ Satellite Radio offers S-DARS broadcast of 100 channels available anywhere in the lower 48 states. Programming consisting of music, news, weather, and sports will be uplinked from Washington D.C. Services stated in the first half of 2001. XM™ Satellite Radio uses two satellites in GEO orbit (115º and 85º West Longitude). The 100 channels will take up 12.5 MHz in the 2332.5 to 2345.0 MHz band. In addition to the satellite broadcast, a terrestrial repeater network is used to fill in gaps in coverage caused by obstructions (buildings, mountains, etc.). Users are able to receive the digital audio on a receiver that includes the current AM and FM bands as well as the XM band. The AM/FM/XM radios replace the traditional AM/FM radios.

6.3.3.2 Sirius Satellite Radio

The other winner of S-DARS licenses, CD Radio, became *Sirius Radio* in 1999. Sirius Radio offers 50 music channels and up to 50 channels of news, weather, and sports w/ display of information about the channel/programming beginning the fourth quarter of 2000. Programming is uplinked from Rockefeller Center in Manhattan, NY. to satellites - covering the lower 48 states coast-to-coast.
Unlike the GEO satellites used by XM Radio, Sirius Radio uses three *bent-pipe* satellites in inclined orbits such that each satellite spends at least 16 hours above the equator and allows for complete coverage of the lower 48 states. Sirius Radio will broadcast in the 2320-2332.5 MHz band, to receivers identified as AM/FM/Sirius radios. Sirius will also require terrestrial repeater networks to fill in gaps in coverage due to obstructions. (buildings, mountains, etc.).

6.3.3.3 Potential Aviation Weather Application of S-DARS

As a broadcast system covering the entire lower 48 states, there is limited opportunity for use of S-

DARS to deliver aviation weather information. Dedicated programming for aviation weather products could be provided in voice format on one or more of the 100 channels. A more limited approach would be to get the Weather Channel to include national aviation weather products and alerts. Since both S-DARS systems are national broadcasts (lower 48 states), aviation weather products best supported would be those defined for large areas such as:

- Area Weather Forecast
- AIRMETS / SIGMETS
- Other Weather Alerts / Warnings

6.3.4 Airborne Internet

Other satellite systems offer greater potential for aviation weather aviation communications. Two in particular include Teledesic and DirectPC™.

6.3.4.1 Teledesic: Internet-in-the-Sky™

The Teledesic system referred to as the Internet-in-the-Sky™ promises a broadband satellite network to provide “fiber-like” access to telecommunication services worldwide. Applications will include broadband internet access, interactive multimedia, and high quality voice at cost that are expected to be competitive with wireline/fiber optic systems. Service is scheduled to begin in 2004. Teledesic uses 288 satellites in Low Earth Orbit (LEO) to provide data rates of 2 mbps uplink and 64 mbps downlink direct to home/office computers. The system is designed for Fixed Satellite Services but expects to serve marine and aviation customers as well. With the expected data rates, Teledesic could address communication requirements for all aviation weather products including voice, text, graphics and girded data. To make Teledesic available for aviation use, components designed for fixed based system operation would have to be adapted for flight deck application. This would include low cost tracking antennas for Ka band: 28.6-29.1 GHz Uplink, 18.8-19.3 GHz Downlink.

6.3.4.2 DirectPC™ Internet-from-the-Sky

Another satellite system supporting internet applications is DirectPC™ from Hughes Network Systems. DirectPC™ is like a normal internet service via modem but with high speed download (up to 400 kbps) via satellite.

DirectPC™ is a product and service of Hughes Network Systems. Services are currently available in the United States using the Galaxy III-R - GEO satellite located at Longitude -96º but are expected to be available worldwide over other satellites by 2002. The system appears to the user like any other modem internet service but with much faster downloads of large blocks of data. A request for URL has a "tunneling code" attached which directs the request to the DirectPC™ Network Operations Center (NOC). The NOC retrieves information via multiple T-3 lines then beams the data to the user system via satellite using the Ku Band. The components required to receive the service include: a personal computer with a modem and an internet service provider (ISP) plus a DirectPC™ antenna, a satellite modem, and satellite access software.

Two services offered by Hughes that are unique to DirectPC™ are Turbo Webcast™ and Turbo Newscast™. These two services take advantage of the one way high speed data characteristics of the satellite system by pre-packaging large amounts of data for bulk download to the subscribing user. Turbo Webcast™ combines multiple layers of user selected web sites (7 to 9 layers deep) for download all at once. The user can then browse the data offline. Turbo Newscast™ is a similar service that delivers regular updates of news related web sites. In this case the updates can be received by the user over the satellite system without the computer having to be connected to the internet service provider over the phone system.

6.3.4.3 Potential Aviation Weather Applications

A low cost data link system capable of delivering high volumes of information to the cockpit would address many of the emerging needs for better weather information delivery responsive to the needs of individual flights. Both request/reply and broadcast type services could be supported, delivering weather in a variety of formats (text, radar graphics, satellite photos, etc.). In addition, individualized, flight specific, weather updates could be supported much the same as Turbo Newscast™ is provided to home and office computers today.

6.3.5 Software Defined Radios (SDR)

A communication technology rather than a communication system, Software Defined Radios (SDR) have the potential to revolutionize communications in ways that make the current method of allocating portions of the frequency spectrum obsolete. Software Defined Radios are wide band transceivers that implement transmit/receive functions in software rather than hardware. The SDR processes complete "waveforms" rather than just filtering, and demodulating signals from a carrier frequency. The concept of radios defined as AM, FM, FSK, or phase modulation types no longer apply to SDRs. An SDR becomes the "type" radio it is programmed to emulate and can change characteristics on the-fly to support any new waveforms programmed into its memory.

6.3.5.1 Potential Aviation Applications of SDR

SDRs have the potential to provide the same benefit to civil aviation as is needed for military communications. In the air, aviation SDRs could provide multi-band, multimode, multi-function radios able to adapt to all existing and future voice and datalink aviation communication systems, around the world, through software programming. On the ground, SDRs could allow nationwide management of aviation frequencies. A centralized optimization system could change assigned aviation frequencies as required to balance load and optimize spectrum usage - across the nation. Airborne systems using SDRs would be able to adapt in real-time to re-allocated spectrum. With Software Defined Radios, there would no longer be a need to satisfy all types of communication requirements using a single waveform (like VDL Mode 3). Frequency, bandwidth, modulation type, multiple access techniques, etc. could be defined to optimize for the information type rather than trying to force-fit all media types (voice, data, video) into the same communication system.

6.3.6 Summary of Solutions Available from Non-Aviation Communication Systems

6.3.6.1 Voice Weather Products

Cellular and LEO/MEO satellite phone systems could provide request/reply capabilities in the cockpit to access weather services from the air as is done on the ground today using terrestrial telephones. Research is needed to expand the availability of Cell/SAT technology to all category of flights and all airspace. S-DARS is a system for broadcasting digitized voice and music and has wide coverage but has been narrowly defined around the entertainment industry in the United States. Opportunities for aviation weather applications are very limited.

6.3.6.2 Text Weather Products

FAX, and Internet access over cellular and LEO/MEO satellite phones could provide access to text and some graphic products from FSS / AFSS and the World Wide Web.

6.3.6.3 Graphics / Gridded Data

Limited request/reply capability is possible using Cell/Sat phone access internet aviation weather sites. Bandwidth over voice grade communication systems is limited, however, and this could prevent widespread usage. Future cell phone technologies being developed could address flight deck weather needs if aviation is included in the definition of the using community.

Large graphic & gridded files could be delivered using a combination of Cell/Sat phone technology and DirectPC™ like download of large data files. The technology already exists for ground based applications and airborne adaptations seem feasible. Future Internet-in-the-Sky™, could address a wide range of aviation communication needs if the system designed for Fixed Satellite Service (FSS) can be extended to airborne mobile.

The technology needs further development. Software Defined Radios (SDR) may change the way RF spectrum is allocated and used in the future. Opportunities exist for adapting SDRs to solve the wide range of communication needs resulting from the transition to CNS/ATM and free flight.

CHAPTER 7

Model Application and Economic Impact of Aviation Weather

In the previous chapters, the Air Traffic Flow Model (ATFM) and Aviation Weather Information and Bandwidth Requirement Model (AWINBRM) were developed. This chapter presents the applications of these models and also develops a model to conduct the economic impact of an aviation weather system considering en-route flights for further research in aviation weather system. Three sections are included in this chapter and they are:

- Air Traffic Flow Model Application
- Aviation Weather Information and Bandwidth Requirement Model Application
- Aviation Weather Economic Impact

7.1 Air Traffic Flow Model Application

Atlanta Air Route Traffic Control Center (ARTCC) is chosen as an example to run the ATFM models. **Figure 7.1** shows the sectorization of Atlanta ARTCC.

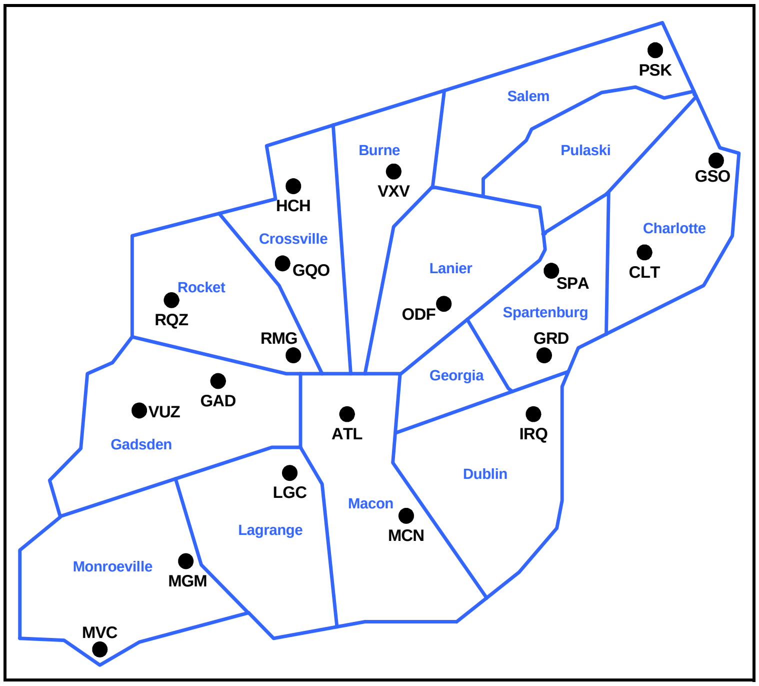


Figure 7.1 Atlanta ARTCC and Sectorization.

Atlanta ARTCC is currently the busiest air route traffic control center in the world working over 3 million aircraft operations a year. Atlanta ARTCC is responsible for en-route air traffic control operations in the skies over Georgia and portions of Alabama, Tennessee, Virginia, Kentucky, West Virginia, North Carolina and South Carolina. The airspace is designed primarily to serve two of the world's busiest airports, Atlanta Hartsfield International, Georgia and the Charlotte Douglas International, North Carolina. Additionally, the en-routes in the airspace feed from western US airports to and from the major airports of the northeast, and the ever-increasing traffic to and from the State of Florida. In addition to approach controls for the international airports in Atlanta and Charlotte, the airspace overlies 11 fast growing regional airport approach controls. (Macon and Columbus GA now located at Atlanta Large Terminal Approach Control, Birmingham and Montgomery AL, Knoxville, Chattanooga, and Tri-Cities TN, Greer SC, Asheville and Greensboro NC, and Augusta GA.) Atlanta ARTCC is known for providing Southern-style hospitality and service in spite of the demands of some of the world's busiest and most complex airspace. Air traffic control is provided utilizing 47 radarscopes divided into seven areas of specialization.

7.1.1 Model Data

7.1.1.1 Data Sources

The ATFM model needs some major input data such as the aircraft based at airport, flight demand, and aircraft dwell times etc. These data are mainly obtained from several sources: 1) on-site observations, 2) the existing database - Enhanced Traffic Management System (ETMS) data, radar data, Official Airline Guide (OAG), Flight Information Display System (FIDS), Aviation System Performance Metrics (ASPM), Terminal Area Forecast (TAF), and flight manual, and 3) Simulation Models - SIMMOD, PathPlanner, and Aircraft Gate Model.

On-site Observations

Combining the on-going projects, the on-site data collection was conducted in the following airports from large airlines hubs - Philadelphia, Pittsburgh, mid-size airlines hubs - Louisville, Milwaukee, Sacramento, San Jose, small airlines hub - Buffalo, to GA airport - Cincinnati Municipal Lunken Field. At those airports, the following data were collected: preflight operations, taxi out and take off operations, departure operations, approach operations, landing operations, taxi in and parking operations, and posting flight operations.

Existing Database

The existing databases data described above are used to determine aircraft dwell time in the airspace such as initial climb segment operations, initial cruise operations, cruise operations, and approach operations.

Simulation Model

Simulation models are used to further verify the data from observation and existing data.

7.1.1.2 Aircraft and Flight Data

Based on the aircraft performance characteristics aircraft is divided into four categories which are Air Carrier (AC), Air Taxi/Commuter (TC), General Aviation (GA), and Military (ML). Air Carriers operate large, high performance airplanes that cruise at altitudes above 18,000 feet. Air Taxi/Commuters characteristically operate smaller and lower performance aircraft with passenger seats ranging from 10 to 70. As the FAA forecast, this category has been growing at a faster pace than other aircraft categories since they are comfortable to passengers and they are more profitable for airlines. Usually, General Aviation aircraft are smaller than Air Taxi/Commuter aircraft, it includes personal, private, and business aircraft with less navigation equipment on board. From an operational point of view, Military flight activities comprise a sub-system that must be fully integrated with the NAS.

According to the existing base aircraft and flight schedule and the FAA's Terminal Area Forecast (TAF) **Table 7.1** lists the base aircraft in Atlanta ARTCC for years 2005 and 2025. The aircraft based at airport contained inside the ARTCC and the aircraft operations are collected at the most major airports in Atlanta ARTCC except some very small airports without data in the FAA's TAF.

Table 7.1 Base Aircraft in Atlanta ARTCC.

Year	Air Carrier	Air Taxi/ Commuter	General Aviation	Military	Total
2005	600	500	6,000	200	7,300
2025	1,000	1,200	12,000	400	14,600

In the future, the number of aircraft based at airport are not projected in the FAA's TAF. The future base aircraft in **Table 7.1** is estimated based on the total aircraft operations projected in FAA's TAF and the average turns per aircraft per day.

Table 7.1 shows that general aviation has the largest fleet in four aircraft categories, however, only one sixth of the general aviation fleet operate each day and the rest of them are parked at airport. Therefore, one sixth of general aviation fleet will be the initial value in the ATFM model.

7.1.1.3 Aircraft Dwell Time

The dwell times at each flight phase are an important input data in the ATFM model. Aircraft dwell times at each phase of flight have the different values corresponding to different performance of each class of vehicles. Also, different aircraft types at the same flight phase have the different dwell times. The dwell times are collected based on the aircraft categories defined above. The large samples of aircraft dwell time were collected from on-site observations at airports, existing data, and simulation scenarios. Based on the data characteristics the normal distribution is used to deal with these dwell time data.

The following tables illustrate the mean dwell times and their variances at each phase of flight for difference aircraft categories.

Military aircraft category usually operates large aircraft, for example, C-130 and KC-135 aircraft. Their performances characteristics are similar to air carrier aircraft. **Table 7.2** lists the mean dwell times and their variances for air carrier and military aircraft.

Table 7.2 Air Carrier and Military Aircraft Mean Dwell Time and Variance.

Flight Phase	Mean Time (minute)	Variance (minute)
1. Preflight Planning, Flight Plan Filing	30	10
2. Preflight Operation	10	5
3. Taxi Out and Take Off Operations	15	5
4. Departure Operations	5	2
5. Initial Climb Segment Operations	15	5
6. Initial Cruise Operations	10	5
7. Cruise Operations	30	10
8. Approach Operations	20	5
9. Landing Operations	5	2
10. Taxi In and Parking operation	10	5
11. Post Flight Operations	30	10
12. Alternative Operations (if requred)	75	15

Air carrier and military aircraft are the large jets, they have a fast cruise speed in the airspace and on the runways. Dwell times in the airspace and on the runways are smaller than other aircraft categories. However, pilots need to collect more weather and flight plan information to fly longer distances for air carrier and military aircraft. Consequently the dwell times would be longer in the first two phases of flight - preflight planning, flight plan filing and preflight operations. The dwell times during taxi-in and taxi-out operations are almost same for all aircraft categories because various aircraft types follow each other on the taxiways.

Air taxi/commuter aircraft fly slower speeds than air carrier aircraft. The dwell times at each phase of flight for air taxi/commuter are shown in **Table 7.3**.

Table 7.3 Air Taxi and Commuter Aircraft Mean Dwell Time and Variance.

Flight Phase	Mean Time (minute)	Variance (minute)
1. Preflight Planning, Flight Plan Filing	25	10
2. Preflight Operation	10	5
3. Taxi Out and Take Off Operations	15	5
4. Departure Operations	7	3
5. Initial Climb Segment Operations	10	5
6. Initial Cruise Operations	10	5
7. Cruise Operations	35	10
8. Approach Operations	25	5
9. Landing Operations	7	3
10. Taxi In and Parking operation	10	5
11. Post Flight Operations	20	10
12. Alternative Operations (if requred)	60	15

The mean dwell times in the airspace for air taxi/commuter aircraft are more than air carrier aircraft because of their lower speed. However, the dwell times in the phase of the preflight planning and flight plan filing are less than air carrier because these aircraft fly shorter distances and need less information comparing with air carrier.

General aviation aircraft is the smallest aircraft group in size in aviation system but the most numerous. Their speed, range, climb rate are smaller than other aircraft categories. **Table 7.4** lists the mean dwell times and their variances for the general aviation aircraft category. The dwell times in the phases of the preflight planning and flight plan filing and preflight operations are the least in all aircraft categories. However, general aviation aircraft would spend more times in the airspace.

Table 7.4 General Aviation Aircraft Mean Dwell Time and Variance.

Flight Phase	Mean Time (minute)	Variance (minute)
1. Preflight Planning, Flight Plan Filing	20	10
2. Preflight Operation	8	3
3. Taxi Out and Take Off Operations	15	5
4. Departure Operations	10	5
5. Initial Climb Segment Operations	10	5
6. Initial Cruise Operations	15	5
7. Cruise Operations	50	20
8. Approach Operations	30	10
9. Landing Operations	10	5
10. Taxi In and Parking operation	10	5
11. Post Flight Operations	15	5
12. Alternative Operations (if requred)	30	10

Aircraft are generally idle aircraft occurring between the late night and early morning period. During this time period, aircraft arriving at airports and will generally stay overnight. **Table 7.5** presents the mean dwell times of idle aircraft for four aircraft categories.

Table 7.5 Idle Aircraft Dwell Times at Airports.

Time (hours)	Air Carrier (minute)	Air taxi/ Commuter (minute)	General Aviation (minute)	Military (minute)
01	360	360	480	360
02	300	300	420	300
03	240	240	360	240
04	180	180	300	180
05	120	120	240	120
06	90	90	180	90
07	75	75	120	75
08	60	45	60	60
09	60	45	30	60
10	60	45	30	60
11	60	45	30	60
12	60	45	30	60
13	60	45	30	60
14	60	45	30	60
15	60	45	30	60
16	60	45	30	60
17	60	45	30	60
18	60	45	30	60
19	75	50	840	75
20	75	50	780	75
21	600	600	720	600
22	540	540	660	540
23	540	540	600	540
24	480	480	540	480

The arrival flights in nighttime for air carrier, air taxi/commuter, and military categories will stay shorter times than general aviation flights because most general aviation operations occur during the daytime. Air taxi/commuter and general aviation flights during daytime stay shorter times than air carrier and military aircraft at airports since the turnarounds for air taxi/commuter and general aviation aircraft are quicker than air carrier and military aircraft.

7.1.2 Model Result and Analysis

7.1.2.1 Base Year in 2005

Based on the existing data the initial number of aircraft at all phases of flight for air carrier, air taxi and commuter, general aviation, and military are 600, 500, 1000 and 200, respectively. A small portions of the initial number of aircraft are assigned to each phase of flight at midnight (0:00) of the beginning of simulation. The number of aircraft at each phase of flight as well as number of idle aircraft at the airport and number of flyover aircraft in the airspace are changed over time. **Table 7.6** represents the instantaneous number of aircraft at the phases of flight at the airports in Atlanta ARTCC at 10:00 a.m. for year of 2005.

Table 7.6 Air Traffic Volume at the Airport in 2005.

Flight Phase	Phase Description	Military	General Aviation	Air Taxi/ Commuter	Air Carrier	Total
I*	Idle Aircraft on Airport	27	397	142	141	707
I	Preflight Planning, Flight Plan Filing	7	14	64	73	158
II	Preflight Operations	2	10	23	30	65
III	Taxi Out and Take Off Operations	2	17	29	17	65
X	Taxi In and parking Operations	5	31	9	25	70
XI	Post Flight Operations	15	78	44	43	180
XII	Alternative Operations	0	0	0	0	0
Total		58	547	311	329	1,245

It is assumed that there are no flights in alternative operations. More than half of total of aircraft of 2,300 stay at the airport and most of them are in idle condition, post flight operation, preflight planning and flight plan, filing operation, and preflight operation. Only eleven percent of total aircraft at the airport move on the airfield for taxi in and taxi out operations.

Table 7.7 shows the number of aircraft at the flight phases of the terminal region in Atlanta ARTCC at 10:00 a.m. for year of 2005. In the terminal region, aircraft operations are included departure and arrival procedures. The small number of aircraft operate in the terminal region because of the separation limitation between aircraft and the relative narrower departure and arrival corridor area.

Table 7.7 Air Traffic Volume in the Terminal in 2005.

Flight Phase	Phase Description	Military	General Aviation	Air Taxi/ Commuter	Air Carrier	Total
IV	Departure Operations	1	5	6	7	19
VIII	Approach Operations	12	80	36	49	177
VIIII	Landing Operations	2	19	9	7	37
Total		15	104	51	63	233

Although the spacing between aircraft in the airspace is bigger than the spacing in the terminal region, the airspace still accommodates the second large number of aircraft due to the broad airspace area. **Table 7.8** show the number of aircraft at the phases of flight in the airspace region in Atlanta ARTCC at 10:00 a.m. for year of 2005. Most aircraft operate in cruise operations.

Table 7.8 Air Traffic Volumes in the Airspace in 2005.

Flight Phase	Phase Description	Military	General Aviation	Air Taxi/ Commuter	Air Carrier	Total
V	Initial Climb Segment Operations	4	9	16	33	62
VI	Initial Cruise Operations	2	5	9	21	37
VII	Cruise Operations	25	178	62	86	351
Total		31	192	87	140	450

In order to show the changes of air traffic flow over time, the following figures illustrate the changes of number of aircraft in three regions - in the airspace, in the terminal, and at the airport over a 24-hour period for air carrier, taxi/commuter, general aviation, and military aircraft categories in 2005.

Figure 7.2 demonstrates the changes of the air carrier traffic at the airport, in the terminal, and in the en-route airspace in Atlanta ARTCC over 24-hour period. There are two peak operations for air carriers traffic which occur in the morning and evening period. The morning peak operations are mainly comprised of departure flights, while most of the arrival flights occur in the evening peak operations. Most air carrier aircraft are at the airport because air carrier pilots need to take longer times to collect data than other aircraft categories. Also air carrier aircraft need more time to load and unload passengers at the airport. There are least number of air carrier aircraft in the terminal area. This is because the terminal areas are relative narrow and the separations between airplanes have to be maintained. The maximum number of aircraft at the airport reaches about 205 in the morning and evening. The maximum number of aircraft in the terminal and in the airspace are 135 and 155, respectively. As shown in the figure, most air carrier flights operate between 6:00 A.M. to 22:00 P.M.

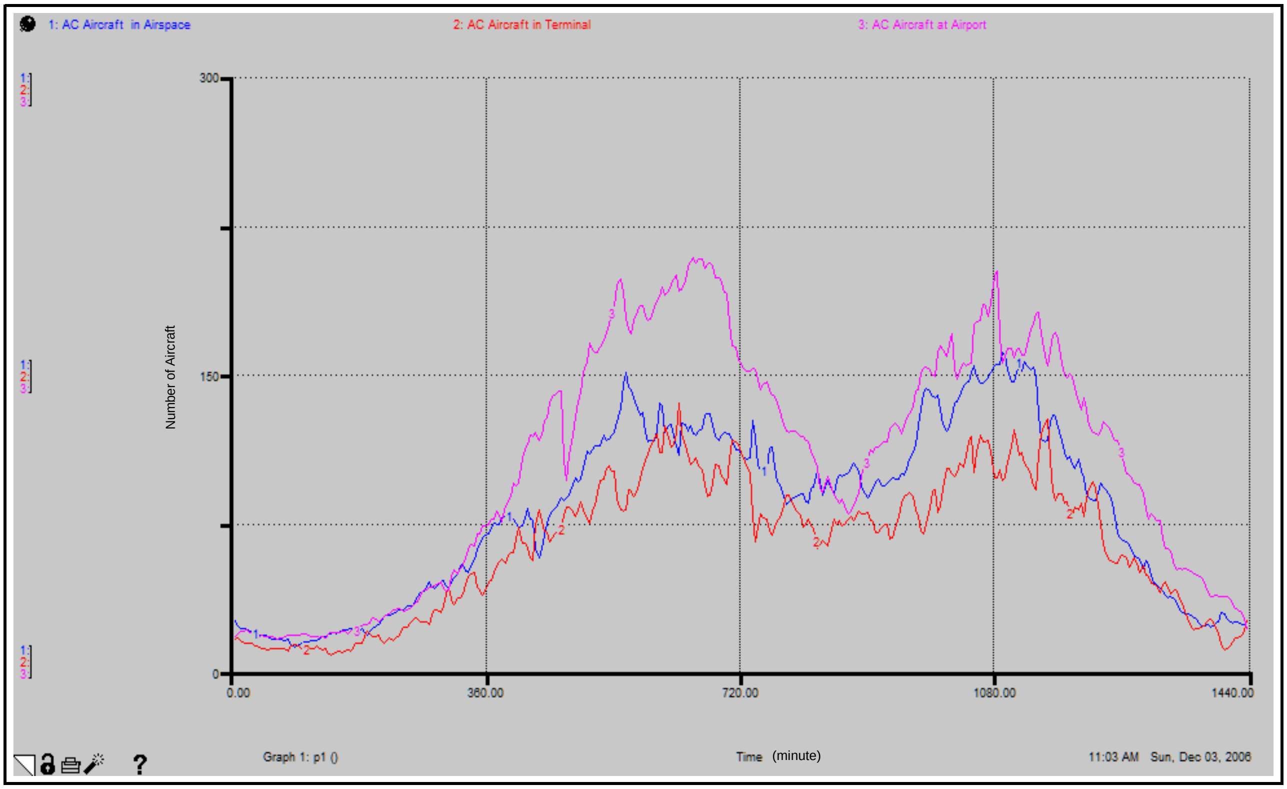


Figure 7.2 Number of Air Carrier Aircraft over 24 Hour in 2005.

Figure 7.3 depicts the distribution of the air taxi/commuter aircraft traffic flow at the airport, in the terminal, and in the en-route airspace inside Atlanta ARTCC over a 24 hours period. Similar to air carriers, air taxi/commuter aircraft traffic also has two peak operations in the morning and at the evening. There are no big differences between number of air taxi/commuter aircraft at the airport and other regions. This is because air taxi/commuter airplanes take less passengers and fly shorter distances than air carrier airplanes, therefore the times for collecting data and load and unload passengers at the airport are shorter. The maximum number of air taxi/commuter aircraft at the airport operations is about 190 in the morning. In the airspace and in the terminal regions, the maximum number of aircraft are 170 and 160, respectively. Most air taxi/commuter aircraft operate between 6:00 A.M. and 21:00 P.M.

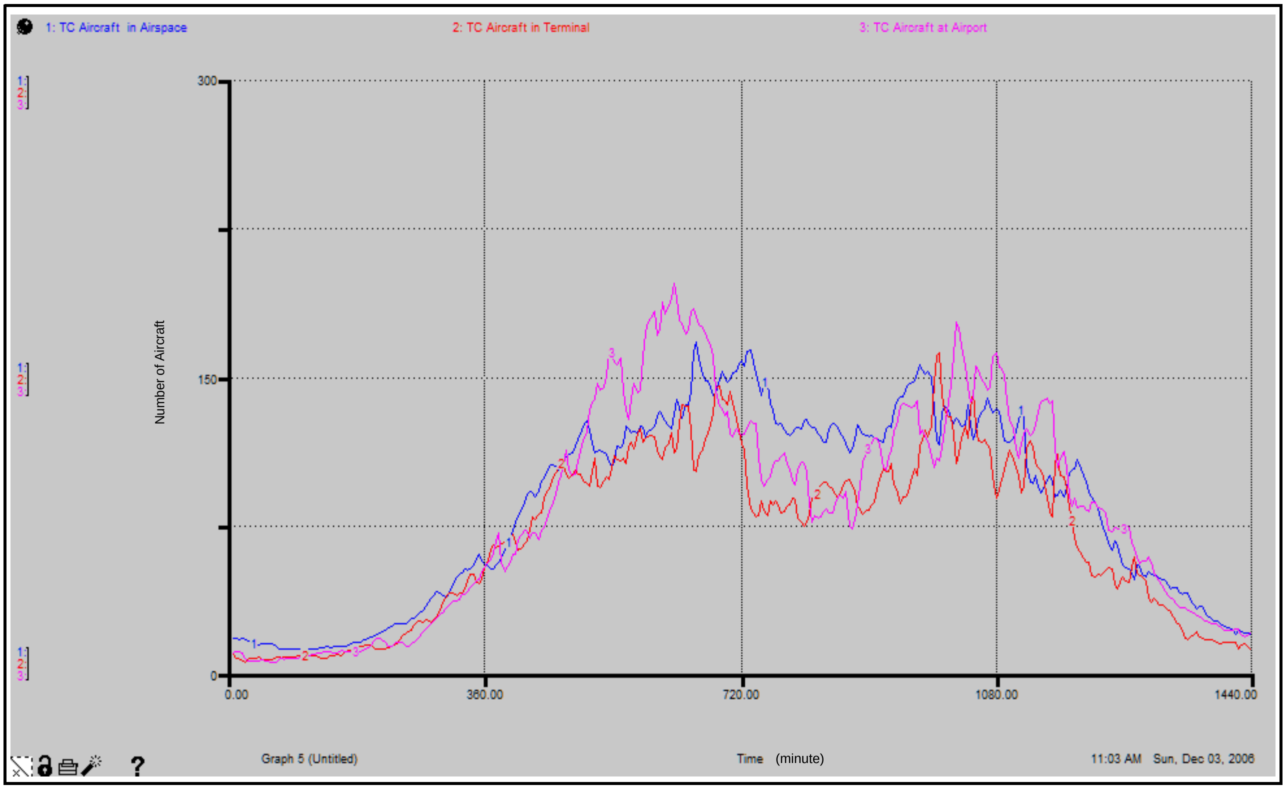


Figure 7.3 Number of Air Taxi/Commuter Aircraft over 24 Hour in 2005.

The changes of general aviation aircraft traffic flow over time are not like air carrier and air taxi/commuter categories due to the limitation of the equipment like radar system on board. Most general aviation aircraft operate between 8:00 a.m. and 18:00 p.m. There is only one peak flight operation for general aviation traffic in the afternoon. Comparing with the distribution of the number of air carrier and air taxi/commuter aircraft over time in Figures 4.7 and 4.8, the number of general aviation aircraft in the terminal area are more than the general aviation aircraft at the airport. This is because most of general aviation aircraft conduct training flights which fly in the terminal area. **Figure 7.4** shows the changes of the general aviation aircraft traffic at the airport, in the terminal, and in the en-route airspace in Atlanta ARTCC over a 24-hour period.

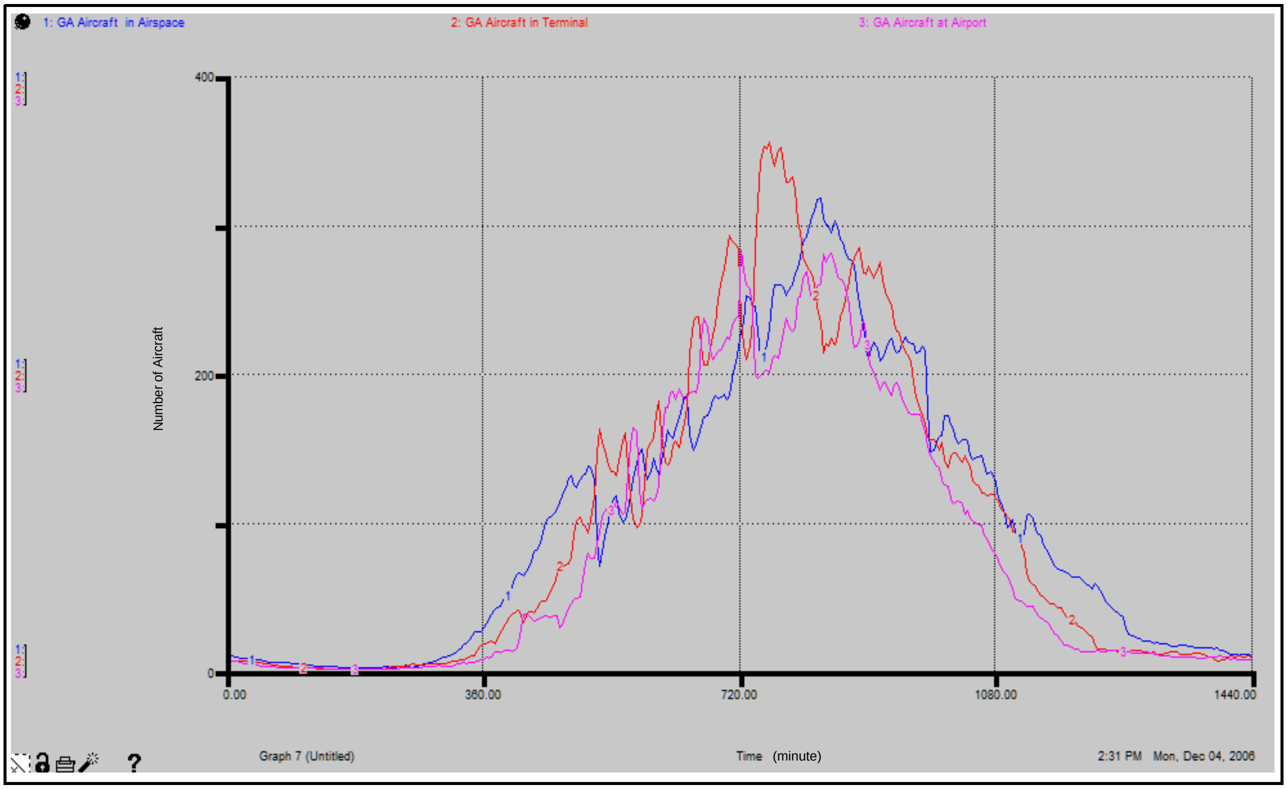


Figure 7.4 Number of General Aviation Aircraft over 24 Hour in 2005.

Figure 7.5 depicts the changes of military aircraft traffic in the airspace, in the terminal, and at the airport. Similar to air carrier and air taxi/commuter categories, the number of military aircraft at the airports are more than in the terminal or in the airspace. Like general aviation category, the military aircraft category has only one peak flight operation and most of military aircraft operate on daytime.

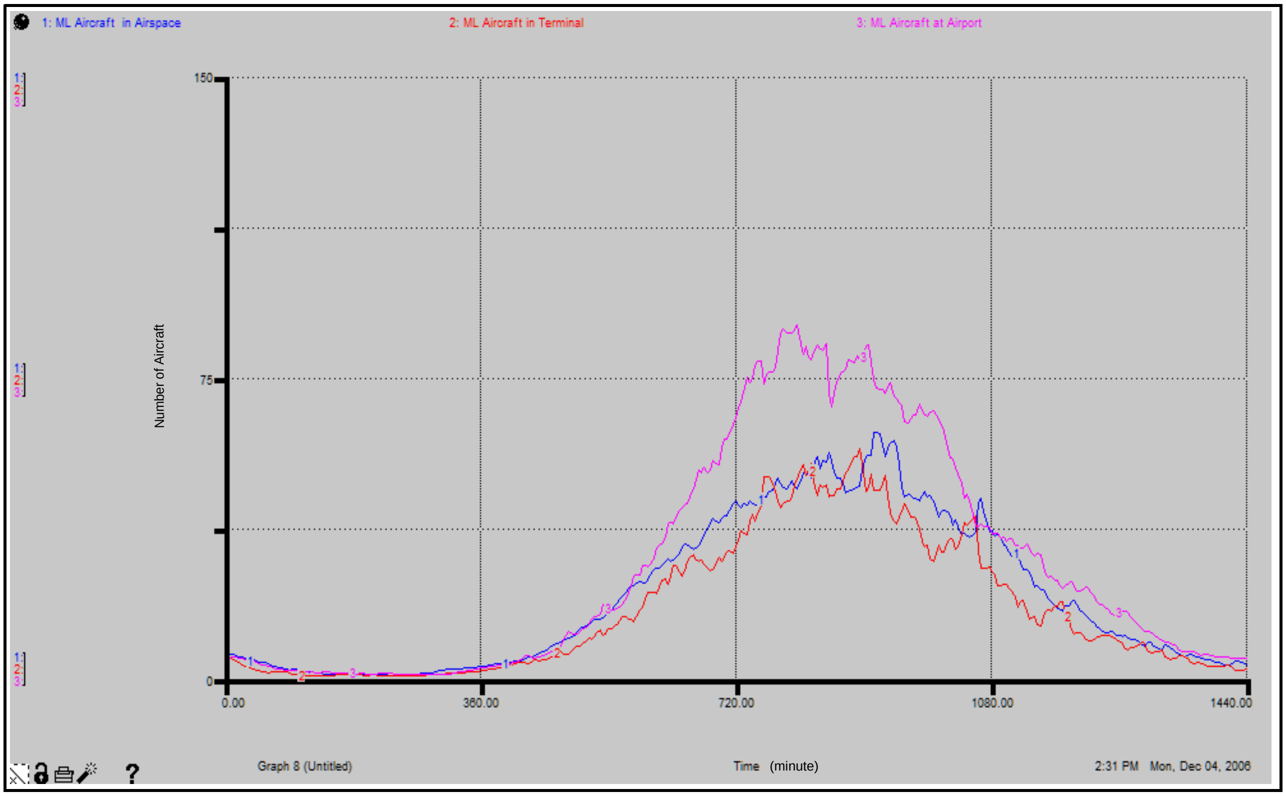


Figure 7.5 Number of Military Aircraft over 24 Hour in 2005.

7.1.2.2 Future Year in 2025

Based on the FAA TAF forecast data the initial number of aircraft in 2025 for air carrier, air taxi and commuter, general aviation, and military aircraft categories are 1,000, 1,200, 2,000 and 400, respectively. Like the base year in 2005, the number of aircraft at each phase of flight as well as idle aircraft at the airport and flyover aircraft are changed over time.

Table 7.9 represents the forecast number of aircraft at each phase of flight at the airports inside Atlanta ARTCC at 10 A.M. in the year of 2025. The number of aircraft of four aircraft categories at the airport in 2025 are more than double of the number of aircraft in the base year. The growth rate of the air taxi/ commuter aircraft is more than other aircraft categories. Like the base year, More than half of total aircraft of 4,600 operate at the airport and more than 60 percent of them are in idle condition. the rest of them are in post flight operation, preflight planning and flight plan, filing operation, and preflight operation or operate on the airfield for taxiing in and taxiing out.

Table 7.9 Air Traffic Volume at the Airport in 2025.

Flight Phase	Phase Description	Military	General Aviation	Air Taxi/ Commuter	Air Carrier	Total
I*	Idle Aircraft on Airport	148	949	268	260	1,625
I	Preflight Planning, Flight Plan Filing	14	32	130	126	302
II	Preflight Operation	6	111	71	38	226
III	Taxi Out and Take Off Operation	4	60	50	73	187
X	Taxi In and parking Operation	12	100	18	18	148
XI	Post Flight Operation	19	79	55	63	216
XII	Alternative Operation	0	0	0	0	0
Total		203	1,331	592	578	2,704

Table 7.10 lists the air traffic volumes at the phases in the terminal region for all aircraft categories at 10:00 A.M. for the future year of 2025. Comparing with the air traffic volumes in the terminal area in 2005, the air traffic volumes for air carrier, air taxi/commuter, and general aviation categories are increased at double rates.

Table 7.10 Air Traffic Volume in the Terminal in 2025.

Flight Phase	Phase Description	Military	General Aviation	Air Taxi/ Commuter	Air Carrier	Total
IV	Departure Operation	2	9	26	24	61
VIII	Approach Operation	17	156	99	81	353
VIIII	Landing Operation	7	47	24	19	97
Total		26	212	149	124	511

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Table 7.11 Air Traffic Volume in the Airspace in 2025.

Flight Phase	Phase Description	Military	General Aviation	Air Taxi/ Commuter	Air Carrier	Total
V	Initial Climb Segment Operation	3	25	22	68	118
VI	Initial Cruise Operation	4	8	35	36	83
VII	Cruise Operation	48	350	220	170	788
Total		55	383	277	274	989

Table 7.11 represents the number of aircraft in various phases of flight in the en-route airspace for all aircraft categories studied at 10:00 A.M. in 2025. The results for the year 2025 show that air traffic volume increase significantly at the airport, in the terminal region, and in the en-route airspace. Especially, the volume of air taxi/commuter aircraft in the airspace in 2025 is more than three times of the base year.

Similar to the existing condition, the model's results also show the traffic flow changes over time. The following figures graphically illustrate the changes in the number of aircraft in three regions - in the en-route airspace, in the terminal, and at the airport over a 24-hour period for air carrier, taxi/commuter, general aviation, and military categories in the year 2025.

Figure 7.6 shows that the distribution of the number of air carrier aircraft in the airspace, in the terminal, and at the airport over a 24-hour period inside Atlanta ARTCC in 2025. There are also two peak operations in the morning and in the evening, however, the number of air carrier aircraft in the peak operation reaches 410, 315, and 300 at the airport, in the airspace, and in the terminal, respectively, which is more than double the demand function of the base year.

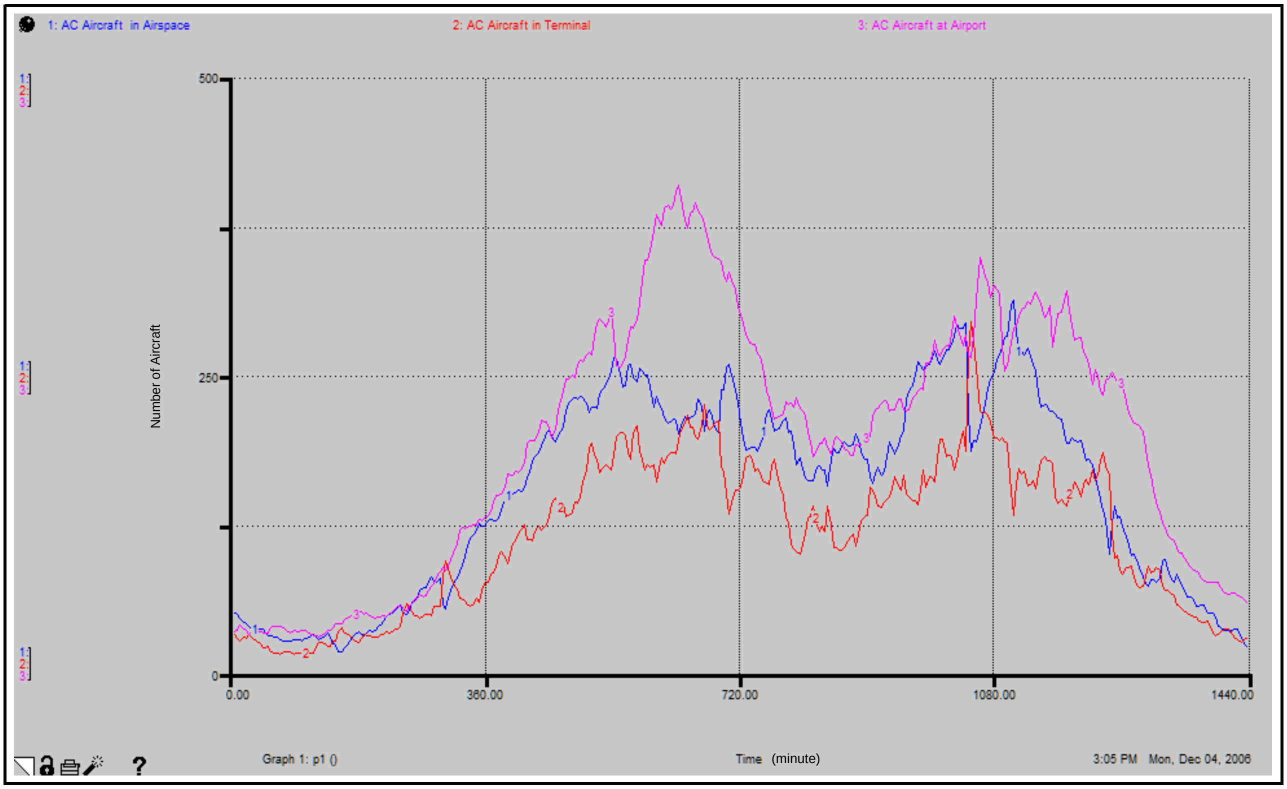

Figure 7.6 Number of Air Carrier Aircraft over 24 Hour in 2025.

For the air taxi/commuter category in the future, **Figure 7.7** demonstrates the changes of air taxi/commuter traffic flow in the airspace, in the terminal, and at the airport over a 24-hour period in the Atlanta ARTCC in 2025. Similar to the base year, there are two peak operations in the morning and in the evening. The maximum number of air taxi/commuter aircraft at the airport is approximately 380 which doubles the base year's. The distribution curves of air taxi/commuter aircraft traffic flow over time at the airport, in the terminal, and in the airspace regions are similar to the base year except the number of air taxi/commuter aircraft.

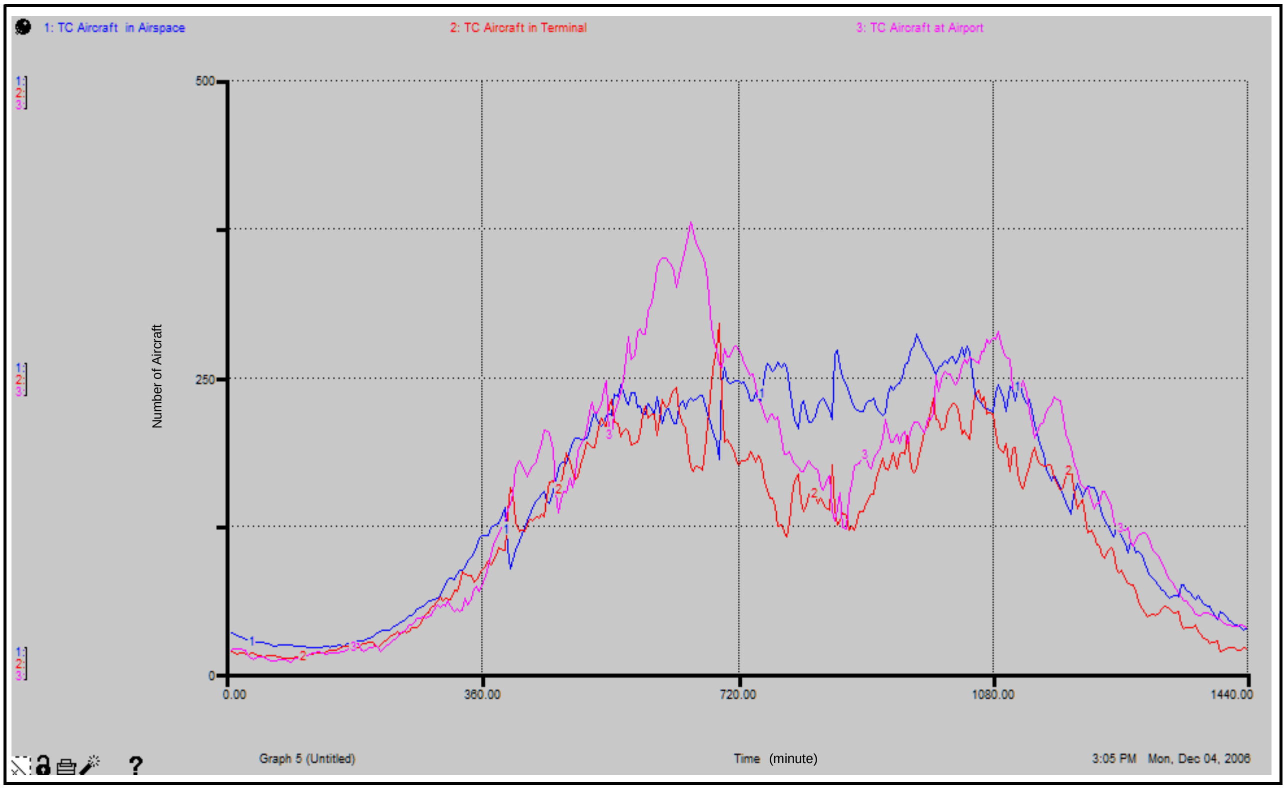

Figure 7.7 Number of Air Taxi/Commuter Aircraft over 24 Hour in 2025.

For general aviation operations, **Figure 7.8** depicts graphically the distributions of general aviation traffic flow in the airspace, in the terminal, and at the airport over a 24-hour period in the Atlanta ARTCC in 2025. The volumes of general aviation traffic are increased in three regions. The maximum number of general aviation aircraft in the peak operation reaches at 580. The distribution of the GA flight in three regions is similar to the base year. The number of general aviation aircraft in the terminal system is more than the number of aircraft at the airport. This is because that most of the general aviation aircraft conduct local training operations inside terminal region.

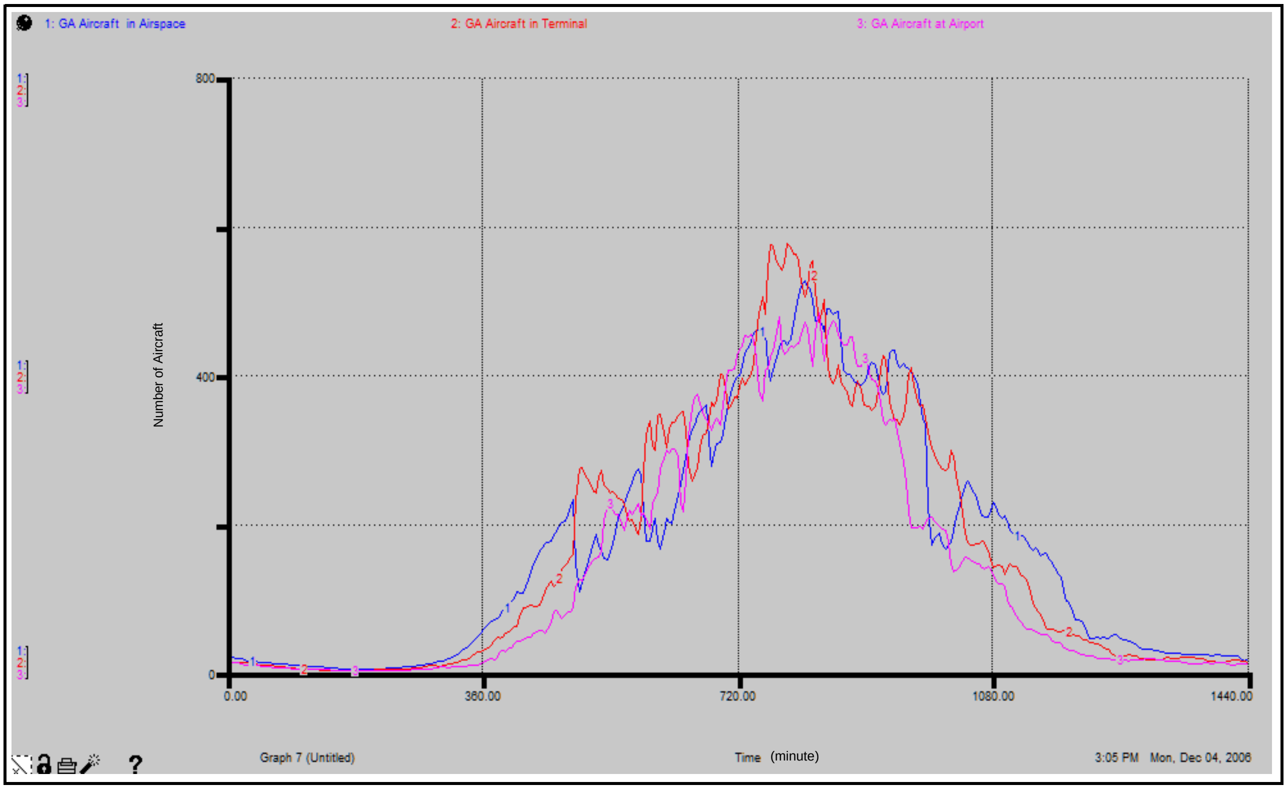

Figure 7.8 Number of General Aviation Aircraft over 24 Hour in 2025.

Figure 7.9 represents the distribution of military aircraft in the airspace, in the terminal, and at the airports over a 24-hour period inside Atlanta ARTCC in 2025. Comparing with the base year, the distribution of military aircraft traffic in three regions is similar to the base year's. Like other aircraft categories, the maximum number of military in the peak operation at the airport are increased and reached to 170. Generally the military aircraft category is the smallest aircraft group in aviation system.

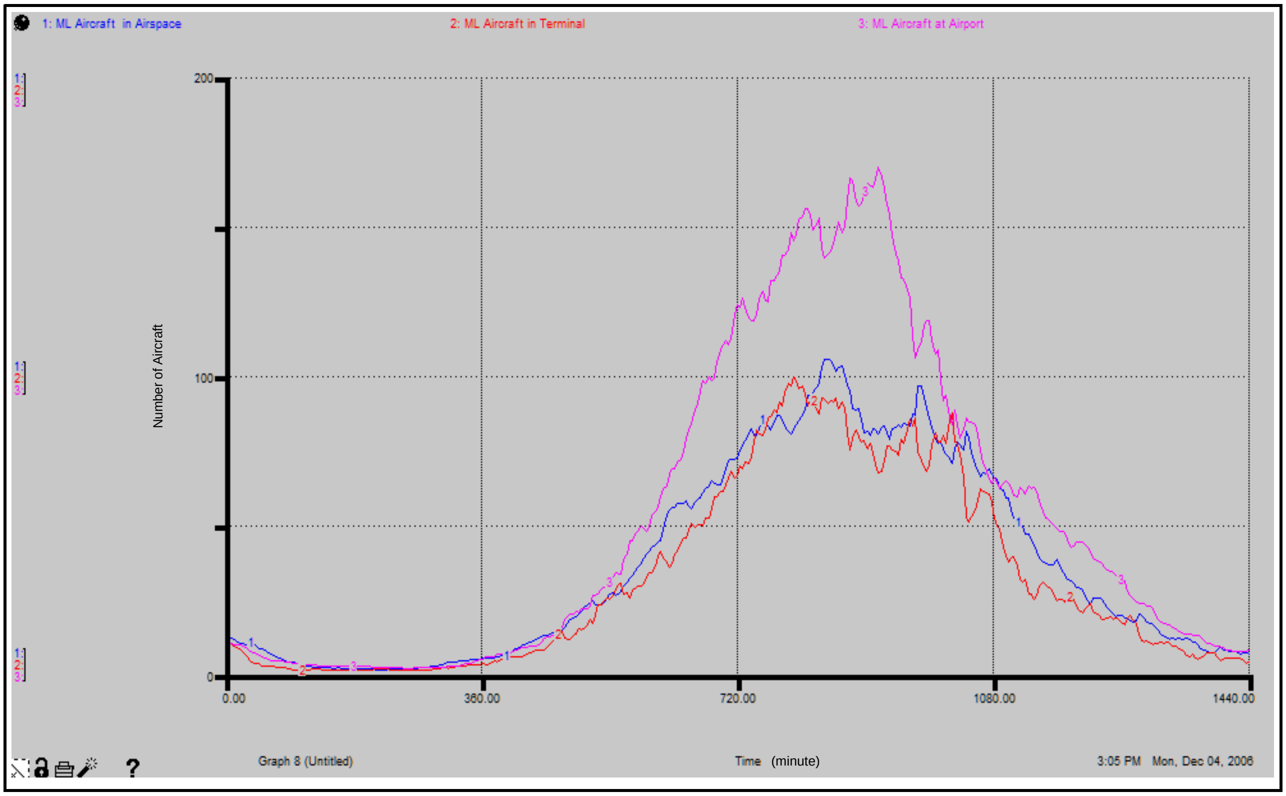

Figure 7.9 Number of Military Aircraft over 24 Hour in 2025.

The ATFM can also output other variables such as the number of aircraft at approach flight phase or idle aircraft at the airport etc. depending on the user’s requirements. Also users can manipulate the ATFM through the model interface to change input parameters such as the year of analysis, aircraft dwell times, number of aircraft, and output variables like air traffic volumes at a specific flight phase etc. ATFM will produce the distribution of any aircraft category at any phase of flight over a 24-hour period for the years between the base year (2005) and the future year (2025). For example, **Figure 7.10** shows the changes of air carrier aircraft traffic during approach operations and initial climb segment operations over a 24-hour period in 2015.

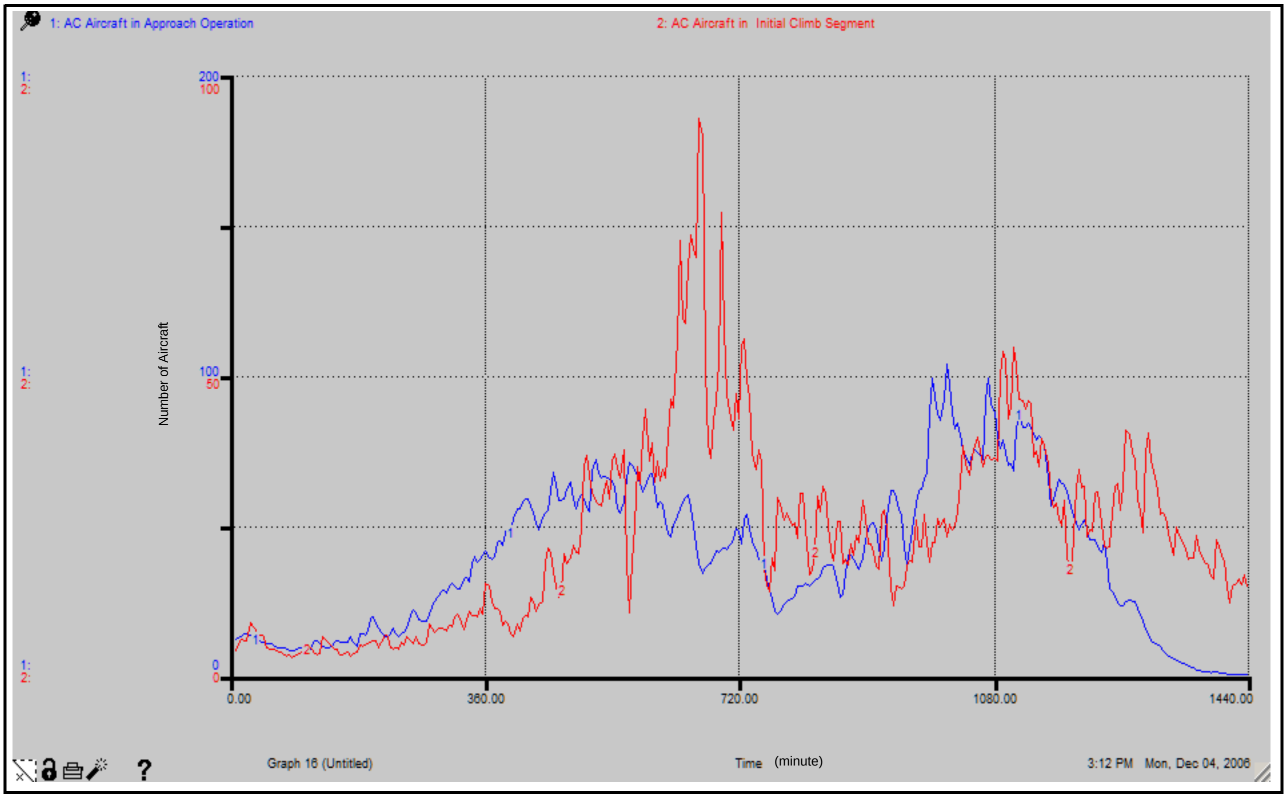

Figure 7.10 Number of Air Carrier Aircraft at Approach Operation and Initial Climb Segment Phases over 24 Hours in 2015

The results discussed above are the partial outputs from the ATFM. ATFM can be output more results based on user’s requirements.

7.2 Aviation Weather Information and Bandwidth Requirement Model Application

In this section, the application of the Aviation Weather Information and Bandwidth Requirement Model (AWINBRM) will be discussed. This model uses the output from the ATFM model to study aviation weather information and bandwidth requirements. The number of aircraft at each phase of flight over time are required by AWINBRM to determine the weather information and bandwidth necessary at each phase of flight.

7.2.1 Model Result and Analysis in Base Year

AWINBRM model determines the bandwidth of aviation weather product requirements and the packet size at each phase of flight in three regions for uplink. The model also determines the size of aviation weather data from aircraft sensors to the ground or to aircraft in downlink mode. The following sections will demonstrate and discuss the results obtained using the AWINBRM model with a specific application to Atlanta ARTCC en-route center as area of study for the base year in 2005.

7.2.1.1 Tactical Aviation Weather Requirements and Analysis in 2005

There are nine aviation weather products used for making the tactical decision. Each aviation product has its own distribution rate and life-time. Usually the interval of the rate and life of the aviation weather products for the tactical decision are short. The AWINBRM model maintains the validation of the aviation weather products and updates the aviation weather products immediately as soon as a updated tactical aviation weather products are published. For example, the METAR/SPECI product is published every hour the AWINBRM model will update the METAR/SPECI very hour to each aircraft.

Figure 7.11 shows the sizes of the tactical aviation weather information requirements at the airport, in the terminal, and in en-route airspace operations over a 24-hour period for air carrier aircraft in 2005. The sizes of the tactical aviation weather product requirements over the time in three regions are changed with the changes of air carrier traffic. More aircraft operations in the region and more the tactical aviation weather product needed.

The curves in the figure show that the size of the tactical aviation weather information requirements for the operations at the airport is bigger than the requirements in the terminal or in the airspace. Tis is because more airplanes are at the airport and the pilots need to collect more the tactical aviation weather information before planning a flight. The maximum size of the tactical aviation weather product requirement is around 75 MB for the operations at the airport. The size of the tactical aviation weather information requirement in the airspace is the second large in three regions. The least size of the tactical aviation weather information requirement occurs in the terminal area. These results are consistent with the traffic volumes from the ATFM model.

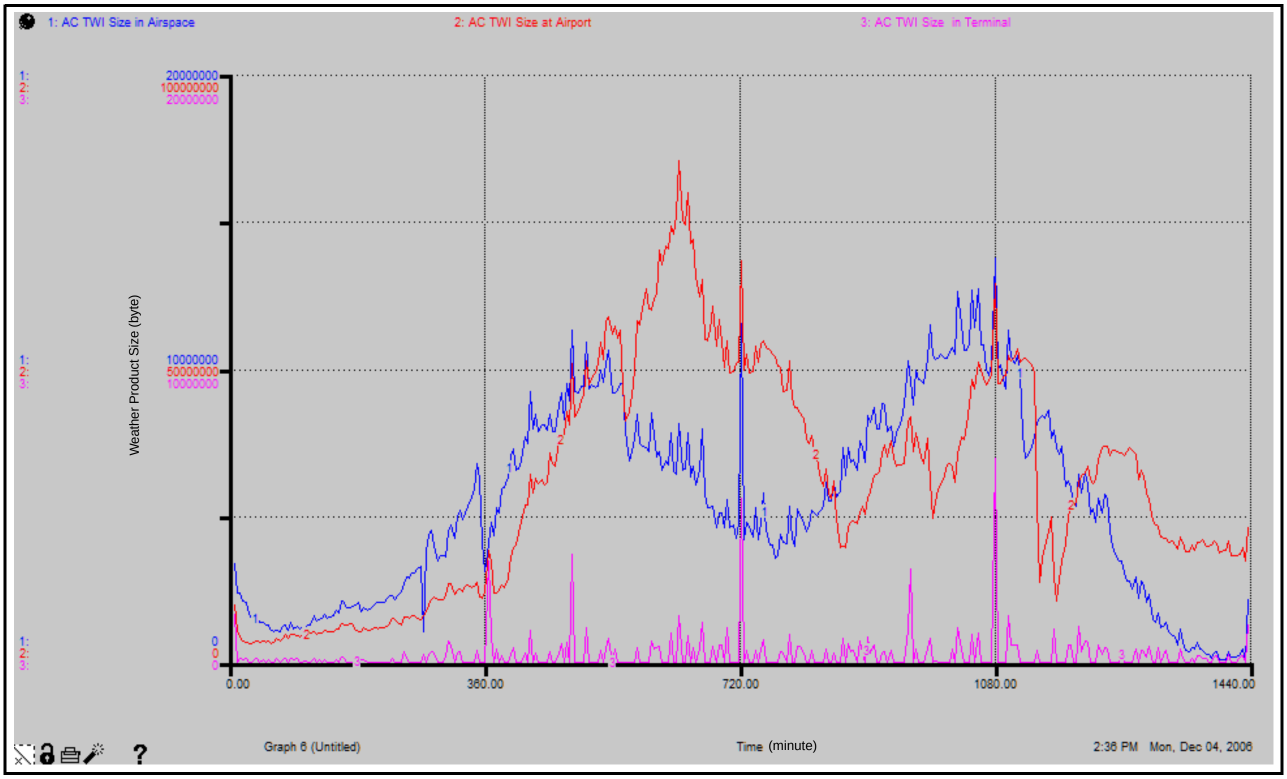

Figure 7.11 Tactical Aviation Weather Information Requirement Size for Air Carrier in 2005.

Like air carrier category, the changes of the size of the tactical aviation weather information requirement over time for air taxi/commuter aircraft category are consistent with the air taxi/commuter traffic flow. The maximum size of the tactical aviation weather information requirement occurs at the airport and the total size of the tactical aviation weather information requirement at the airport is also larger than the requirements in the terminal or in the airspace. The total size of the tactical aviation weather information requirement in three regions is less than the size for air carrier aircraft because the total number operations of air taxi/commuter are less than air carrier. The maximum size of the tactical aviation weather information requirement at the airport is about 70 MB. **Figure 7.12** demonstrates the changes of the size of the tactical aviation weather information requirement for air taxi/commuter aircraft over a 24-hour period in 2005.

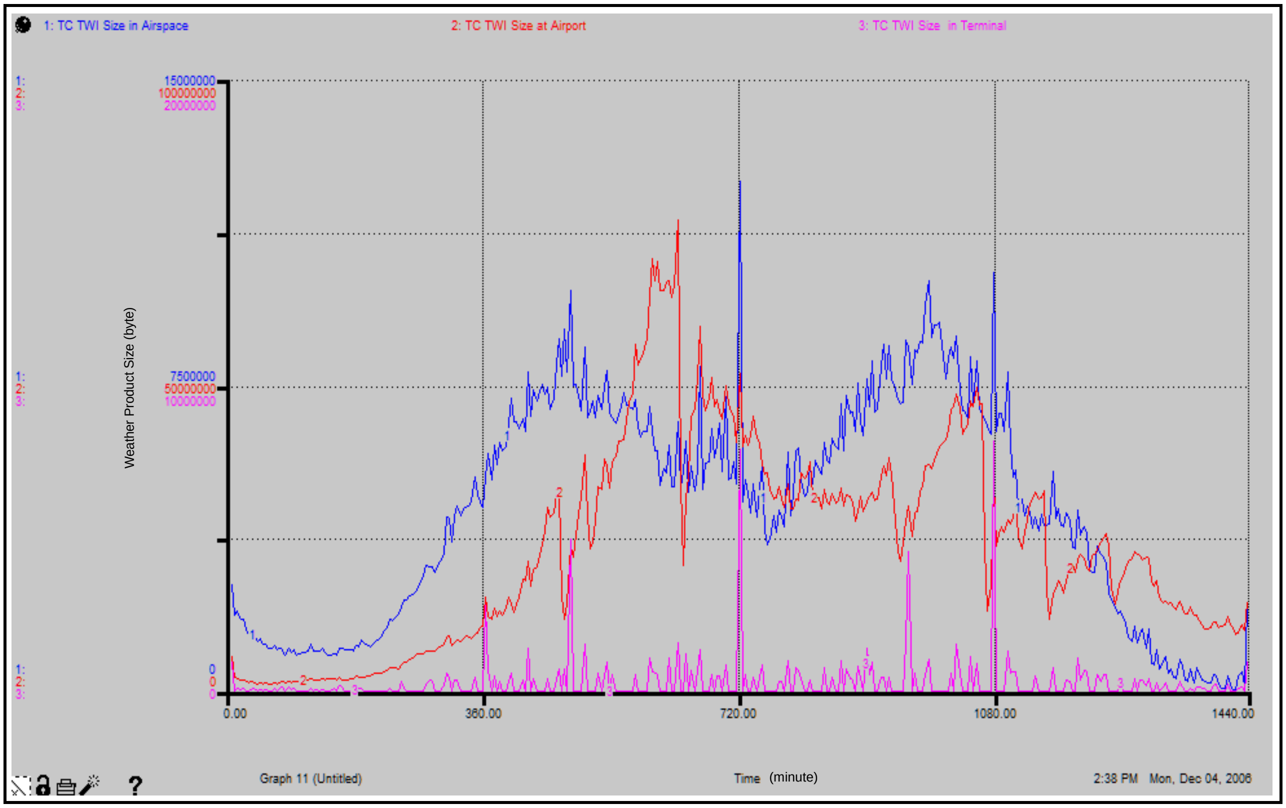

Figure 7.12 Tactical Aviation Weather Information Requirement Size for Air Taxi/Commuter in 2005.

Figure 7.13 depicts the changes of the size of the tactical aviation weather information requirement for general aviation aircraft at the airport, in the terminal area, and in the airspace over a 24-hour period in the year 2005. The size of the tactical aviation weather information requirements for the operations at the airport is bigger than the requirements in the terminal or in the airspace. The maximum size of the tactical aviation weather information requirement at the airport is about 95 MB which is larger than air carrier and air taxi/commuter categories because there are more general aviation operations than other aircraft categories.

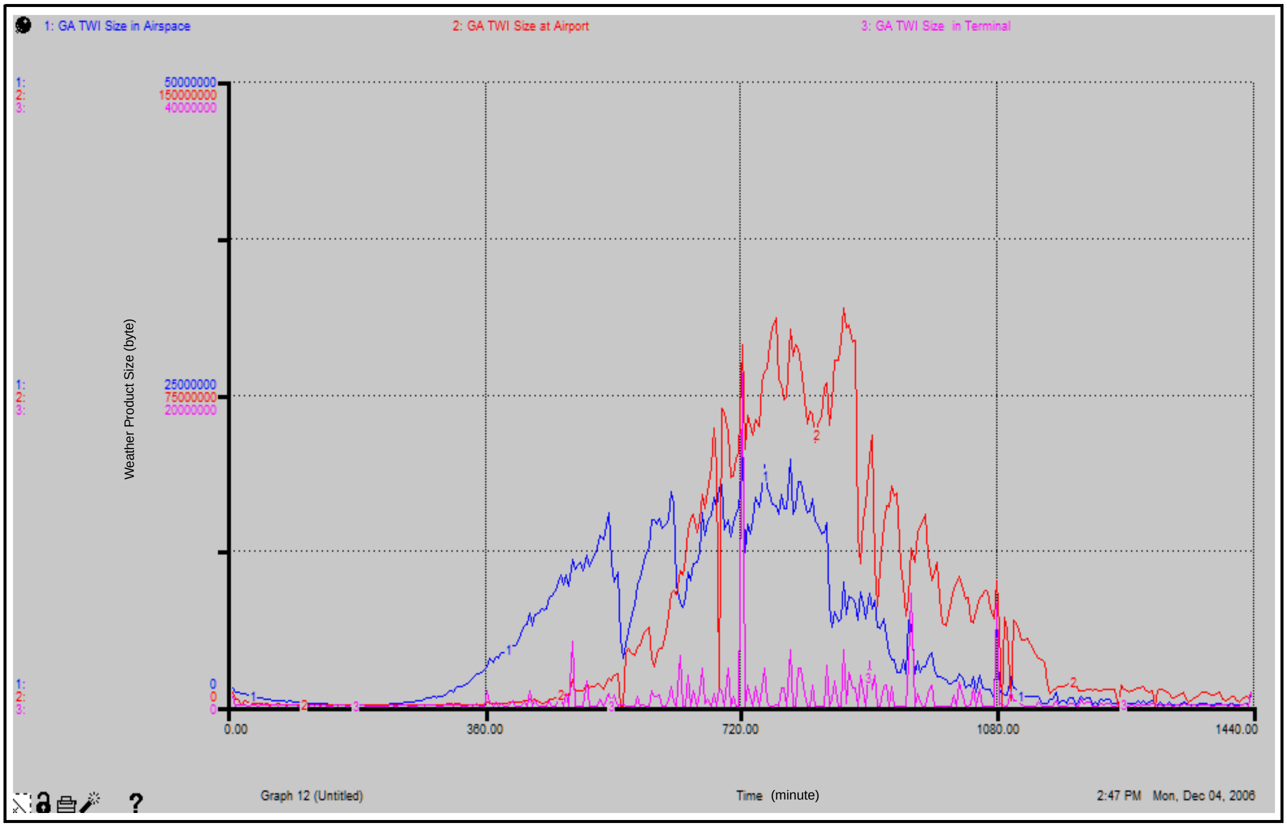

Figure 7.13 Tactical Aviation Weather Information Requirement Size for General Aviation in 2005.

Figure 7.14 shows the changes of the size of the tactical aviation weather information requirement for military aircraft over a 24-hour period at the airport, in the terminal, and in the airspace in 2005. Like other aircraft categories, the size of the tactical aviation weather information requirement at the airport is more than the size of tactical aviation weather requirements in the terminal or in the airspace. The maximum size of the tactical aviation weather information requirement for military aircraft occurs at the airport and is about 28 MB.

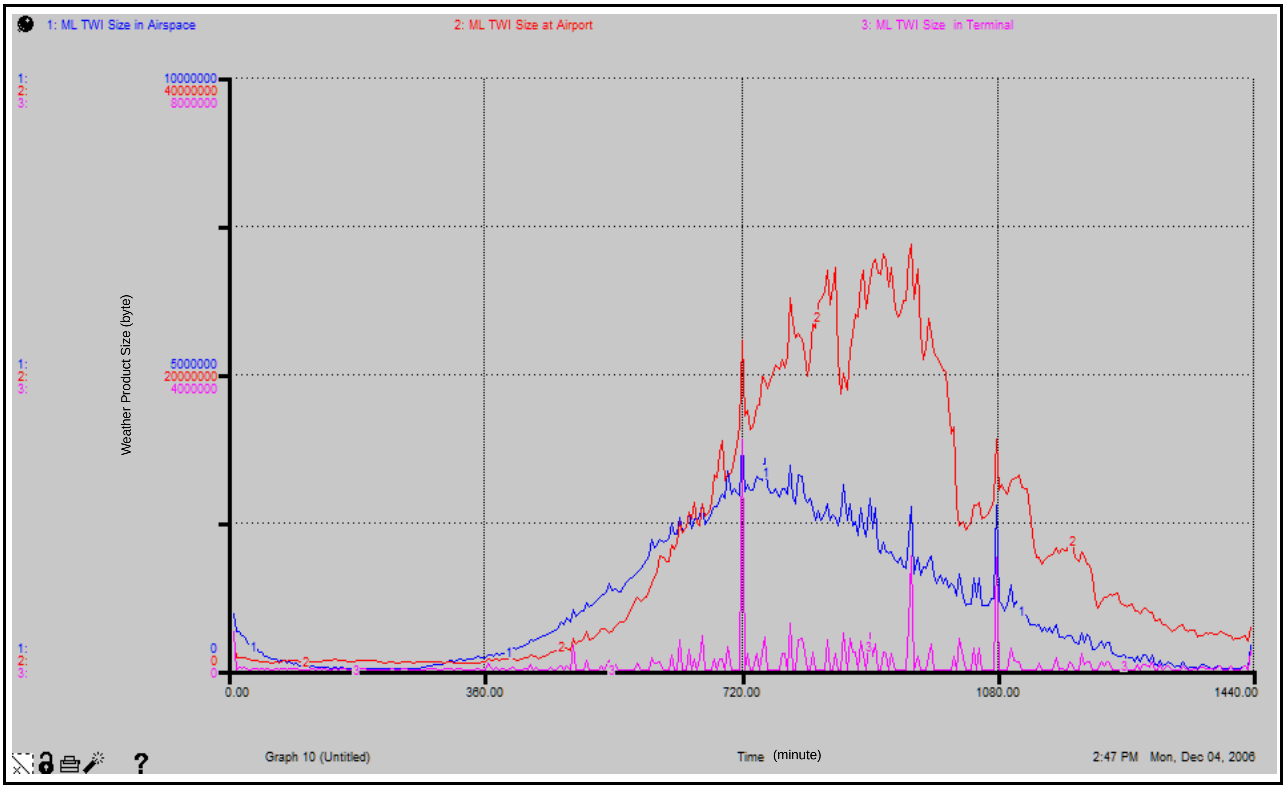

Figure 7.14 Tactical Aviation Weather Information Requirement Size for Military in 2005.

7.2.1.2 Strategic Aviation Weather Requirements and Analysis in 2005

There are fourteen strategic aviation weather products in the existing aviation weather service. Each product has been modeled for each aircraft category. Generally, the strategic aviation weather products have long life-time and publish a couple of or several times per day. The AWINBRM model also maintains the validation of the strategic aviation weather products and updates the strategic aviation weather products immediately as soon as a updated strategic aviation weather product is published.

The following paragraphs describe the analysis of the results of the strategic aviation weather information requirement for the base year of 2005.

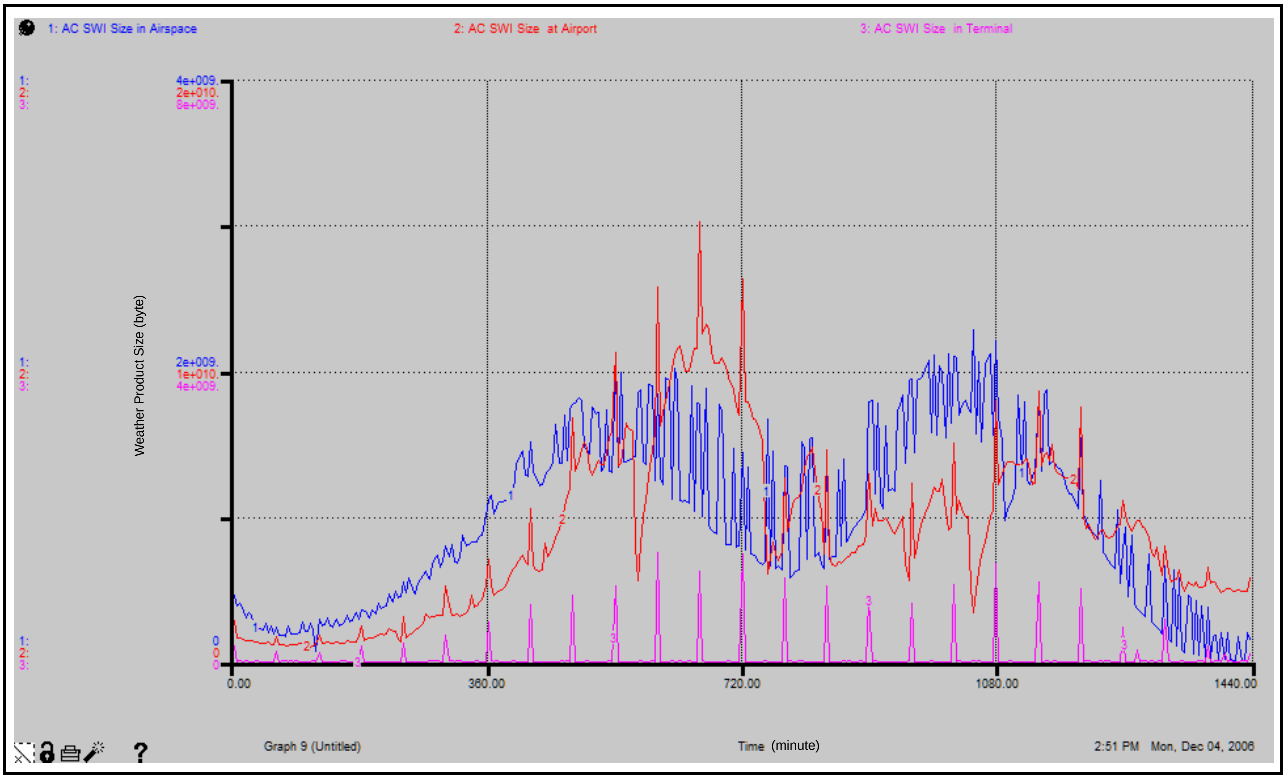

Figure 7.15 Strategic Aviation Weather Information Requirement Size for Air Carrier in 2005.

Figure 7.15 represents the changes of the size of the strategic aviation weather information requirements at the airport, in the terminal, and in the airspace over a 24-hour period for the air carrier aircraft category in 2005. There are two peak strategic aviation weather information requirements in the airspace and one peak at the airport for air carrier aircraft. The maximum size of the strategic aviation weather information requirement for air carrier aircraft at the airport is about 15 GB and is larger than the size in the airspace or in the terminal. This is because the pilots will collect more strategic aviation weather information for origin and destination airports and en-route before they begin a flight. The maximum size of the strategic aviation weather information requirement for air carrier aircraft in the airspace is around 2.3 GB. The sawtooth curves in the figure show that the interval for updating strategic aviation weather products is larger than the tactical aviation weather products.

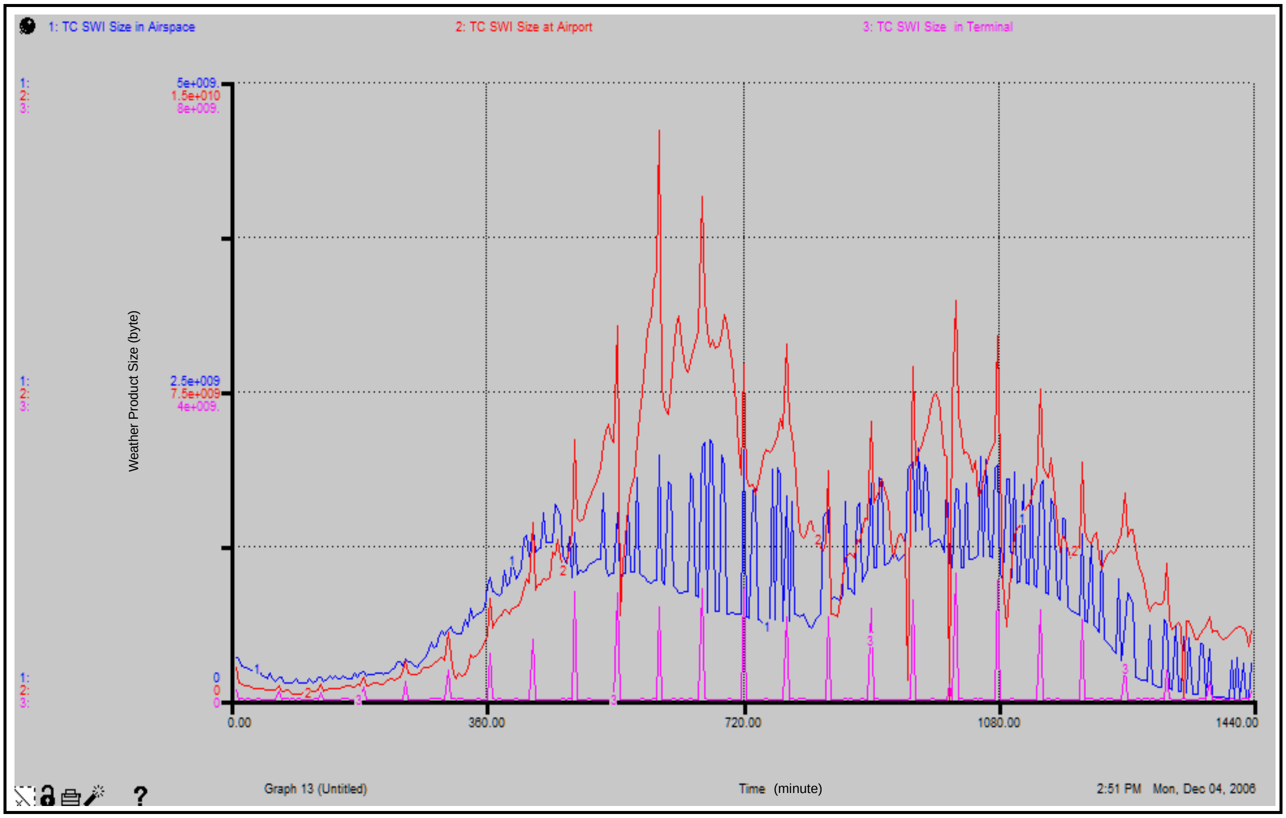

Figure 7.16 Strategic Aviation Weather Information Requirement Size for Air Taxi/Commuter in 2005.

Figure 7.16 depicts the changes of the size of the strategic aviation weather information requirements over a 24-hour period for air taxi/commuter aircraft category at the airport, in the terminal, and in the airspace in 2005. The maximum size of the strategic aviation weather information requirements occurs at the flight phases at the airport and is about 14 GB. There are two peak strategic aviation weather information requirement in the airspace operations. The maximum size of the strategic aviation weather information requirements in the airspace is around 2 GB. The air taxi/commuter aircraft in the terminal system request the strategic aviation weather information less than at the airport and in the airspace.

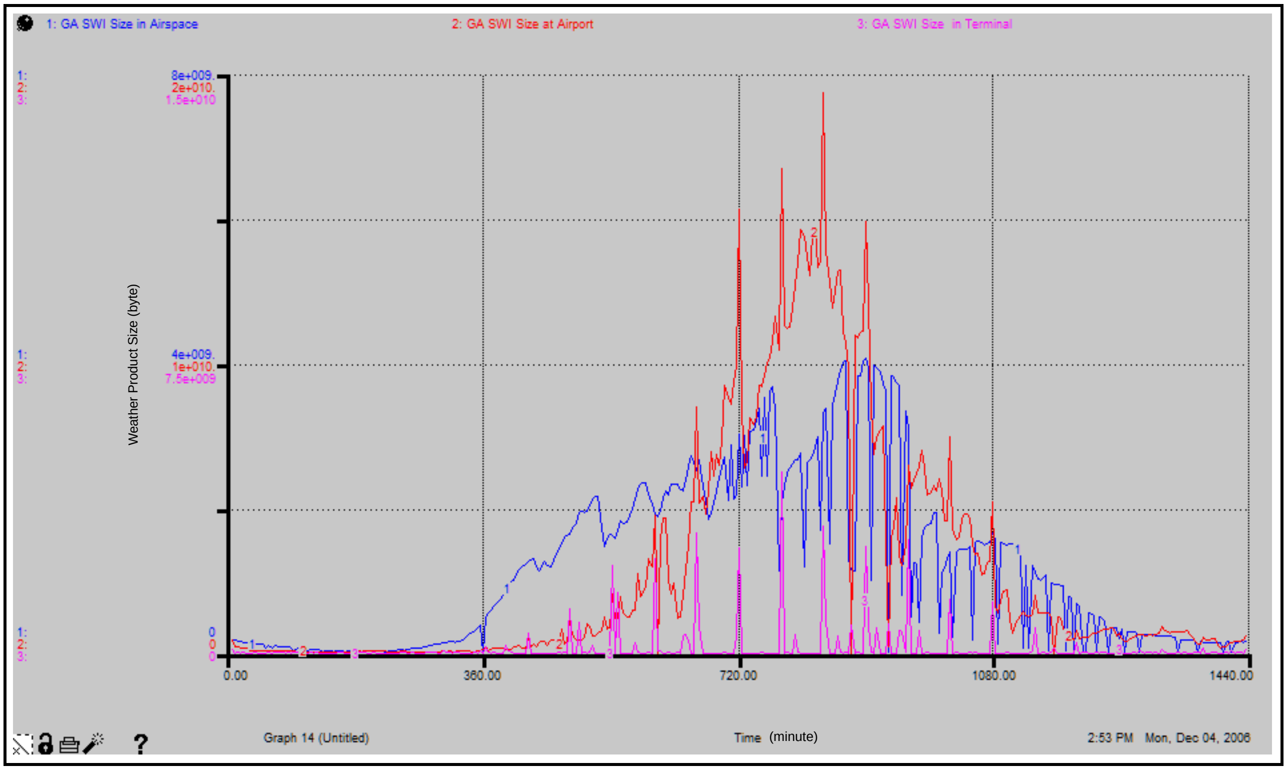

Figure 7.17 Strategic Aviation Weather Information Requirement Size for General Aviation in 2005.

General aviation aircraft category also requests a large number of the strategic aviation weather information because general aviation has the largest fleet in four aircraft categories. **Figure 7.17** shows the changes of the size of the strategic aviation weather information requirements over a 24-hour period for general aviation aircraft category at the airport, in the terminal, and in the airspace in 2005. The maximum size of the strategic aviation weather information requirements occurs at the airport and is about 19 GB. There are only one peak strategic aviation weather information requirement in the airspace and at the airport.

Figure 7.18 demonstrates the changes of the size of the strategic aviation weather information requirements over a 24-hour period for the military aircraft category at the airport, in the terminal, and in the airspace in 2005. The maximum size of the strategic aviation weather information requirements occurs at the airport and is reached 6 GB.

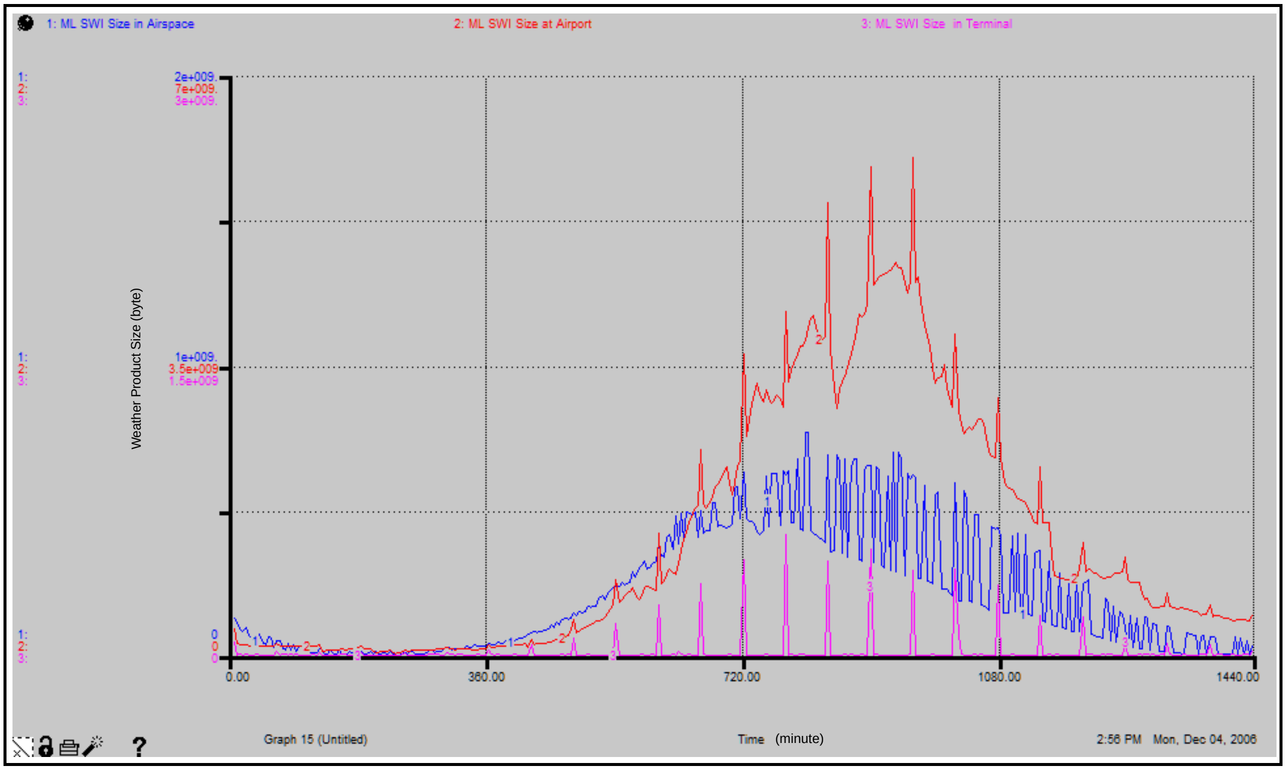

Figure 7.18 Strategic Aviation Weather Information Requirement Size for Military in 2005.

7.2.1.3 Aircraft as Sensor Results and Analysis in 2005

As discussed in the previous section, the weather sensors on board are useful to collect weather data in the terminal and airspace because aircraft fly anywhere especially in the airspace system. In the AW-INBRM model, four weather data are collected using the sensors, they are icing, turbulence, wind aloft and temperature, and convective weather data. These data will be transmitted to other pilots and ground aviation weather processing centers.

Figure 7.19 demonstrates the changes of the size of icing, turbulence, wind aloft and temperature, and convective weather data over a 24-hour period in the terminal area. The size of the wind aloft and temperature data is the largest in the four weather data. The maximum size of the wind aloft and temperature is around 0.9 MB.

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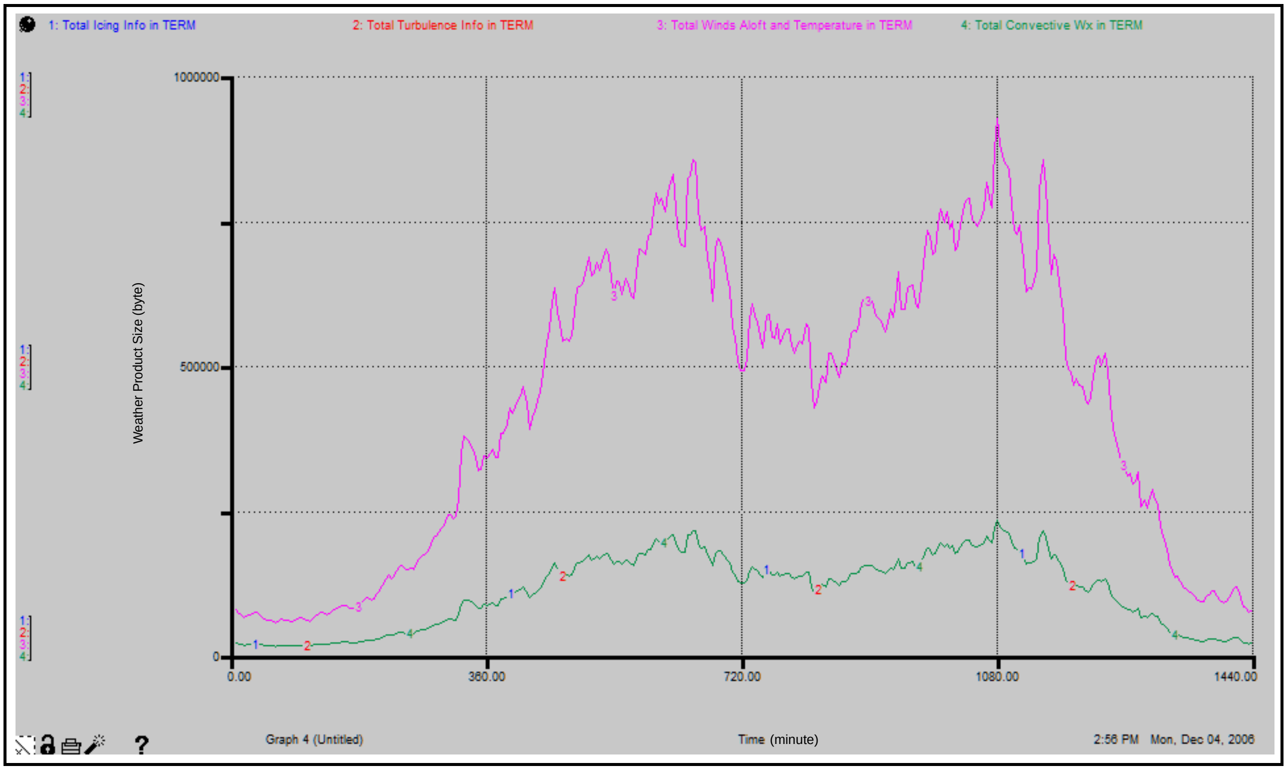

Figure 7.19 Aircraft as Sensor in 2005.

7.2.2 Model Result and Analysis in Future Year

In the future year, the increases of air traffic volume result in the increase of aviation weather information requirement. The AWINBRM model was developed to determine the bandwidth of aviation weather information requirements and the packet size at each phase of flight in any years between 2005 and 2025 for uplink and downlink. The following paragraphs will demonstrate and discuss these results from the AWINBRM model in using Atlanta ARTCC as area of study for the future year (2025).

7.2.2.1 Tactical Aviation Weather Requirements and Analysis in 2025

As known in air traffic flow analysis, the number of air carrier aircraft in 2025 is expected to double of the base year. The similar results for the aviation weather information requirement are obtained from the AWINBRM model, **Figure 7.20** illustrates the changes of the size of the tactical aviation weather information requirements over a 24-hour period for air carrier category at the airport, in the terminal, and in the airspace in 2025. There are also two peak tactical aviation weather information requirements in the airspace operations and one at the airport.

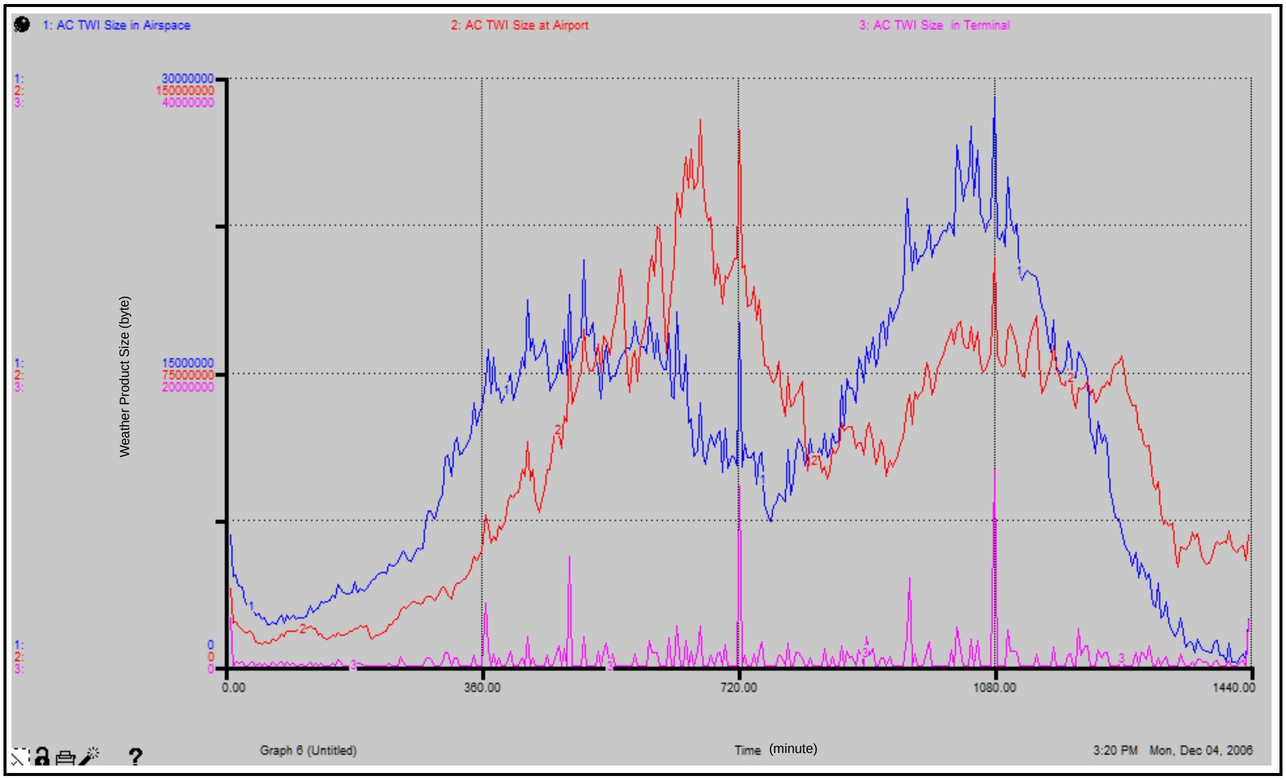

Figure 7.20 Tactical Aviation Weather Information Requirement Size for Air Carrier in 2025.

The maximum size of the tactical aviation weather information requirement at the airport for air carrier aircraft is about 140 MB. The peak tactical aviation weather information requirements in the terminal and in the airspace are 12 MB and 28 MB, respectively. These numbers are consistent with the increases of traffic volume in three regions.

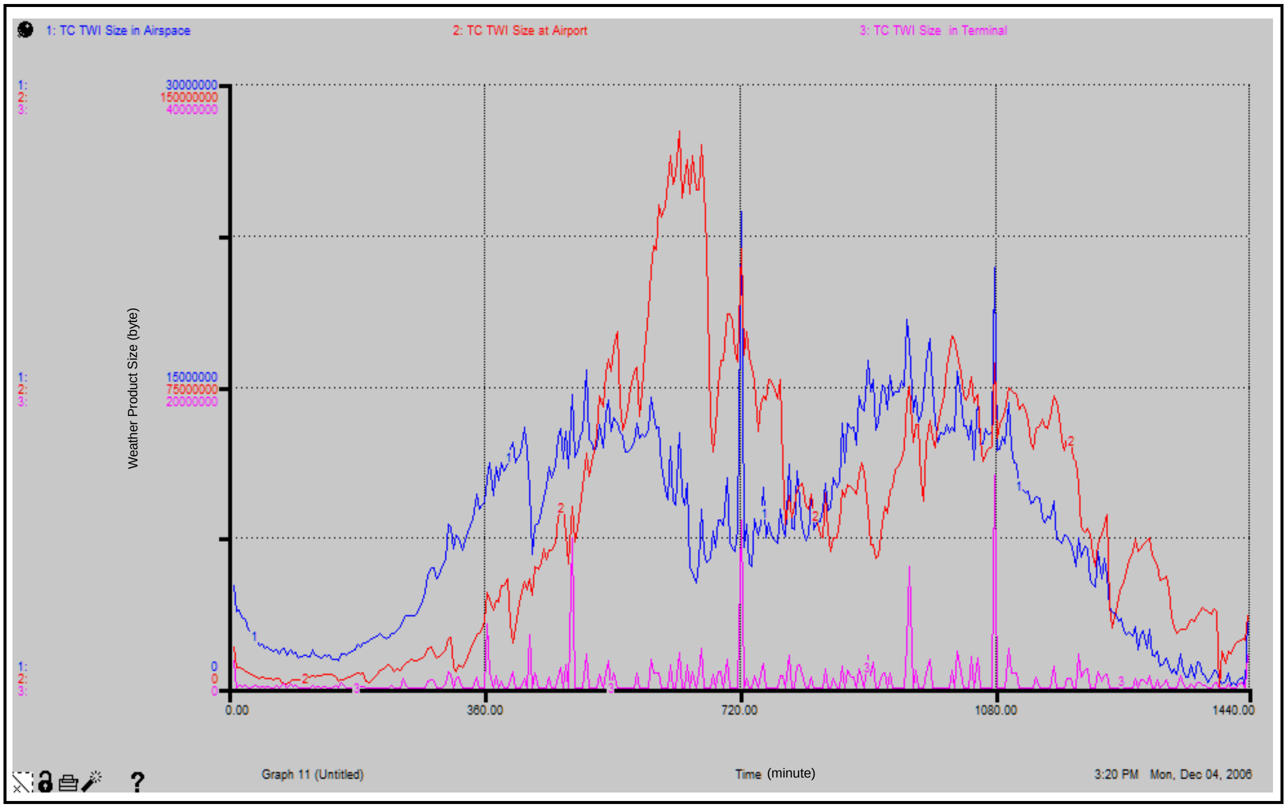

Figure 7.21 Tactical Aviation Weather Information Requirement Size for Air Taxi/Commuter in 2025.

Figure 7.21 represents the changes of the size of the tactical aviation weather information requirements over a 24-hour period at the airport, in the terminal, and in the airspace for air taxi/commuter category in 2025. The increase of the tactical aviation weather information requirements for air taxi/commuter aircraft are faster than air carrier aircraft. This is consistent with the increase of air taxi/commuter aircraft traffic volume in the future. The maximum size of the tactical aviation weather information requirement at the airport for air taxi/commuter aircraft is about 140 MB which is double of the base year.

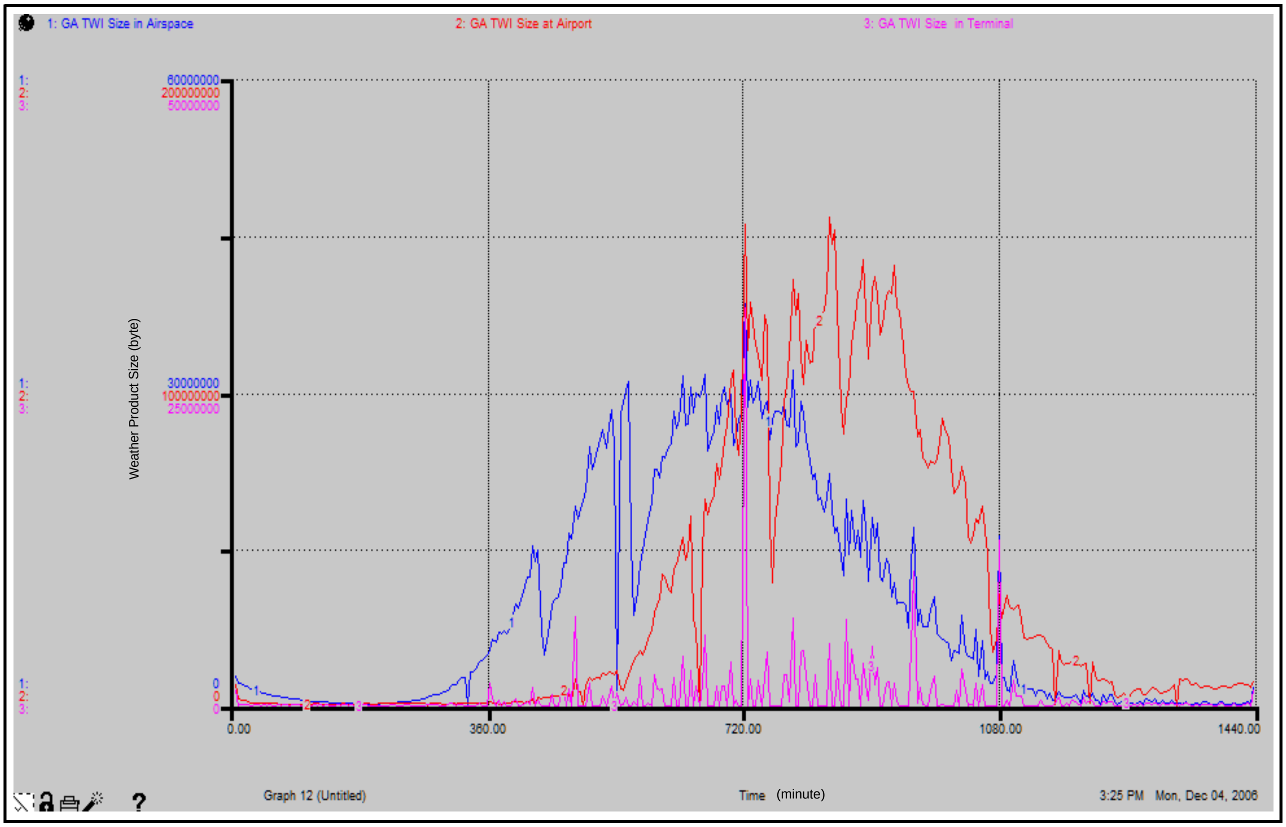

Figure 7.22 Tactical Aviation Weather Information Requirement Size for General Aviation in 2025.

Figures 7.22 and **7.23** show the changes of the size of the tactical aviation weather information requirements over a 24-hour period at the airport, in the terminal, and in the airspace for general aviation and military categories in 2025, respectively. Both graphics demonstrate the same trend of the tactical aviation weather information requirement over time as the base year except the size increases. The maximum sizes of the tactical aviation weather information requirement for general aviation and military aircraft categories at the airport are 160 MB and 56 MB, respectively.

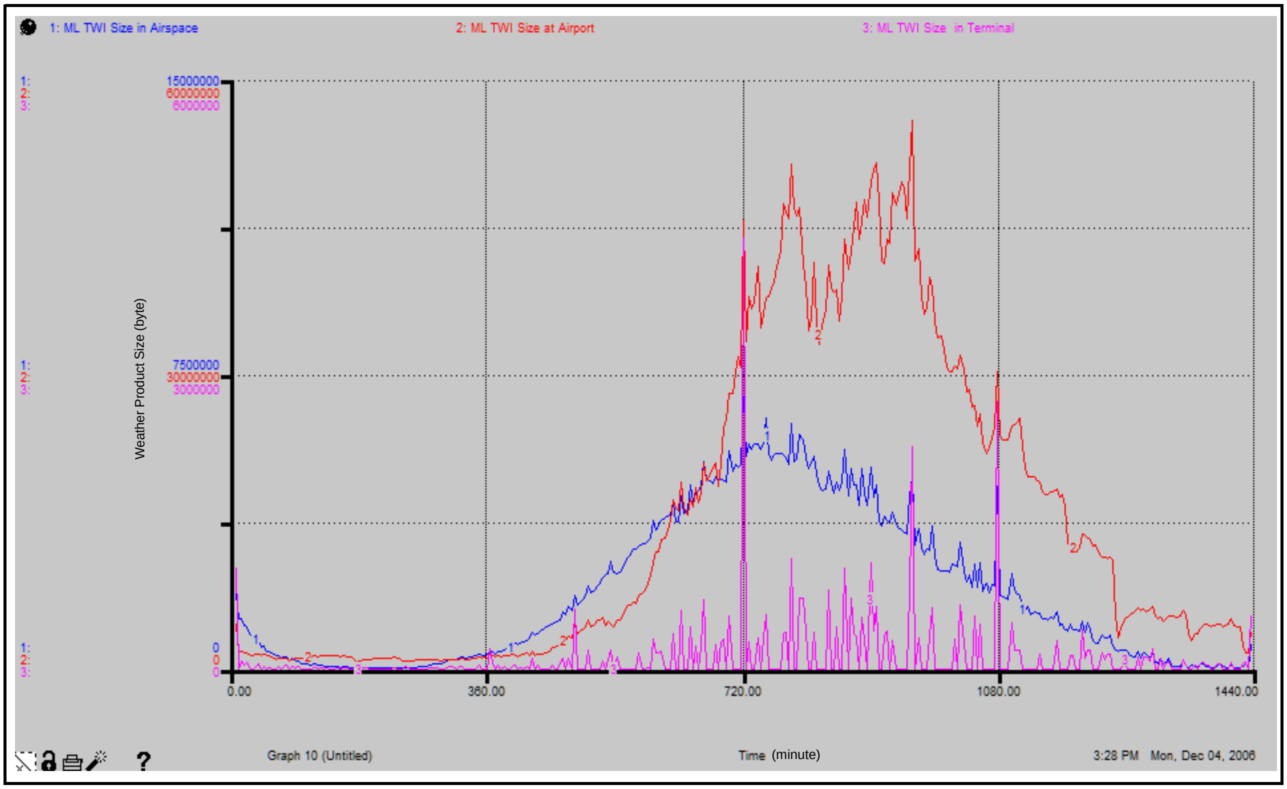

Figure 7.23 Tactical Aviation Weather Information Requirement Size for Military in 2025.

7.2.2.2 Strategic Aviation Weather Requirements and Analysis in 2025

Regarding the strategic aviation weather information requirement for the year of 2025, the following figures depict graphically AWINBRM model results of the strategic aviation weather information requirement in three regions.

Figure 7.24 demonstrates the changes of the size of the strategic aviation weather information requirements in the airspace, in the terminal, and at the airport over a 24-hour period for air carrier aircraft categories in 2025.

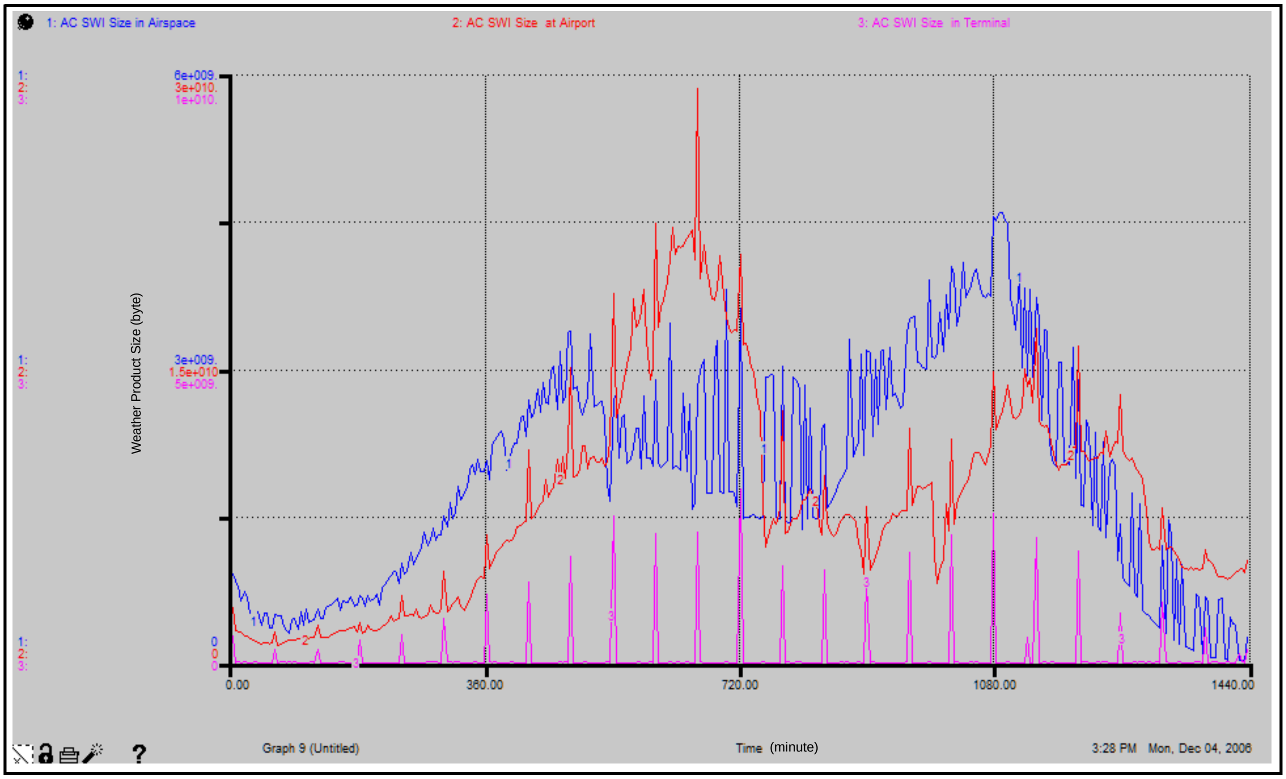

Figure 7.24 Strategic Aviation Weather Information Requirement Size for Air Carrier in 2025.

Like the base year, the strategic aviation weather information requirement for air carrier aircraft at the airport has three well-derived regions. The maximum size of the peak strategic aviation weather information requirements at the airport is reached 29 GB. The size of the strategic aviation weather information requirement in the terminal is the smallest in three region. The maximum sizes of the peak strategic aviation weather information requirements in the terminal and in the airspace are 3 GB and 4.7 GB, respectively.

Figure 7.25 depicts the changes of the size of the strategic aviation weather information requirement in the airspace, in the terminal, and at the airport over a 24-hour period for air taxi/commuter aircraft categories in 2025. The maximum size of the strategic aviation weather information requirements at the airport is reached 24 GB. Like air carrier category, the size of the strategic aviation weather information requirement in the terminal for air taxi/commuter aircraft is the smallest in three regions. The maximum sizes of the peak strategic aviation weather information requirements in the terminal and in the airspace are 3 GB and 4.1 GB, respectively.

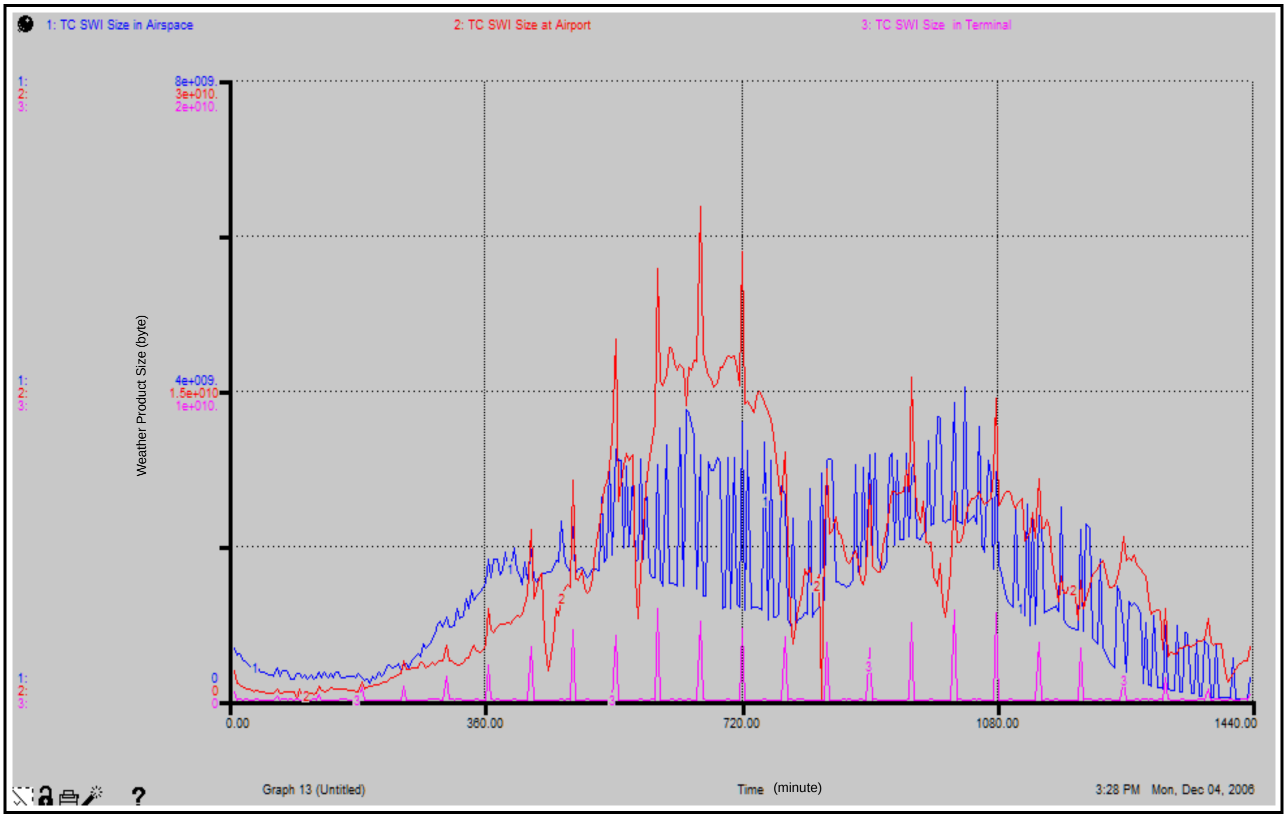

Figure 7.25 Strategic Aviation Weather Information Requirement Size for Air Taxi/Commuter in 2025.

Both of general aviation and military aircraft categories need more strategic aviation weather information on daytime. **Figure 7.26** represents the changes of the size of the strategic aviation weather information requirement in the airspace, in the terminal, and at the airport over a 24-hour period for general aviation aircraft categories in 2025. There are only one peak strategic aviation weather information requirements in the airspace. The maximum size of the strategic aviation weather information requirements at the airport is approximate 29 GB.

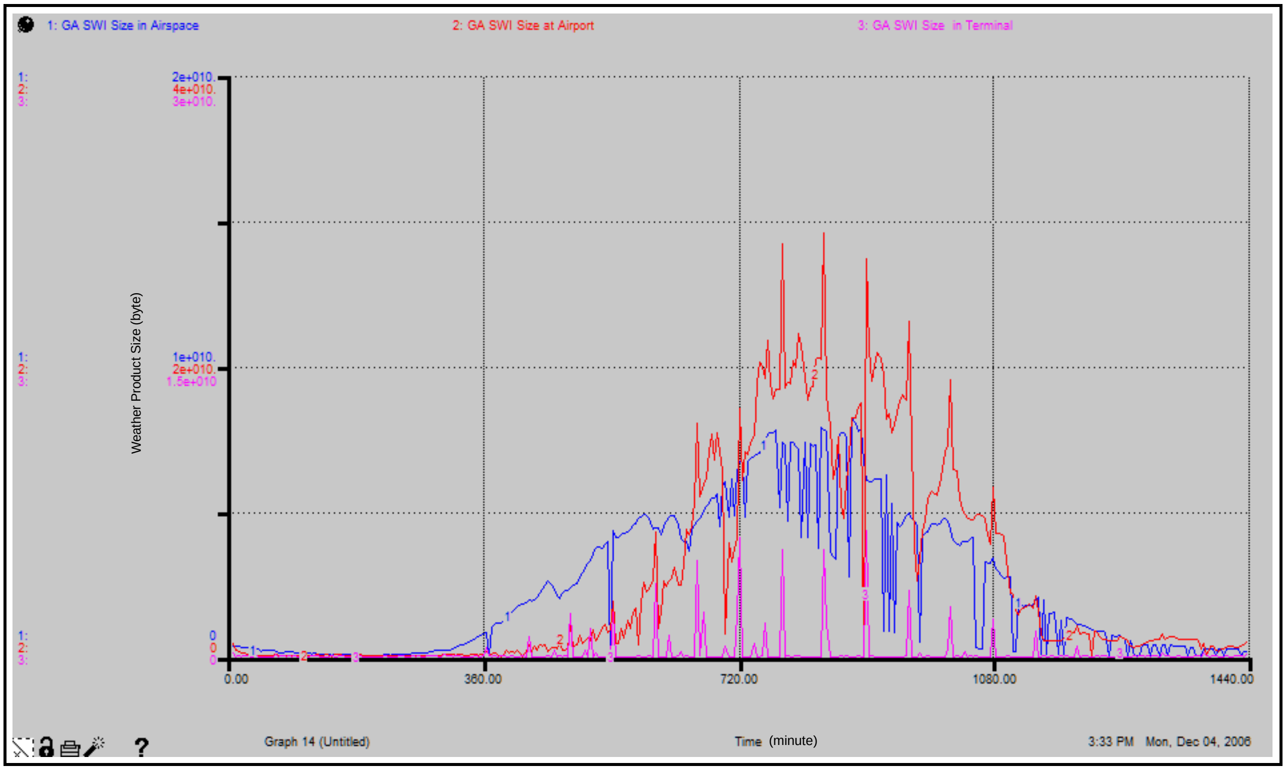

Figure 7.26 Strategic Aviation Weather Information Requirement Size for General Aviation in 2025.

Regarding to military aircraft category, **Figure 7.27** illustrates the changes of the size of the strategic aviation weather information requirement in the airspace, in the terminal, and at the airport over a 24-hour period for military aircraft categories in 2025. The size of the strategic aviation weather information requirement at the airport is bigger than other two flight regions. The maximum size of the strategic aviation weather information requirements at the airport is about 10.5 GB.

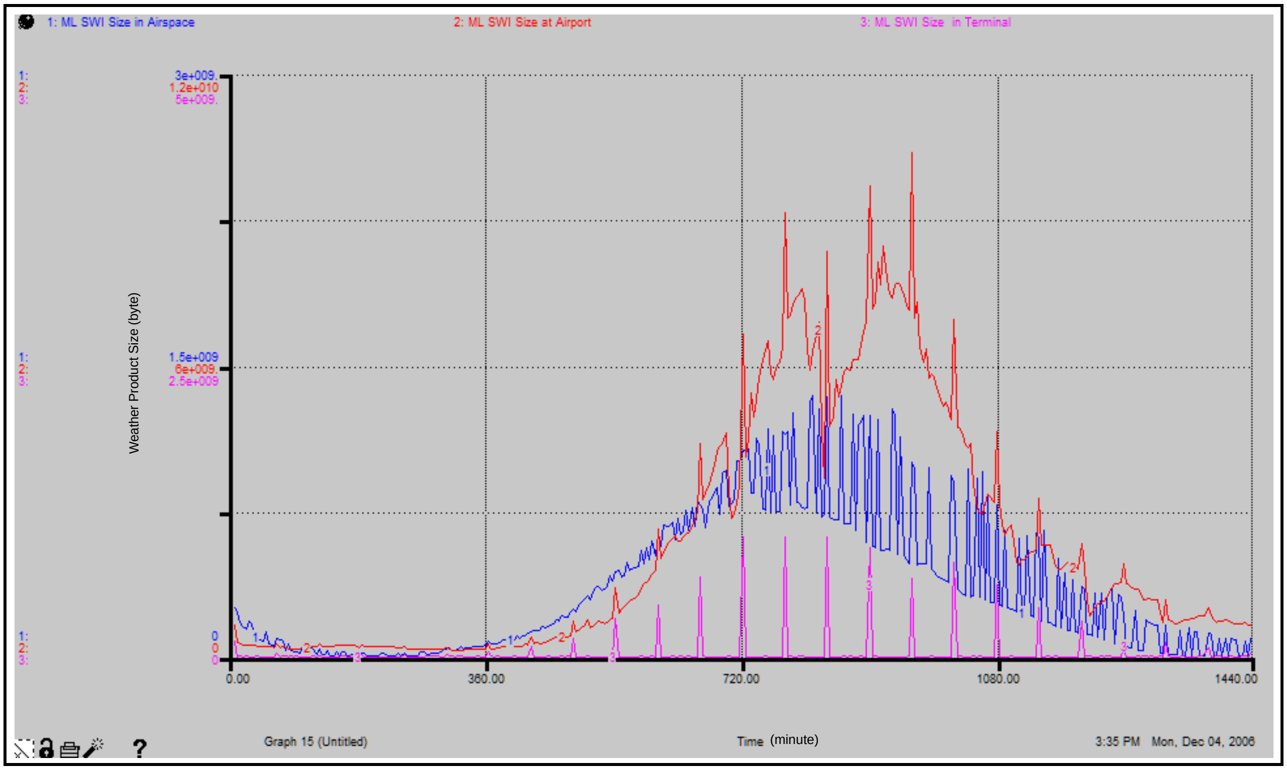

Figure 7.27 Strategic Aviation Weather Information Requirement Size for Military in 2025.

7.2.2.3 Aircraft as Sensor Results and Analysis in 2025

More air carrier and air taxi/commuter aircraft fly in the airspace and in the terminal system more aviation weather data collected by sensor on the board. **Figure 7.28** represents the changes of the size of the aviation weather data collected from air carrier and air taxi/commuter aircraft in the terminal over a 24-hour period in 2025. The maximum size of the wind aloft and temperature data reaches 1.75 MB.

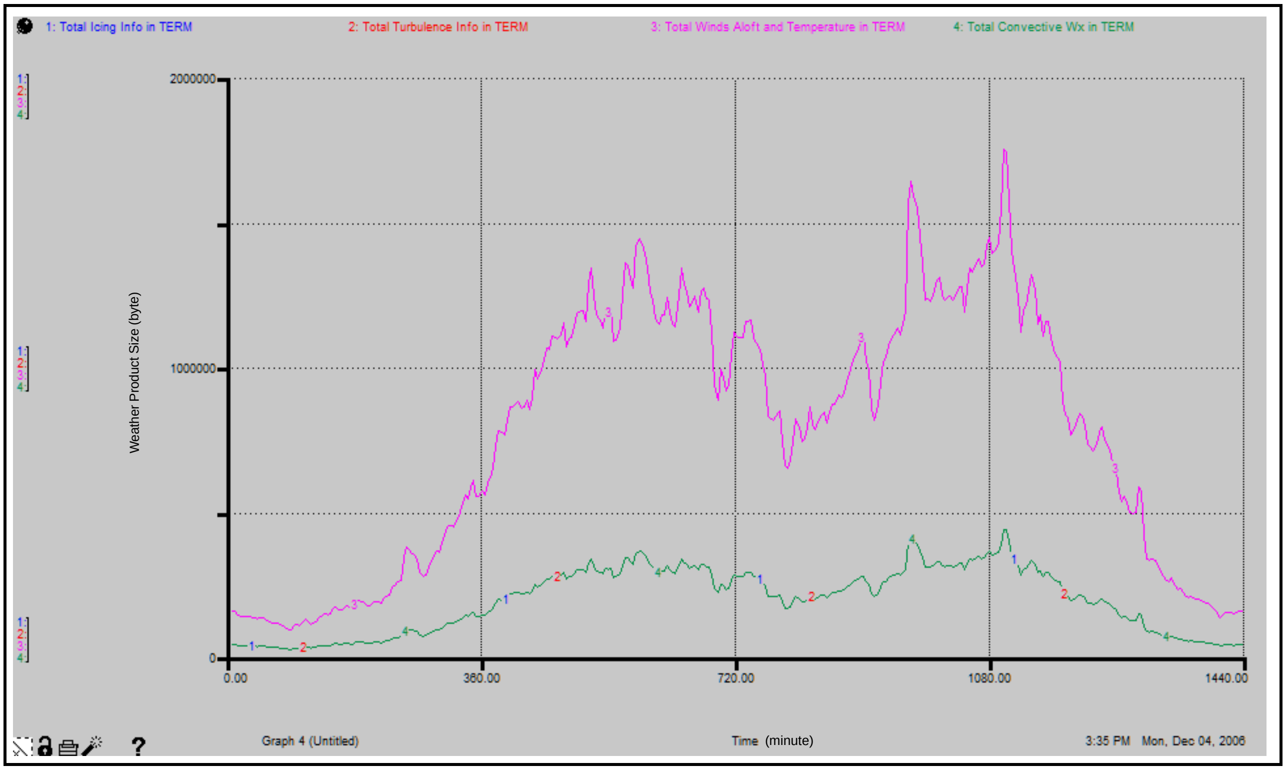

Figure 7.28 Aircraft as Sensor in 2025.

7.2.3 AWINBRM Sensitivity Analyses

As discussed in Chapter 5, the aviation weather information and products and requirements are divided into two major aviation weather domains: tactical and strategic. The time period for the tactical decision is between 0 to 15 minutes, and 15 to 60 minutes for the strategic decision. However, the interval of the sampling rates of the existing aviation weather observations and forecasts are more than one hour. These intervals are longest used in the aviation industry. As new technologies develop, the intervals between the sampling rates of aviation weather products are expected to be shorter in the future. The following paragraphs demonstrate some sensitivity analyses done using the AWINBRM model to understand the effect of shorter sampling rate time intervals.

7.2.3.1 Doubling the Existing Sampling Rate of Aviation Products

The first sensitivity study assumes that the future sampling rate for the tactical and strategic weather products will double the existing sampling rate. For example, the existing sampling rate for METAR is once per hour, the future sampling rate will be twice per hour. The following figures are outputs from the AWINBRM model after changing the sampling rates.

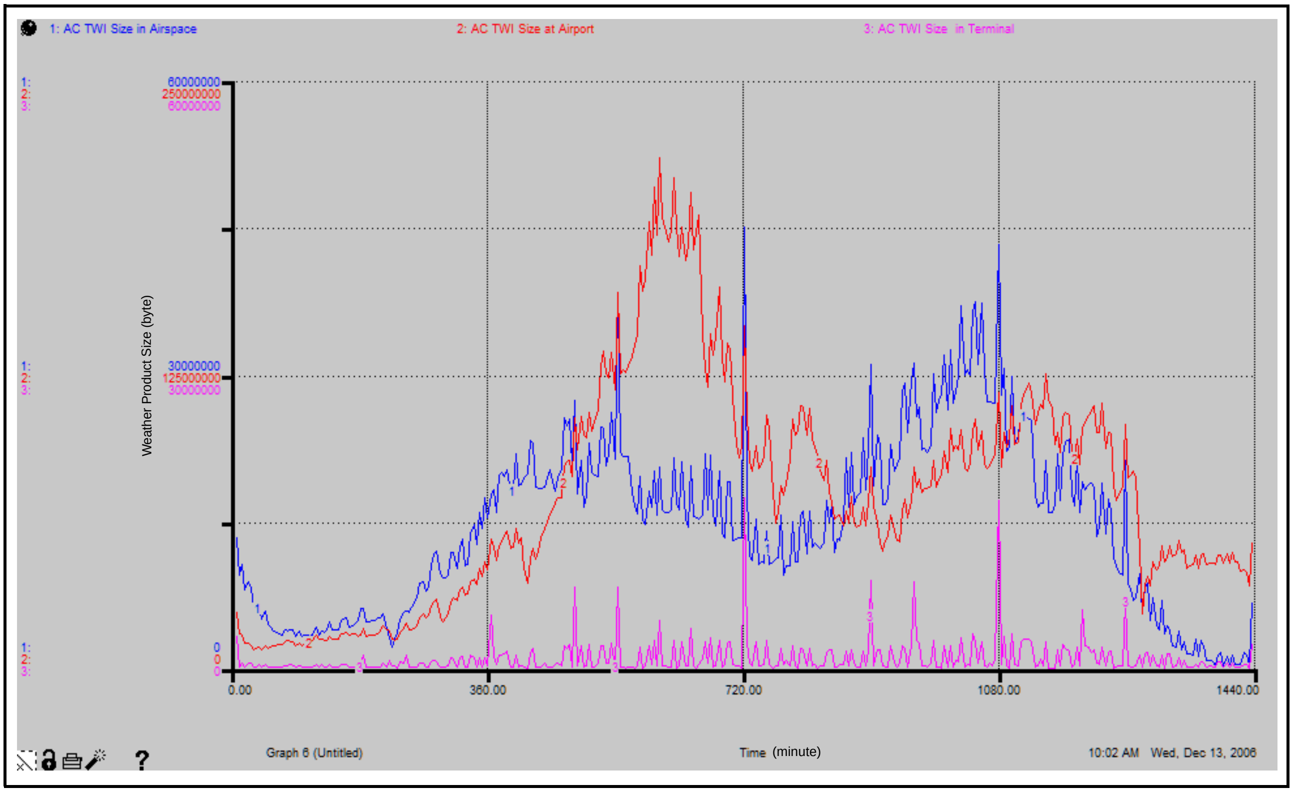

Figure 7.29 Tactical Aviation Weather Information Requirement Size at Double of Existing Sampling Rate for Air Carrier in 2025.

Figure 7.29 depicts the changes of the size of the tactical aviation weather information requirement at double of the existing sampling rate in the airspace, in the terminal, and at the airport over a 24-hour period for air carrier aircraft categories in the year 2025. The sizes of the tactical aviation weather requirements are increased in three regions. The maximum size of the tactical aviation weather requirements at the airport is anticipated to increase from 140 MB in the existing sampling rate to 218 MB using double of existing sampling rate. This increment represents a growth rate of 56 percent. The maximum size of the tactical aviation weather requirements in the airspace is expected to increase from 28 MB using the existing sampling rate to 45 MB with double of existing sampling rate - an increase of 61 percent. The size of the tactical aviation weather requirements in the terminal also increases but at a lesser pace.

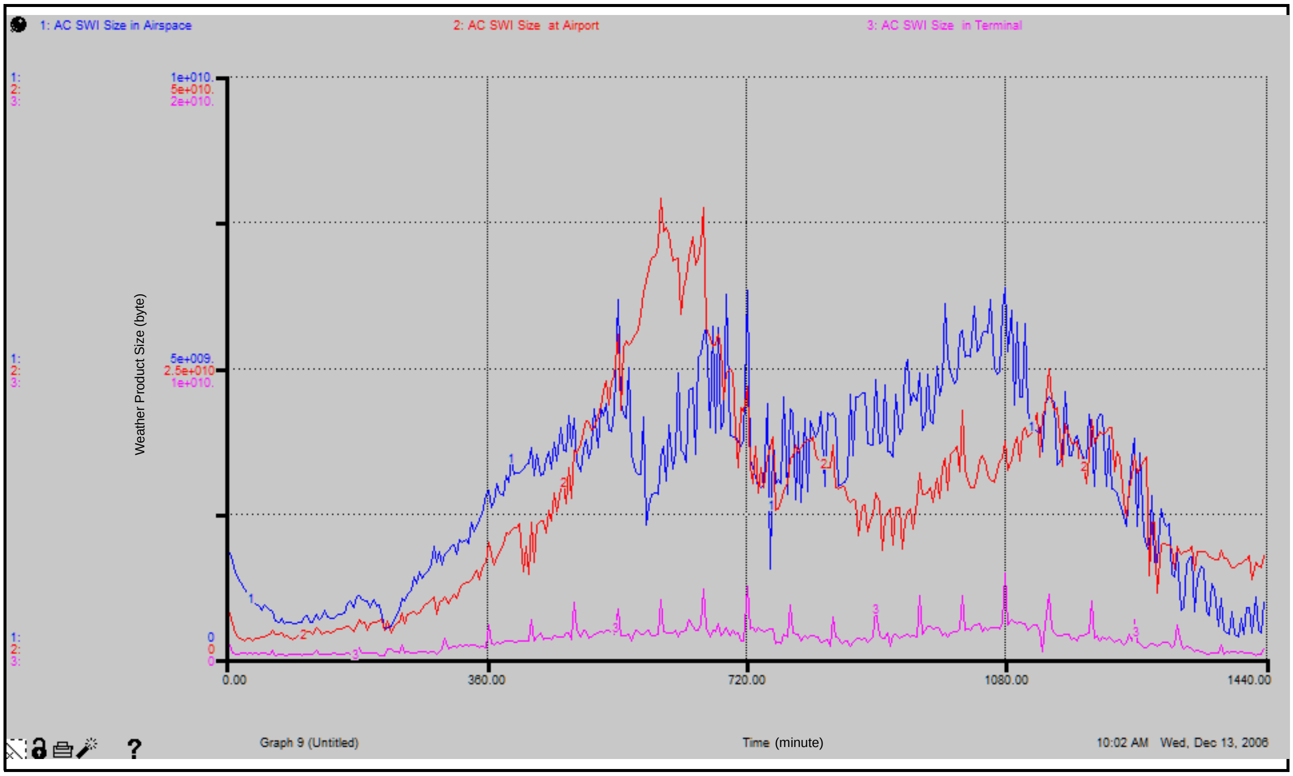

Figure 7.30 Strategic Aviation Weather Information Requirement Size at Double of Existing Sampling Rate for Air Carrier in 2025.

Figure 7.30 illustrates the changes of the message size of the strategic aviation weather information requirement at double of the existing sampling rate in the airspace, in the terminal, and at the airport over a 24-hour period for air carrier aircraft categories in 2025. Comparing with the existing sampling rate, the maximum size of the strategic aviation weather requirements at the airport is anticipated to increase from 29 GB in the existing sampling rate to 40 GB using double of existing sampling rate.

This increase represents a growth rate of 38 percent. The maximum size of the strategic aviation weather requirements in the airspace is expected to grow at an rate of 36 percent from 4.7 GB in the existing sampling rate to 6.4 GB with double of existing sampling rate. The growth rates for strategic aviation weather information are smaller than the changes for tactical aviation weather information. The reason is that aviation industry needs more the tactical aviation weather information than the strategic aviation weather information. Although the peak sizes of the strategic aviation weather information requirement in the terminal are similar in both sampling rates, the overall size using double the existing sampling rate is larger than the size at the existing sampling rate (Figure 7.24).

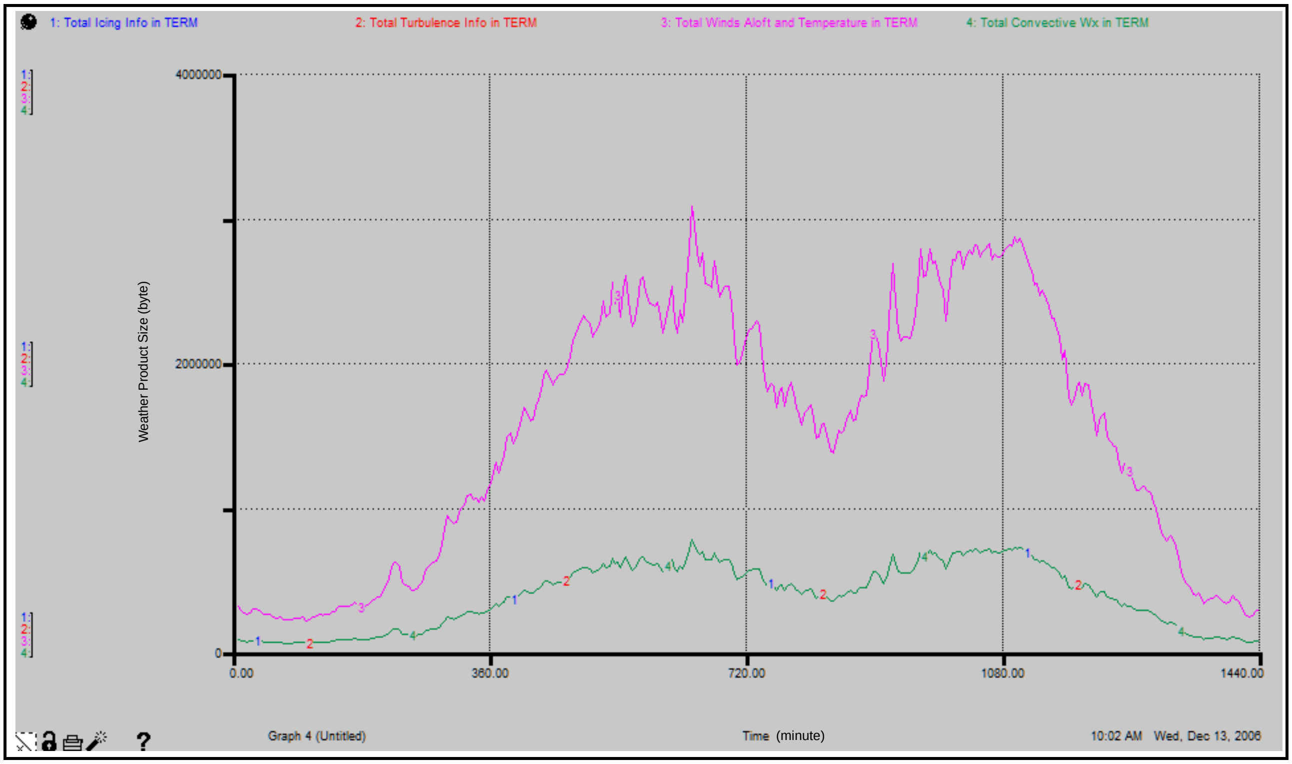

Figure 7.31 Aircraft as Sensor at Double of Existing Sampling Rate in 2025.

With a decrease in the sampling interval more aviation weather information will be sent to the ground or to the aircraft from the on board sensors. **Figure 7.31** presents the changes of the size of the aviation weather data collected from air carrier and air taxi/commuter aircraft doubling the existing sampling rate in the terminal area over a 24-hour period in 2025. The maximum size of the wind aloft and temperature data doubling the existing sampling rate reaches 3.1 MB. This represents a growth of 77 percent.

7.2.3.2 Quadrupling the Existing Sampling Rate of Aviation Product

The following paragraphs discuss the results output from the AWINBRM model when the future sampling rate is four times of the existing sampling rate.

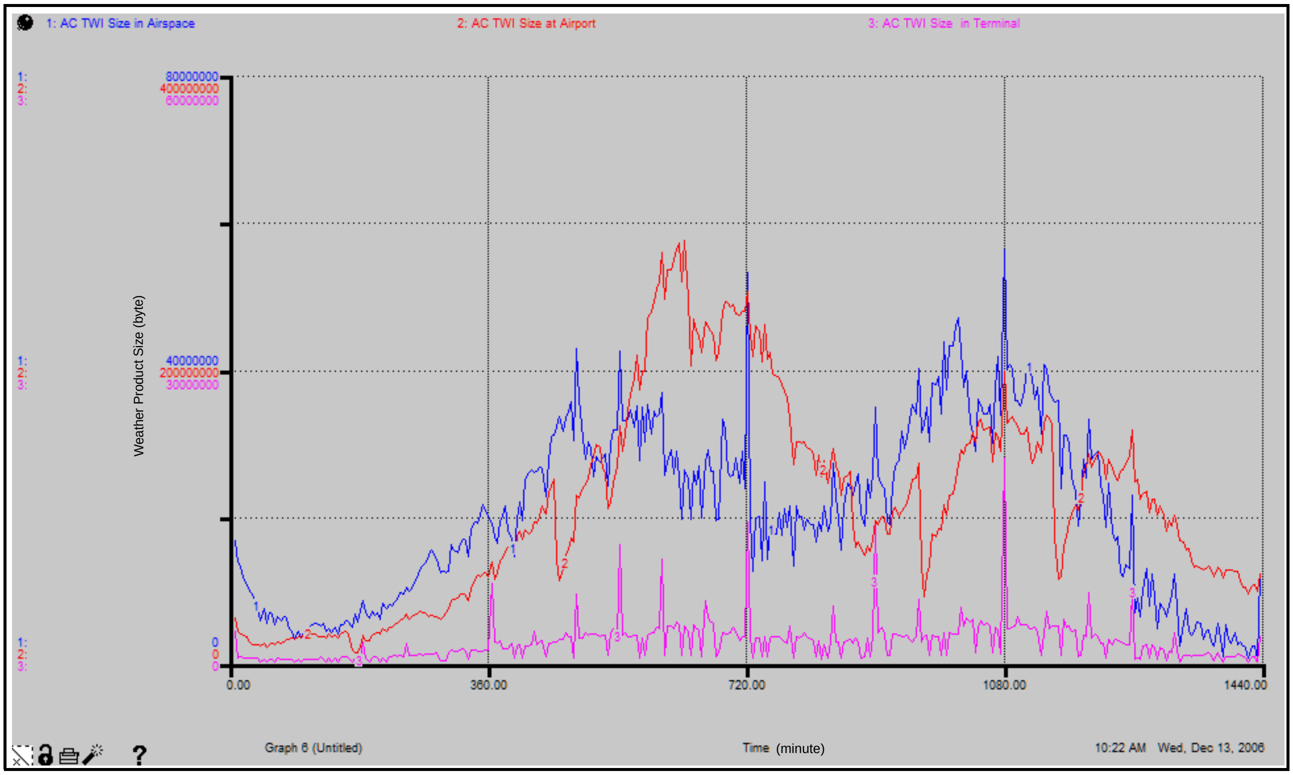

Figure 7.32 Tactical Aviation Weather Information Requirement Size at Four Times of Existing Sampling Rate for Air Carrier in 2025.

Figure 7.32 shows the changes of the size of the tactical aviation weather information requirement at four-time the existing sampling rate in the airspace, in the terminal area, and at the airport over a 24-

hour period for air carrier aircraft categories in 2025. The maximum size of the tactical aviation weather requirements using four times of existing sampling rate at the airport and in the terminal reaches 290 MB and 56 MB, respectively. These changes double the size of the tactical aviation weather requirements compared to the existing sampling rate.

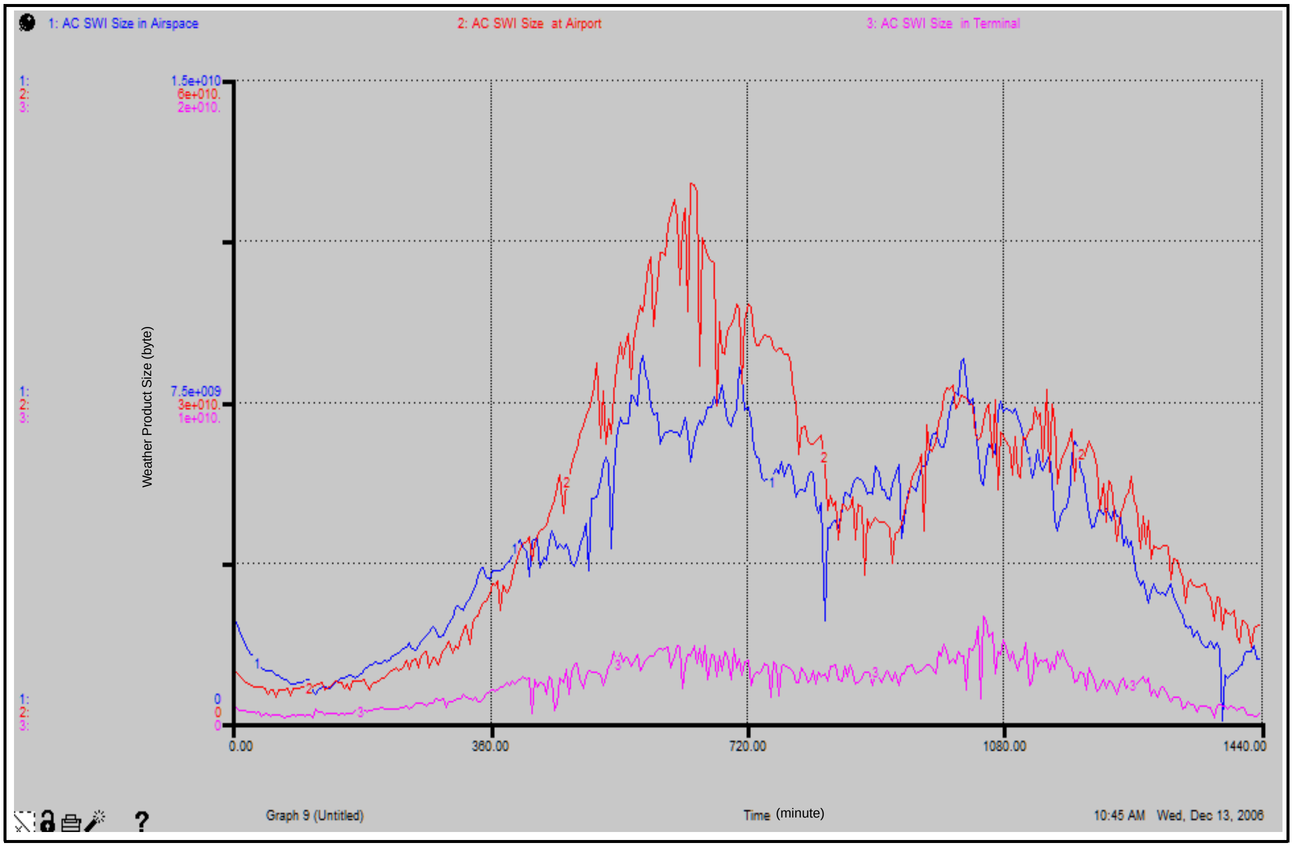

Figure 7.33 Strategic Aviation Weather Information Requirement Size at Four Times of Existing Sampling Rate for Air Carrier in 2025.

Figure 7.33 depicts graphically the changes of the size of the strategic aviation weather information requirement at four times of the existing sampling rate in the airspace, in the terminal, and at the airport over a 24-hour period for air carrier aircraft categories in 2025. Comparing the results to those using the existing sampling rate, the maximum size of the strategic aviation weather requirements at the airport and in the terminal are expected to grow 51 GB and 8 GB, which represent growth rates of 76 and

70 percent, respectively.

Figure 7.34 Aircraft as Sensor at Four Times of Existing Sampling Rate in 2025.

Figure 7.34 illustrates the changes of the size of the aviation weather data collected from air carrier and air taxi/commuter aircraft using four times the existing sampling rate in the terminal over a 24-hour period in 2025. The maximum size of the wind aloft and temperature data using four times of the existing sampling rate reaches 6.3 MB. This size is more than three times of the existing sampling rate.

7.2.4 AWINBRM Summary

The AWINBRM model can output the specific tactical and strategic aviation weather requirements, such as METAR/SPECI, at any phase of flight in any year. The AWINBRM model can update new features of tactical and strategic aviation weather products, for example, adding new items to the existing aviation weather products. The AWINBRM can be used to predict future weather information requirements at an airport system, in the air route traffic control center or several centers or even the complete national airspace system.

7.3 Aviation Weather Economic Impact

As described in previous chapters, aviation weather is an important factor in aviation activities. How aviation weather systems affect aviation activities and how the benefits be made if aviation weather information and data can be provided to users timely? This section will develop a study for conducting the economic impact of an aviation weather system considering en-route flights. In this study, it is assumed that various existing and forecast aviation weather information and products are available and there is no communication congestion between the pilots and ground aviation weather service centers. Also pilots will need some level of artificial intelligence to handle the aviation weather information and to provide interpretation/analysis based on a particular flight plan. The models developed in this section can be used by pilots, ATC controllers, and other users. This section is divided into three parts included:

- Modified Airspace Occupancy Model (MAOM)
- Aircraft Impacted and Detour Model (AIDM)
- Model Result and Analysis

7.3.1 Modified Airspace Occupancy Model

7.3.1.1 MAOM Overview

The Airspace Occupancy Model (AOM) was developed for the project - “Integration of Reusable Launch Vehicle (RLV) into Air Traffic Management” at Virginia Tech **[Sherali, et al., 2000]**. The

Enhance Traffic Management System (ETMS) flight data and Airspace Concept Evaluation System (ACES) sector data were used for input. The original purpose of the AOM was to output air traffic volumes over time each Air Route Traffic Control Center (ARTCC) and sectors. For this research, The AOM has been modified to conduct the impact of an aviation weather system on en-route flights. The Modified Airspace Occupancy Model (MAOM) can read and input another airspace sector data - Sector Design and Analysis Tool (SDAT) data which includes the entire 21 ARTCCs data. Also the MAOM has been modified to output air traffic volume in the aviation weather system. The flights in the aviation weather system are defined the impacted flights. Extrapolated ETMS data on November 12, 2015 are used to run the models.

Figure 7.35 shows a flowchart of the MAOM. There are two major input data sets 1) flight plan information and 2) airspace sector data. The MAOM reads a flight plan path based on its way-points (latitude, longitude, altitude, and time) and also reads airspace sector data which includes ARTCC center, sector, and modules. Through analysis, the MAOM determines the flight path crossing a sector or a center. The modified codes for reading the SDAT and special output of aviation weather system are listed in Appendix C - MATLAB Code. The outputs from the MAOM to be used as the inputs for the Aircraft Impacted and Detour Model (AIDM).

The following paragraphs described briefly the features of the MAOM model. More detail information and codes for the AOM are described - in “Integration of Reusable Launch Vehicle (RLV) into Air Traffic Management” report.

7.3.1.2 MAOM Assumptions and Input

The assumptions made in the development of MAOM are as follows:

1. All flights are assumed to fly along straight lines between way-points, (dummy way-points could be specified to further discretize curvilinear flight trajectories).
2. Two nodes which are less than 0.35 nautical miles apart are assumed to define the same point in the airspace. This assumption is made to correct for inaccuracies in data that

sometimes assign different slightly perturbed locations to the same node, and hence create vacuums within the airspace.

3. A flight that moves along a common boundary of some sector modules, is assumed to pass through only one of them. The choice is made based on selecting the currently occupied sector, if applicable, or arbitrarily otherwise **[Sale, 1999]**.

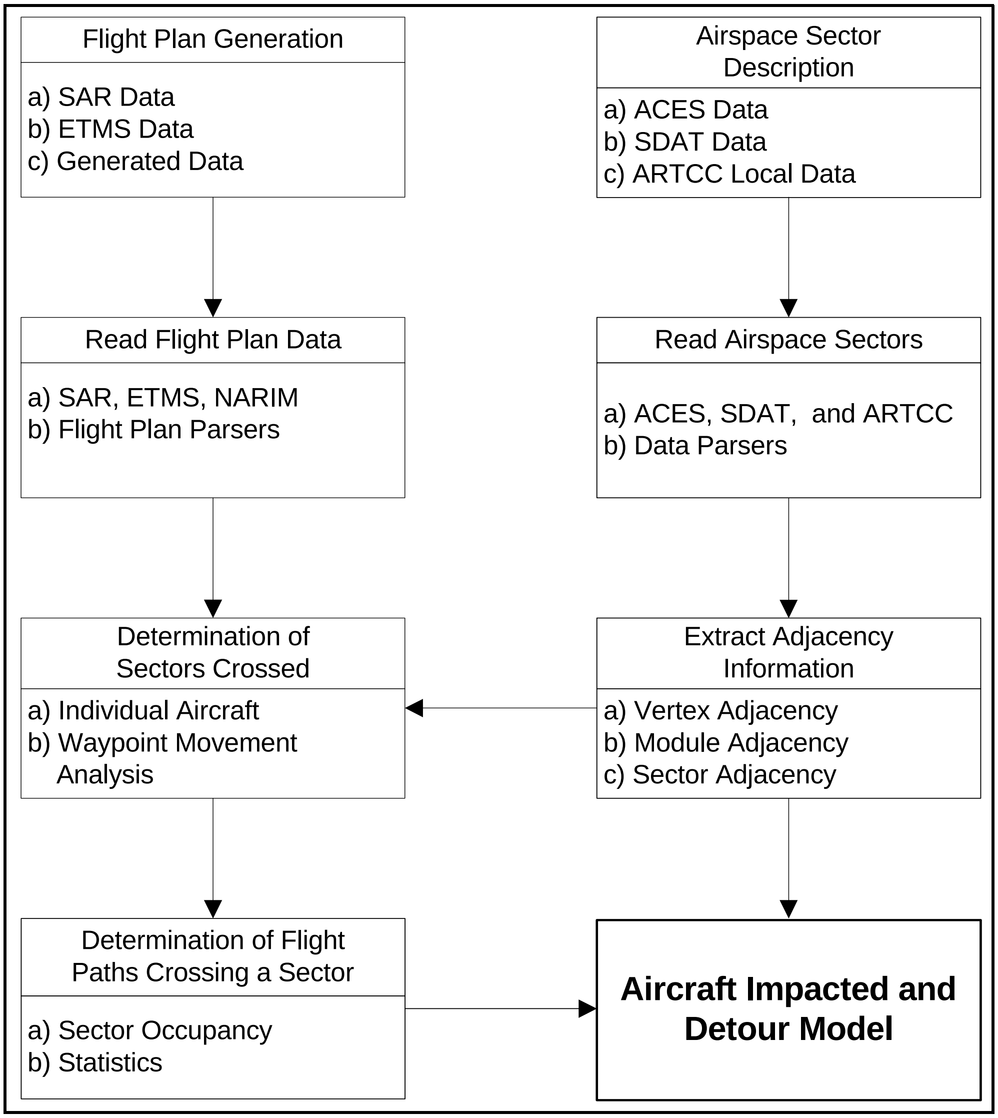

Figure 7.35 Modified Airspace Occupancy Model Flowchart.

MAOM requires a series of aircraft flight plans and the sector geometry as inputs. The model processes the information to determine the occupancy of each sector by different flights over time. The essence of the model lies in storing the adjacency information of sectors, and identifying the sectors crossed by a flight plan. MAOM analyzes individual flight paths from an origin to a destination airport and estimates time traversals over each sector encountered. The following describe the MAOM inputs:

7.3.1.2.1 Flight Plan Generation

The flight plans for a particular day were used for the purpose of analyzing these scenarios. Flight plans obtained from the FAA's ETMS database along with the corresponding air traffic situation were used for this research. Extrapolated ETMS data on November 12, 2015 are used to run the models. Whenever a flight is assumed not to rely on the ground-based navigation aids, a wind-optimized trajectory is adopted. Wind optimized routing is the three dimensional trajectory that will have the least possible impedance considering the reported prevailing winds.

The flight plan inputs to the MAOM can take three forms: 1) flight plans filed by pilots in a given day (ETMS data), 2) flight tracks extracted from System Analysis Recording (SAR) data, or 3) flight plans predicted by National Airspace Resource Investment Model (NARIM) flight plan generators such as Optimized Trajectory Generator (OPGEN). There are common elements to all these data sources and, in general, a flight plan should contain the following information.

- Way-points in latitude (degree), longitude (degree) and altitude (hundreds of feet)
- Time tags corresponding to the crossing of each of the above way-points (during any time interval)
- The originating airport (a three letter airport designator)
- The destination airport (a three letter airport designator) **[Sale, 1999]**

The flight plans for any particular day in the past can be obtained from the FAA ETMS database using the SDAT or a file parser developed for this research.

7.3.1.2.2 Airspace Sector Description

Sectors are well-defined airspace regions specified by the FAA for regulating air traffic. Each sector is comprised of Fixed Posting Airspace units (FPA) and each of these FPAs is made up of modules. A module is a convex or non-convex airspace polytope in shape defined by its vertices and its floor and ceiling altitudes. Modules are stacked one over another to form an FPA, and several such adjacent FPAs form a sector. The main source of en-route and Terminal Radar Approach Control (TRACON) sector information used in this study came from the FAA SDAT database.

7.3.1.3 MAOM Process

7.3.1.3.1 Processing Flight Plans, Sector, and Airport Data

Flight Plans Data

This processing routine identifies the first sector module that a flight trajectory encounters. It also records the entry point and the time of entry. If the originating airport lies within the defined airspace, the identification process will be trivial. If the flight originates outside the defined airspace, the point of entry and the first module entered will be determined by checking each of the flight segments for a possible crossing of an extreme face of the defined airspace. Dummy sectors are defined in order to speed up the computations in this step. More details on dummy sectors are explained below.

Dummy Sectors

During the initialization step, the first module that each flight encounters is determined. If the origin airport does not lie in the defined airspace, then the program will move along the flight trajectory, segment by segment, to identify that flight segment that crosses any extreme face of the defined airspace. Since this is computationally intensive, dummy sectors are defined around the modeled airspace so that the airports of concern lie within this extended airspace. This cuts down the search during the initialization step drastically.

Vacuums

The dummy sectors defined around the defined airspace under consideration are trapezoidal polytopes. Within the rectangular region formed by these sectors, that contains the airspace under consideration, exists an undefined airspace. This space is termed as the vacuum airspace. The program will handle the case of a flight passing through this vacuum and identify its entrance into the defined airspace, if at all or its re-entrance into the dummy trapezoidal polytopes. In addition to this deliberately created vacuum between the dummy sectors and the actual sectors under consideration, there may be instances of vacuums being present between actual sectors because of inaccuracies in sector definitions.

Sector Data

The processing of the sector data involves: 1) reading sector data (from the SDAT database), and 2) converting the sector information into suitable mathematical representations to simplify the occupancy analysis. The analysis is initially done at the module level and later, the occupancy information is aggregated to the sector level. The adjacency information with respect to the faces and vertices is determined and stored during processing.

Airport Data

Airport data constitutes one of several inputs defining an aircraft's three-dimensional trajectory. The processing routine identifies each airport with a sector by checking if the airport lies in any of the low lying sector modules. The built-in Matlab function in polygon is used to check if a point lies within a polygon. If the airport lies outside the defined airspace, no sector module will be associated with it.

7.3.1.3.2 Occupancy Determination

A flight that crosses a sector will be detected by the model based on the adjacency information that is generated and stored during the pre-processing step. Since each sector is complex in shape, the analysis is done at the module level and the result is translated to the sector level by considering the particular modules that make up the sector.

The model first identifies the initial module encountered by the flight. This may be the module that encompasses the originating airport. Sometimes, the originating airport may not lie within the defined modules. In such a case, the model identifies the module through which the flight enters the defined airspace. Once the initial module through which the flight passes is detected, the point and time of exit is identified. This point is found by checking if the flight crosses any of the faces, the floor, or the ceiling defining the module, without merely glancing at it and remaining within the same module.

The program also identifies the way a flight exits the module, i.e., if the flight exits across a face, or the floor, or the ceiling, or at a vertex, or across an edge. With this knowledge, and since module adjacency information is known, the next module into which the flight enters is determined. This process of identifying each traversed module and the corresponding occupancy time is continued until the flight reaches its destination. Next, the sectors through which the flight passes is identified by examining the modules that comprise each sector. This provides information on all flights that cross a particular sector along with related occupancy times **[Sale, 1999]**. The outputs from the MAOM are then used automatically by the Aircraft Impacted and Detour Model (AIDM).

7.3.2 Aircraft Impacted and Detour Model

7.3.2.1 AIDM Flowchart

Based on the flight plan and aviation weather system information the Aircraft Impacted and Detour Model (AIDM) is used to detect impacted flights by the weather system, generate new detour flight paths around the weather system, and optimize flight detour paths according to the travel time and fuel consumption. **Figure 7.36** depicts the flowchart of the AIDM model. Like the MAOM model, there are also two major input data; 1) the original flight path information and 2) aviation weather system information. The MAOM model provides a detail flight path analysis and its outputs are the flight path information required by the AIDM model. After building the aviation weather system and combining the flight path information, the AIDM detects the impacted flights by the aviation weather system first and then generates detour flight paths for the impacted flights. Finally the AIDM model selects optimal path for each impacted flight based on the fuel consumption and travel times.

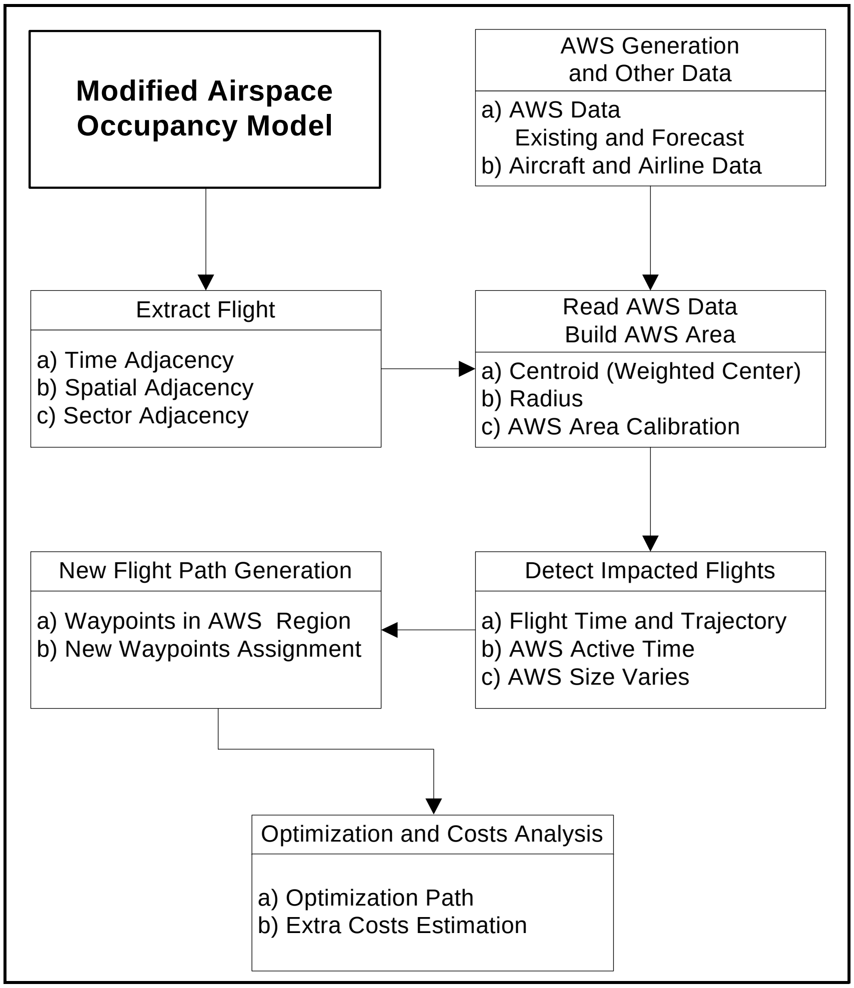

Figure 7.36 Aircraft Impacted and Detour Model Flowchart.

The inter-relationships between the MAOM and AIDM models are illustrated in **Figures 7.35** and **7.36**. The main blocks comprising the AIDM are shown in **Figure 7.36**.

The AIDM was developed using the MATLAB software package. The MATLAB routines of the AIDM are attached in Appendix C - MATLAB Source Code. The routines for the AIDM include the building a weather system, detecting impacted flights, generating surrogate flight paths, check way-point crossings, fuel consumption, and view and plot functions etc.

7.3.2.2 Input Data

7.3.2.2.1 MAOM Output

There are two outputs from the MAOM:

- Sector occupancies and flight path structures
- Adjacency information to local spatial relationships between neighboring sector models

The first task in the AIDM is the extraction of flight proximity information. This is done through the creation of three data structures containing time, spatial, and sector adjacency information.

7.3.2.2.2 Aviation Weather System Data

The aviation weather system is generated according to the geometry of the aviation weather system and the period of the aviation weather system activity. The aviation weather system is a four-dimensional airspace polytope in shape defined by its vertices, floor, ceiling altitudes, and time. Its shape can vary over time, for example, an aviation weather system might exist at certain size at time t. Sometimes later (at time $t + \Delta t$), it might be larger, smaller or it might have disappeared. The current aviation weather system and its forecast would have a physical location and impacted size. However, the real aviation weather system exhibits complex three-dimensional shapes. To simplify the modeling task, the aviation weather system is defined by a circle of radius R and centered at (X_o, Y_o). The third dimension of the aviation weather system is defined as from floor to ceiling boundaries. Since we are interested in modeling aviation weather phenomena, the floor is considered sea level and the ceiling corresponds to the highest flight level of commercial flight. A small scale tropical storm near the Florida Coast is chosen for running this model.

7.3.2.3 AIDM Process

After reading flights paths output from the MAOM and the aviation weather system data the AIDM processes the following steps:

- Build aviation weather system area

- Extract flights,
- Detect impacted flight
- Generate new flight plan
- Optimize flight paths, and
- Output results.

7.3.2.3.1 Process Aviation Weather System Data

A subroutine is used to process the tropical storm system data and conduct the following steps:

1. Find the centroid (X_o, Y_o) of the tropical storm system, which is the weighted average of all vertices
2. Find the radius (R) of the tropical storm system that is the distance between the centroid (X_o, Y_o) and the farthest vertices from the centroid (X_o, Y_o)
3. Construct the tropical storm system to be a circle at the centroid (X_o, Y_o) and with radium R

Based on a 24-hour forecast of the tropical storm system the subroutine will build the projected weather system location and its size.

7.3.2.3.2 Detect Flights Impacted

During the tropical storm system activity the flights passing the tropical storm area will be impacted. One subroutine will be used to detect impacted flights:

1. Obtain the flight way-points and flight times after extracting flight.
2. Calculate the distances between each flight way-point and centroid (X_o, Y_o) of the tropical storm system.
3. Check which way-points will be in the tropical storm system at that time through comparing between the radius R and the distances.

7.3.2.3.3 Generate Detour Flight Plan

The flights will go through according to it’s original plan if there are not flight way-points in the tropical storm system. Otherwise, the flights, which are impacted by the tropical storm system, will be re-route around the tropical storm system area. The following steps are used to generate surrogate flight plans:

Find critical points:

Figure 7.37 shows a typical example for generating a detour flight path. The red circle in this figure represents the tropical storm system. The points *A, B, C, D, E,* and *F* are the some key points related to the tropical storm system. It is assume that the lines between the points $P_0, P_1, P_2\ldots$ and $P_0, Q_0, Q_1, Q_2,\ldots$ be the original way-points in a flight path.

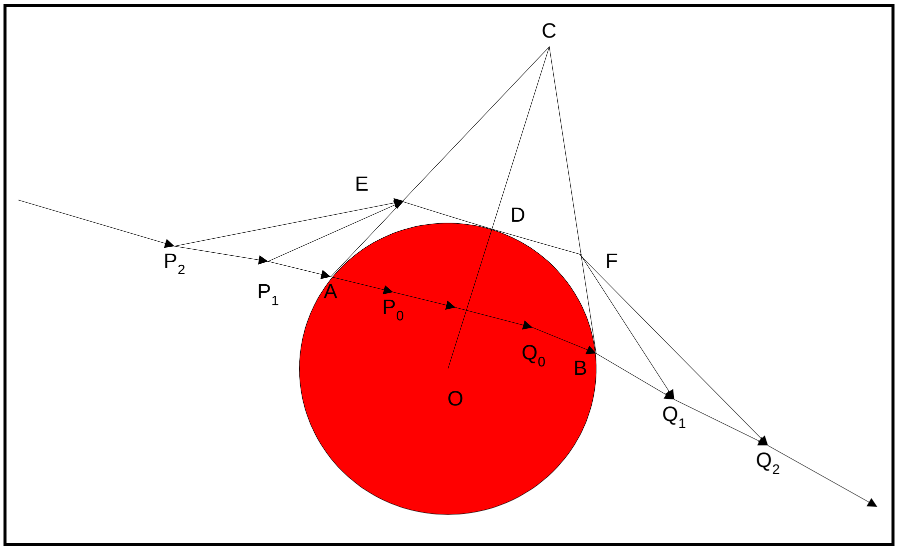

Figure 7.37 Impacted Flight and Re-route Flight Path.

The methodology for finding the key points is described as follows:

- Find Point *A* where the flight accesses the tropical storm system and Point *B* where the flight exits the tropical storm system: the routine will find the first way-point P_0 and last way-point Q_0 in the tropical storm system, P_1 is the last way-point before the flight enters the tropical storm system, Q_1 is the first way-point after the flight exits the tropical storm system. According to the assumptions before, the trajectory between two way-points is straight line, therefore, Points *A* and *B* are the intersects between the tropical storm system and the lines of $P_0 P_1$ and $Q_0 Q_1$.

- Find point *C*: to construct tangents at Points *A* and *B* and the intersection of two tangents is Point *C.*
- Find Points *D, E,* and *F*: to consider the line segment *OC* and the intersection of this line with the tropical storm system is Point *D*. To construct a tangent at Point *D*, two intersections between the tangent at Point *D* and two tangents at Points *A* and *B* are Points *E* and *F.*

A particular case, If the tangents at Points *A* and *B* are parallel, the line *AB* is a diameter, the Point *D* is the intersection of the normal to line *AB* through *O*, then find the Points *E* and *F.* This case is demonstrated in **Figure 7.38**.

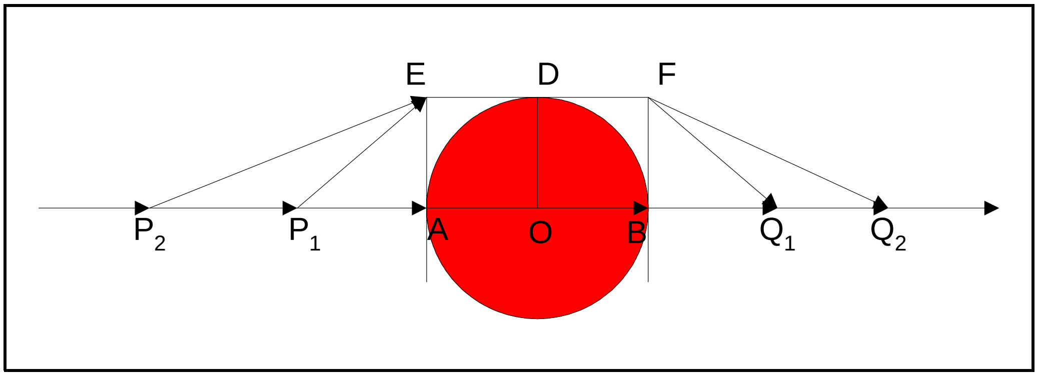

Figure 7.38 Impacted Flight and Re-route Flight Path Special Case.

Detour flight plan generation:

The impacted flights must avoid to enter the tropical storm system for the safety purposes. There are some optional alternatives for these flights, the alternatives include going back to its original airport or landing to alternative airports or staying at airports if the flights didn’t take off until the tropical storm system moves out that area. Another alternative is that the pilot can make a detour around the tropical storm system based on the accurate and timely tropical storm data and its forecast. One routine in the AIDM is used to generate surrogate flight paths.

As shown in **Figures 7.37** and **7.38**, first detour flight path is {••••••P_1 –> A –> E –> D–> F –> B –> Q_1 ••••••}, second detour flight path is {•••••• P_1 –> E –> D–> F –> Q_1 ••••••}, third detour flight path is {•••••• P_2 –> E –> D–> F –> Q_2 ••••••}, and so on. The arrow (–>) represents the direction from one way-point to next way-point. If Points Q_i or P_i at airport, the detour flight paths can use them repeatedly.

As mentioned in Chapter 2, the probability-nets is used to build the detour flight paths. the probability-nets method is based on the Model Output Statistics (MOS) forecast data. The detour flight paths are dependent on the probability threshold level. Here the detour flight paths are dependent on the size of weather systems.

Determination of Optimal Flight Plan:

The AIDM can generate several detour flight paths for each impacted flight. Through calculating the travel time and fuel consumption for each detour flight plan, the optimization flight path with the minimum travel time and fuel consumption will be chosen and provided it to pilots.

7.3.3 Model Results and Analysis

The AIDM model generates detour flight path around bad weather system and also detects impacted flights by bad weather system. The following paragraphs describe the analyses of flight original and detour trajectories and impacted flights around the tropical storm weather system. The cost analysis between the detour flights and delayed flights at airport is presented in the last section.

7.3.3.1 Original and Detour Flight Trajectory Analysis

Figures 7.39 illustrates the output from the MAOM model, which shows original flight trajectories. The red circle in the figure is assumed as a tropical storm system for the further analysis. The flights can fly through the tropical storm area freely.

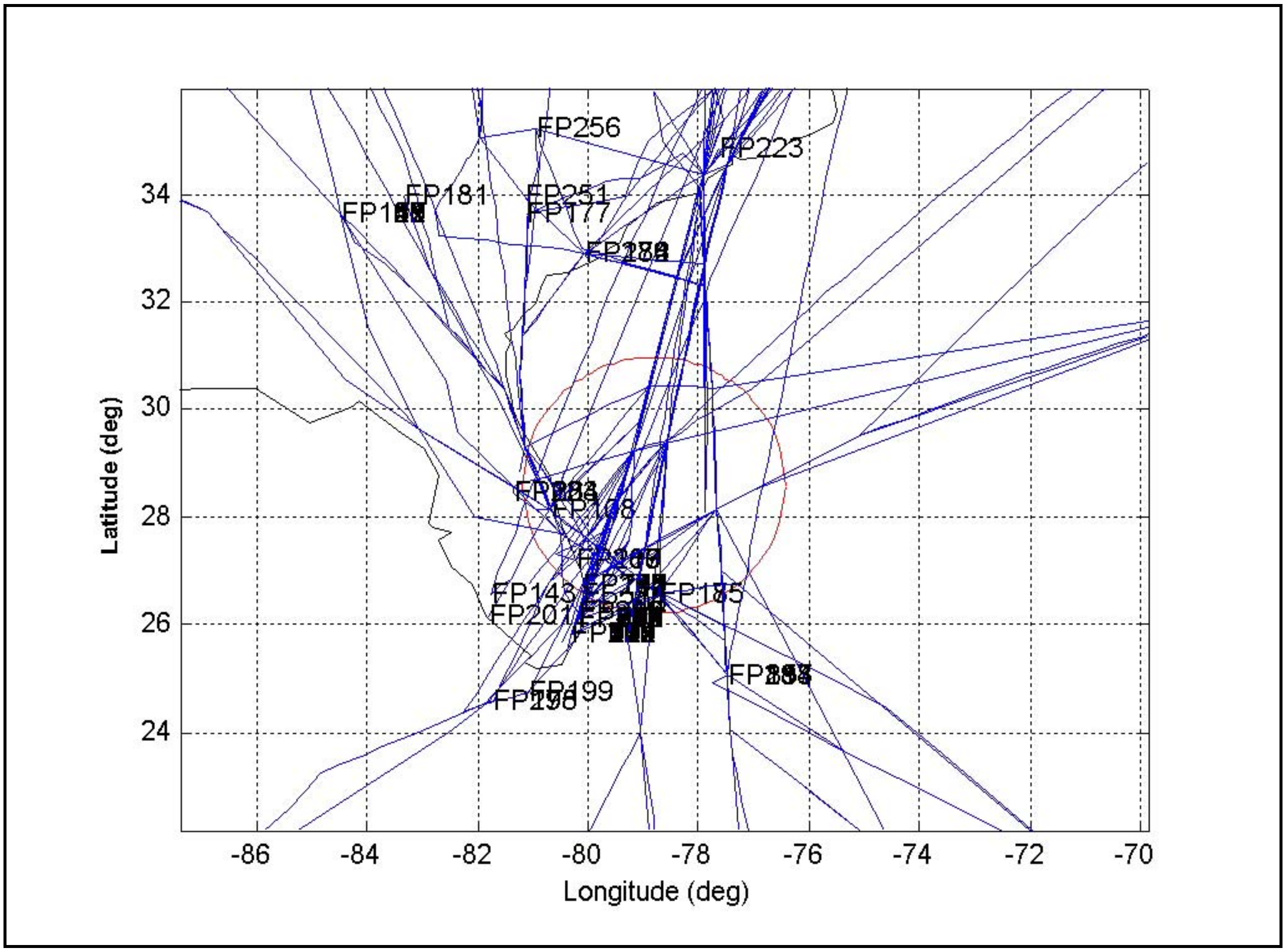

Figure 7.39 Original Flight Trajectories.

When a tropical storm system occurs the flights passing this area are affected and would re-route around the tropical storm system. This situation is shown in **Figure 7.40**. Each impacted flight by the tropical storm system has to change its original flight plan before it reaches the boundary of tropical storm system in order to keep flight safety. This change would increase flight distance and result in more travel time and fuel consumption.

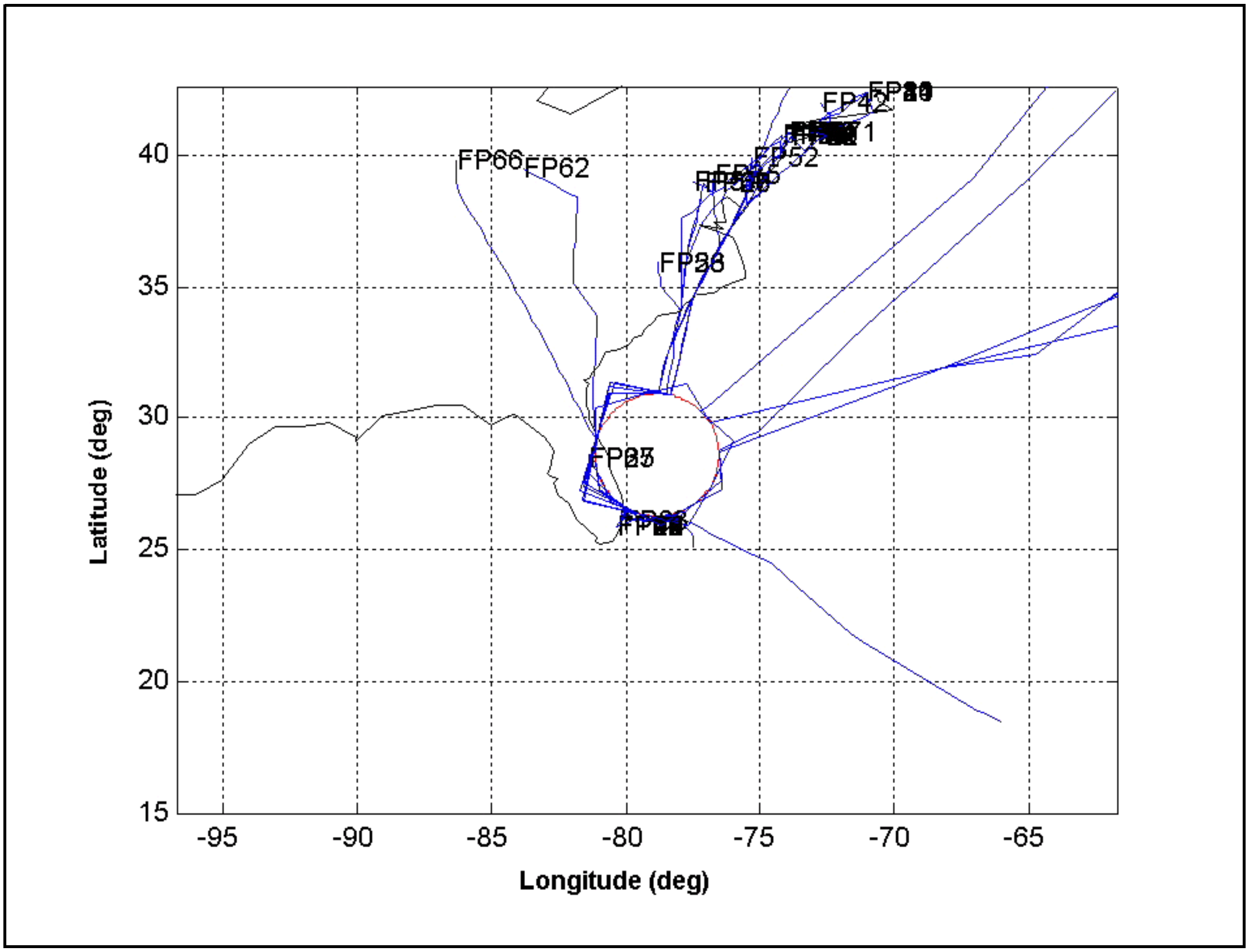

Figure 7.40 Surrogate Flight Trajectories for Impacted Flights.

The AIDM model can generate n surrogate flight plans from an original flight plan. **Figure 7.41** illustrates six possible detour flight plans for one original flight plan. One routine in the AIDM is used to choose an optimal flight plan from these n surrogate flight plans based on their travel time and fuel consumption.

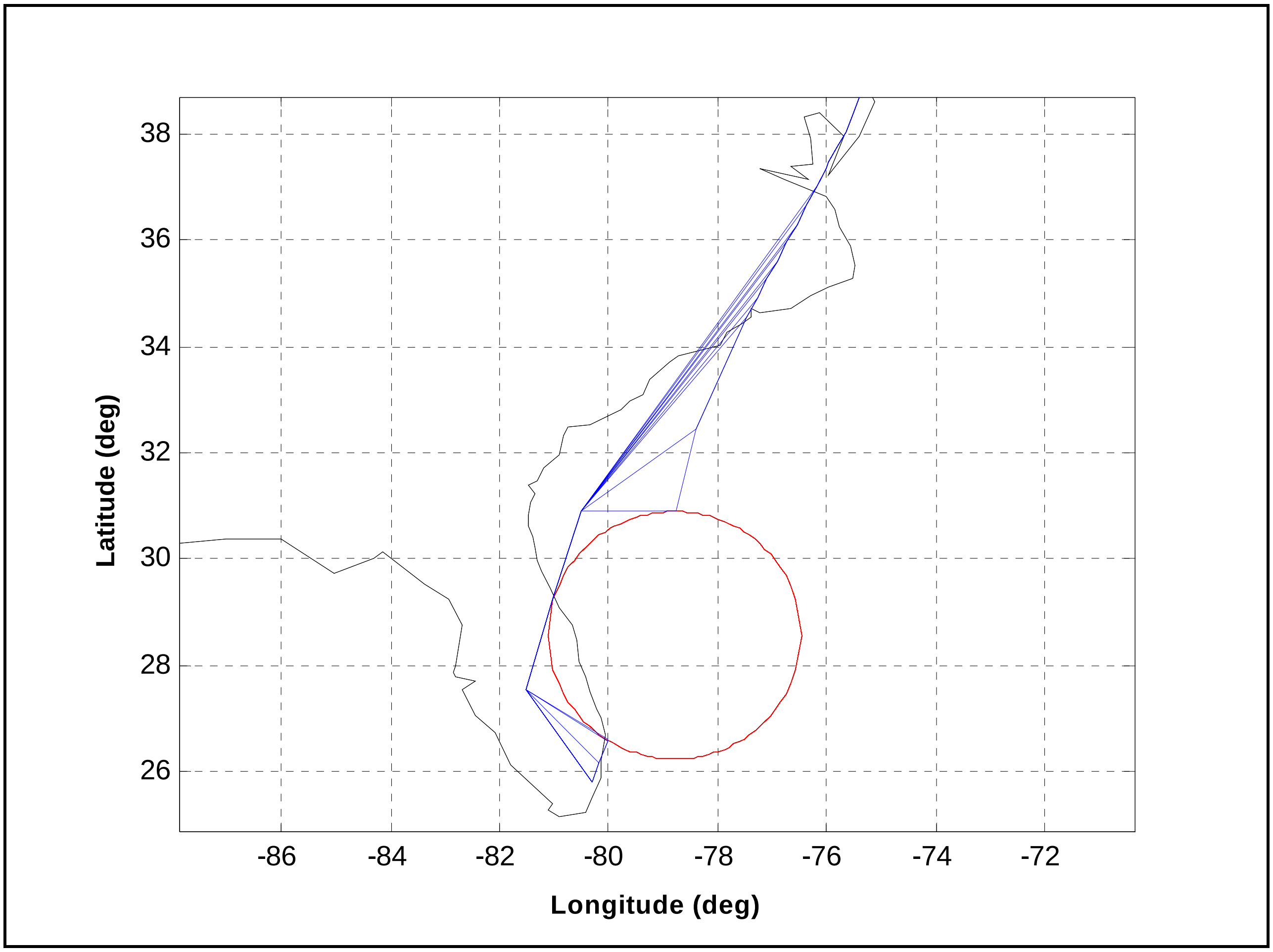

Figure 7.41 N Surrogate Flight Paths for One Impacted Flight.

7.3.3.2 Impacted Flights Analysis

Figures 7.42 indicates the number of flights impacted by the tropical storm system over time in the year of 2015. The R in the figures stands for the radius of the tropical storm system, the R/2 and R/4 are assumed half and quarter of the original tropical storm system. The number of flights impacted by the tropical storm system decreases with the decrease in size of the tropical storm system. When the size of the tropical storm system is a quarter of its original, only a few flights will be affected. The maximum number of impacted flights occur between 1,000 to 1,100 UTC time due to the peak hour of air traffic operations during these times **[Sherali, Smith, and et al., 2001]**.

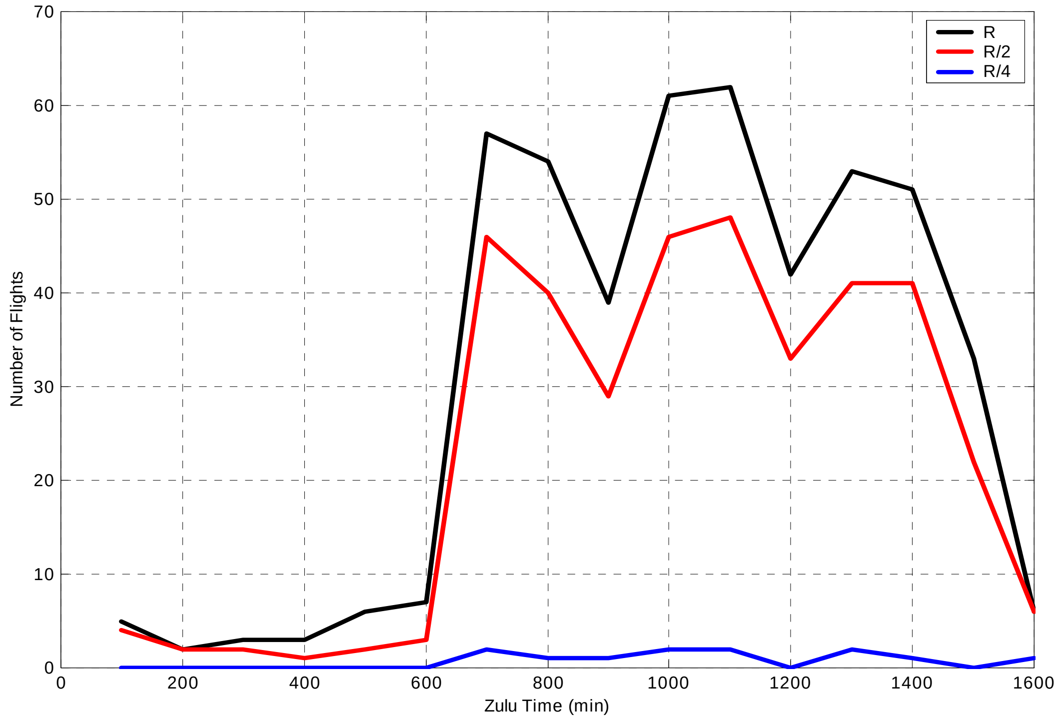

Figure 7.42 Flights Impacted over Time in 2015.

7.3.3.3 Cost Effectiveness Analysis

The following paragraphs describe the comparison of the costs between detour flights and the flights delayed at the airports when the tropical storm weather occurs in 2015. The costs include the values of passenger times and aircraft operating costs.

7.3.3.3.1 Economic Value

There are many economic values in aviation system. The values of passenger time and aircraft operation costs including fuel and oil, maintenance, crew, depreciation, rental, insurance, and other costs are chosen for this research. **Tables 7.12** and **7.13** list the value of passenger time per hour and aircraft operating costs per hour.

Table 7.12 Values of Passenger Time per Hour.

Carrier Category	People	Values
Air Carrier	Personal	$19.50
	Business	$34.50
	All Purposes	$26.70
General Aviation	Personal	$26.30
	Business	$37.50
	All Purposes	$31.10

Table 7.13 Aircraft Operating Costs per Hour.

Carrier Category	Cost Category	Values
Air Carrier	Variable Operating Cost	$2448.00
	Fixed Cost	$645.00
	Total Cost	$3093.00
Commuter/Air Taxi	Variable Operating Cost	$572.00
	Fixed Cost	$276.00
	Total Cost	$848.00
General Aviation	Variable Operating Cost	$190.00
	Fixed Cost	$375.00
	Total Cost	$565.00
Military	Variable Operating Cost	$1631.00

The source of passenger time and aircraft operating cost is from the FAA's "Economic Values for Evaluation of Federal Aviation Administration Investment and Regulatory Programs" [**FAA-APO-98-0, June 1998**]. The variable costs in **Table 7.13** include fuel and oil, total maintenance, and crew costs, the total fixed costs include rental, depreciation, and insurance costs.

7.3.3.3.2 Comparison of the Costs

Table 7.14 shows the comparison of the costs between detour flights and delayed flights at airports. The costs are calculated based on the following data from the AIDM and assumptions:

Table 7.14 Cost Comparison between Detour Flights and Delayed Flights at Airports.

Carrier Category	Cost Category	Detour Flights	Delayed Flights
Air Carrier	Personal Cost	$5,704	$38,101
	Business Cost	$23,546	$157,289
	Variable Operating Cost	$18,360	No
	Fixed Cost	No Change	No Change
Air Taxi/Commuter	Personal Cost	$746	$4,982
	Business Cost	$3,079	$20,569
	Variable Operating Cost	$2,431	No
	Fixed Cost	No Change	No Change
General Aviation	Personal Cost	$237	$1,581
	Business Cost	$788	$5,261
	Variable Operating Cost	$475	No
	Fixed Cost	No Change	No Change
Military	Variable Operating Cost	$1,223	
Total		$56,589	$227,783

There are 62 flights impacted by the tropical storm system between zulu time of 1,000 to 1,100 minutes in 2015. The impacted flights include 30 air carrier flights, 17 air taxi and commuter flights, 12 general aviation airplanes, and 3 military airplanes. The detour flights need an extra travel times of 15 minutes on average to land to their destination airports. It is assumed that all delayed flight at airports will be waited 100 minutes. It is also assumed that the passengers for business travel stand for 70 percent and the rests of passenger are belonging to the personal travel. The passengers on each air carrier, air taxi and commuter, general aviation aircraft are assume to be 130, 30, and 10 people, respectively.

The total extra costs of the detour flights around the tropical storm system is about $56,589, while the extra costs for flights delayed at the airports are reached $227,783 which is four times of the detour flights. It is obvious that detour flights would benefit to airlines and their passengers.

The detour flight paths are dependent on the size of weather systems, the benefit is strongly impacted by the accuracy of severe weather forecast. Tactical weather is often safety related and time-critical. Strategic weather is more pro-active, planning for avoidance rather than weather penetration. It is used to identify a hazard early, collaborate on a plan to avoid it, and make relatively small, well-coordinated changes to the flight trajectory. Therefore, More accurate strategic weather forecast will provide more benefit to aviation industry.

CHAPTER 8

Conclusions and Recommendations

8.1 Conclusions

Three computer models have been developed and presented in this dissertation: the Air Traffic Flow Model (ATFM), the Aviation Weather Information and requirement Model (AWINRM), and the Aircraft Impact and Detour Model (AIDM). The ATFM can analyze the air traffic volumes at twelve phase of flight in three flight regions- en-route airspace, in the terminal, and at the airport for four aircraft categories which are air carrier, air taxi/commuter, general aviation, and military. The AWINRM is used to quantity the size of the aviation weather information transmitted in uplink and downlink communication systems. The AIDM is an useful and practicable flight impacted and detour model around bad weather system. Aviation users can use it to make benefits for air passengers and airlines.

Air traffic flow analysis at the airports, in the terminal, and in the airspace is important for conducting aviation issue analysis. The results from the ATFM demonstrate that all types aircraft in most of times are stayed on the ground, the second large aircraft volume occur in airspace system, the least aircraft are located in the terminal area. The findings from the AWINRM are: 1) In the preflight operations, the pilot (and/or dispatcher and ATC) may need large quantities of data from a number of sources to obtain an accurate picture of the current and forecasted conditions along the intended route. 2) The aircraft in the terminal area need the less aviation weather information but the terminal area has been identified as the area where weather may have the most impact in terms of flight safety. The AIDM can be used by aviation users to make efficient flight path around bad weather system and its results show that the accurate and timely aviation weather information would benefit to airlines and their passenger.

Like other systems in the world, the aviation system would be changed at difference ways. All models developed in this research can be suitable to any changes. All models have an Graphic User Interface which includes various input parameters and output variables, users can change any variable like air traffic demand, flight time, the size of aviation weather information, and so on and re-run the models easily. The models can simulate small aviation system like an airport or lager aviation system from an air route traffic control center to several centers even entire national airspace.

This study also explores another important issue - weather information communication systems that is play a key role in transfer aviation weather information among pilot, air traffic controller, dispatcher, and etc. Except reviewing the existing and planned aviation weather communication systems this research also explore potential new communication systems which can be used to transfer large size aviation weather information like aviation weather graphics etc. These analysis would provide an valuable guidance to develop future aviation weather information communication systems.

8.2 Recommendations

The ATFM and AWINRM models developed in this research can be further develop to model more detail aircraft types even individual aircraft rather than four aircraft categories used in this study.

For the aviation weather information and requirement analysis, the suggestions are as follows: Aviation weather products should be provided: 1) to address the eight categories of weather phenomena defined in this research; 2) to address hazards in terms of forecasted conditions, current conditions (observations/measurements), intensity, location, extent, movement, and life cycle; 3) to provide both strategic and tactical (for forecasted and current conditions) information as a function of the phase of flight; 4) to increase in the update rate associated with a number of weather products used in pre-flight planning; and 5) to add on-board sensors to address in-flight icing and turbulence.

For communication systems, the technologies discussed in Chapter 6 needed to assure that communication systems are available to meet the future weather information delivery requirements are described along with the cost, performance and safety benefits to justify the investment. Not all weather information has the same level of urgency and some information is more critical than another. A risk assessment analysis should be conducted to understand the criticality of each weather service. This risk assessment should consider aviation accident historical data and human factors associated with decision making in aviation. Specific weather products need to be matched with communication systems with appropriate levels of reliability to support the criticality of the information provided to pilots. Available bandwidth for highly critical information should be preserved and dedicated to safety.

Appendices

Appendix A: Acronyms

AAC	Airline Administration Control
ACARS	Aircraft Communications Addressing and Reporting System
ADS-B	Automatic Dependent Surveillance - Broadcast
AFSS	Automated Flight Service Station
AIRMET	Airman’s Meteorological Advisory

AMPS	Advanced Mobile Phone System
AOC	Airline Operation Control
AOM	Aircraft Occupancy Model
AOPA	Aircraft Owners and Pilots Association
ARINC	ARINC Inc.
ARTCC	Air Route Traffic Control Center
ARTCC	Air Route Traffic Control Center
ASOS	Automated Surface Observation System
ATA	Air Transport Association
ATC	Air Traffic Control
ATCSCC	Air Traffic Control System Command Center
ATCT	Airport Traffic Control Tower
ATIS	Automated Terminal Information Service
ATM	Air Traffic management
ATN	Aeronautical Telecommunications Network
ATOFM	Air Traffic Operation Flow Model
AvSP	Aviation Safety Program
AWCSA	Aviation Weather Communication System Architecture
AWINRM	Aviation Weather Information and Requirement Model
AWOS	Automated Weather Observing System
AWW	Severe Weather Forecast Alerts
C&V	Ceiling and Visibility
CATS	Compliance Activity Tracking System
CDMA	Code Division multiple Access
CERAP	Center/Radar Approach Control
CONUS	Continental United States
CPC	Controller Pilot Communication

CPDLC	Controller Pilot Data Link Communication
CSIGMET	Convective Significant Meteorological Information
CSMA	Carrier Sense Multiple Access
CWA	Center Weather Advisory
CWSU	Center Weather Service Unit
D-ATIS	Digital Automated Terminal Information Service
DARS	Digital Audio Radio Service
DBS	Direct Broadcast Satellite
DSIGMET	Domestic Significant Meteorological Information
EAM	Eurocontrol Airspace Model
EEC	Eurocontrol Experimental Center
EFAS	En Route Flight Advisory Service
ETA	Estimated Time of Arrival
ETMS	Enhanced Traffic Management System
FA	Area Forecasts
FAA	Federal Aviation Administration
FCC	Federal Communication Commission
FIDS	Flight Display Information System
FIS-B	Flight Information Services - Broadcast
FSS	Flight Service Stations
FSS	Flight Service Station
GA	General Aviation
GATFM	Ground Air Traffic Flow Model
GEO	Geosynchronous Earth Orbit
GPS	Global Position System
GSM	Global System for Mobile Communications
HF	High Frequency

HFDL	High Frequency Data Link
HIWAS	Hazardous In-flight Weather Advisory Service
HIWAS	Hazardous In-Flight Weather Advisory Service
HLSWC	High Level Significant Weather Charts
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meteorology Conditions
ISIGMET	International Significant Meteorological Information
LAAS	Local Area Augmentation System
LEO	Low Earth Orbit
LLSWC	Low Level Significant Weather Charts
LLWAS	Low Level Wind Shear Alert System
LMDS	Local Multi-point Distribution System
MAOM	Modified Aircraft Occupancy Model
METAR	Aviation Routine Weather Report
MIS	Meteorological Impact Statement
MM5	Mesoscale Model
MMDS	Multi-channel, Multi-point Distribution System
MSL	Mean Sea Level
NARIM	National Airspace Resource Investment Model
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NASPAC	National Airspace System Performance Capability
NAVAID	Navigational Aid
NBTA	National Business Travel Association
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction

NESDIS	National Environmental Satellite, Data, and Information Service
NEXCOM	Next-Generation Air/Ground Communications
NEXRAD	Next Generation Weather Surveillance Radar
NEXTOR	National Center of Excellence for Aviation Operation Research
NM	Nautical Miles
NOAA	National Oceanic and Atmospheric Administration
NOC	DirectPC™ Network Operations Center
NTSB	National Transportation Safety Board
NWS	National Weather Service
OAG	Official Airline Guide
OOOI	Out/Off/On/In
PCS	Personal Communication Systems
PIREPS	Pilot Reports
RAD	Radiosonde Additional Data
RAMS	Reorganized ATC Mathematical Simulator
RAPCON	Radar Approach Control
RF	Route Forecast Winds a
RLV	Reusable Launch Vehicle
RTCA	RTCA, Incorporated
RTCC	Rotational flight
RUC-2	Rapid Update Cycle (version 2)
SAR	System Analysis Recording
SATCOM	Satellite Communication
SDAT	Sector Design Analysis Tools
SDR	Software Defined Radios
SI	Satellite Imagery
SIM	Subscriber Identification Module

SIMMOD	FAA’s current airport and airspace simulation model
SPECI	Aviation Selected Special Weather Report
SUA	Special Use Airspace
TAAM	Total Airspace & Airport Modeller
TAF	Terminal Area Forecast
TDMA	Time Division Multiple Access
TDWR	Terminal Doppler Weather Radar
TRACON	Terminal Radar Approach Control
TWB	Transcribed Weather Broadcast
TWIP	Terminal Weather Information for Pilots
UAT	Universal Access Transceiver
UHF	Ultra High Frequency
UMTS	Universal Mobile Telephone System
VFR	Visual Flight Rules
VHF	Very High Frequency
VMC	Visual Meteorology Conditions
VOR	VHF Omnidirectional Range
WA and TA	Winds and Temperatures Aloft
WFO	Weather Forecast Offices
WINCOMM	Weather Information Communication
WRF	Weather Research and Forecast
WSP	Weather Systems Processor
WW	Severe Weather Watch

Appendix B: ITHINK Source Code

Part I: Aircraft Traffic Flow

There are four traffic flow models which are for Air Carrier, Air Taxi/Commuter, General Aviation, and Military aircraft categories. They have the similar ITHINK source codes. The following is an example of source codes for Air Carrier category.

```
AC_IAA(t) = AC_IAA(t - dt) + (AC_NIALPI1 - AC_NOALIPP) * dt
INIT AC_IAA = AC_Initial_Aircraft_at_Airports

INFLOWS:
AC_NIALPI1 = AC_NIALPI
OUTFLOWS:
AC_NOALIPP = AC_IAA/TC_Inbound__Dwell_Time_Idle_2
AC_NIAA(t) = AC_NIAA(t - dt) + (AC_NIALCA1 - AC_NIALAL) * dt
INIT AC_NIAA = 6

INFLOWS:
AC_NIALCA1 = AC_NIALCA
OUTFLOWS:
AC_NIALAL = AC_NIAA/AC_Inbound__Dwell_Time_Approach
AC_NIAC(t) = AC_NIAC(t - dt) + (AC_NIAEC - AC_NIALCA) * dt
INIT AC_NIAC = 12

INFLOWS:
AC_NIAEC = AC_IADF*AC_Time_Scale_Factor*AC_SATS_Scaling_Factor
OUTFLOWS:
AC_NIALCA = AC_NIAC/AC_Inbound__Dwell_Time_Cruise
AC_NIAL(t) = AC_NIAL(t - dt) + (AC_NIALAL1 - AC_NIALLTIP) * dt
INIT AC_NIAL = 3

INFLOWS:
AC_NIALAL1 = AC_NIALAL
OUTFLOWS:
AC_NIALLTIP = AC_NIAL/AC_Inbound__Dwell_Time_Landing
AC_NIAP(t) = AC_NIAP(t - dt) + (AC_NIALTIPP1 - AC_NIALPI) * dt
INIT AC_NIAP = 3

INFLOWS:
AC_NIALTIPP1 = AC_NIALTIPP
OUTFLOWS:
AC_NIALPI = AC_NIAP/AC_Inbound__Dwell_Time_Post
AC_NIATIP(t) = AC_NIATIP(t - dt) + (AC_NIALLTIP1 - AC_NIALTIPP) * dt
```

```
INIT AC_NIATIP = 3

INFLOWS:
AC_NIALLTIP1 = AC_NIALLTIP
OUTFLOWS:
AC_NIALTIPP = AC_NIATIP/AC_Inbound_Dwell_Time_Taxi_In_and_Parking
AC_NOAC(t) = AC_NOAC(t - dt) + (AC_NOALICC1 - AC_NOALCO) * dt
INIT AC_NOAC = 3

INFLOWS:
AC_NOALICC1 = AC_NOALICC
OUTFLOWS:
AC_NOALCO = AC_NOAC/AC_Outbound__Dwell_Time_center
AC_NOAD(t) = AC_NOAD(t - dt) + (AC_NOALTOTOD1 - AC_NOALDICS) * dt
INIT AC_NOAD = 2

INFLOWS:
AC_NOALTOTOD1 = AC_NOALTOTOD
OUTFLOWS:
AC_NOALDICS = AC_NOAD/AC_Outbound__Dwell_Time_Departure
AC_NOAIC(t) = AC_NOAIC(t - dt) + (AC_NOALICSIC1 - AC_NOALICC) * dt
INIT AC_NOAIC = 3

INFLOWS:
AC_NOALICSIC1 = AC_NOALICSIC
OUTFLOWS:
AC_NOALICC = AC_NOAIC/AC_Outbound_Dwell_Time_Initial_Cruise
AC_NOAICS(t) = AC_NOAICS(t - dt) + (AC_NOALDICS1 - AC_NOALICSIC) * dt
INIT AC_NOAICS = 2

INFLOWS:
AC_NOALDICS1 = AC_NOALDICS
OUTFLOWS:
AC_NOALICSIC = AC_NOAICS/AC_Outbound_Dwell_Time_Initial_Climb_Segment
AC_NOAP(t) = AC_NOAP(t - dt) + (AC_NOALPPP1 - AC_NOALPTOTO) * dt
INIT AC_NOAP = 3

INFLOWS:
AC_NOALPPP1 = AC_NOALPPP
OUTFLOWS:
AC_NOALPTOTO = AC_NOAP/AC_Outbound__Dwell_Time_Preflight
AC_NOAPP(t) = AC_NOAPP(t - dt) + (AC_NOALIPP1 - AC_NOALPPP) * dt
INIT AC_NOAPP = 6

INFLOWS:
AC_NOALIPP1 = AC_NOALIPP
```

OUTFLOWS:

AC_NOALPPP = AC_NOAPP/AC_Outbound_Dwell_Time_Preflight_Planning

*AC_NOATOTO(t) = AC_NOATOTO(t - dt) + (AC_NOALPTOTO1 - AC_NOALTOTOD) * dt*

INIT AC_NOATOTO = 2

INFLOWS:

AC_NOALPTOTO1 = AC_NOALPTOTO

OUTFLOWS:

AC_NOALTOTOD = AC_NOATOTO/AC_Outbound_Dwell_Time_Taxi_Out_and_Take_Off

*AC_TACA(t) = AC_TACA(t - dt) + (AC_NTAECA - AC_NTALCA) * dt*

INIT AC_TACA = 30

INFLOWS:

*AC_NTAECA = AC_Scaling_Factor_for_Enroute_Flights*AC_NIAEC*AC_SATS_Scaling_Factor*

OUTFLOWS:

AC_NTALCA = AC_TACA/AC_MADTTA

AC_Aircraft_at_Airport = AC_Aircraft_in_Preflight_Planning+AC_Aircraft_in_Taxi_In_and_Parking+AC_Aircraft_in_Taxi_Out_and_Take_Off+AC_Aircraft__in_Post+AC_Aircraft__in_Preflight

AC_Aircraft_in_Approach_Operation = AC_NIAA

AC_Aircraft_in_Outbound_Criuse = AC_NOAC

AC_Aircraft_in_Preflight_Planning = AC_NOAPP

AC_Aircraft_in_Taxi_In_and_Parking = AC_NIATIP

AC_Aircraft_in_Taxi_Out_and_Take_Off = AC_NOATOTO

AC_Aircraft_in_Terminal = AC_Aircraft_in_Approach_Operation+AC_Aircraft_in__Initial_Climb_Segment+AC_Aircraft__in_Departure+AC_Aircraft__in_Initial_Cruise+AC_Aircraft__in_Landing_Operation

AC_Aircraft_in__Initial_Climb_Segment = AC_NOAICS

AC_Aircraft__in_Airspace = AC_NIAC+AC_TACA+AC_NOAC

AC_Aircraft__in_Departure = AC_NOAD

AC_Aircraft__in_Idle = AC_IAA

AC_Aircraft__in_Inbound_Cruise = AC_NIAC

AC_Aircraft__in_Initial_Cruise = AC_NOAIC

AC_Aircraft__in_Landing_Operation = AC_NIAL

AC_Aircraft__in_Post = AC_NIAP

AC_Aircraft__in_Preflight = AC_NOAP

AC_Aircraft__in_Transient = AC_TACA

AC_Inbound_Dwell_Time_Taxi_In_and_Parking = NORMAL(AC_MIADTTIP,5)

AC_Inbound__Dwell_Time_Approach = NORMAL(AC_MIADTA,5)

AC_Inbound__Dwell_Time_Cruise = NORMAL(AC_MIADTC,10)

AC_Inbound__Dwell_Time_Landing = NORMAL(AC_MIADTL,2)

AC_Inbound__Dwell_Time_Post = NORMAL(AC_MIADTP,10)

AC_Initial_Aircraft_at_Airports = 537

AC_MADTTA = 40

AC_MIADTA = 20

AC_MIADTC = 45

AC_MIADTL = 5

AC_MIADTP = 30

AC_MIADTTIP = 10

AC_MOADTC = 45

AC_MOADTD = 5

AC_MOADTIC = 10

AC_MOADTICS = 15

AC_MOADTP = 10

AC_MOADTPP = 30

AC_MOADTTOTO = 10

AC_Outbound_Dwell_Time_Initial_Climb_Segment = NORMAL(AC_MOADTICS,5)

AC_Outbound_Dwell_Time_Initial_Cruise = NORMAL(AC_MOADTIC,5)

AC_Outbound_Dwell_Time_Preflight_Planning = NORMAL(AC_MOADTPP,10)

AC_Outbound_Dwell_Time_Taxi_Out_and_Take_Off = NORMAL(AC_MOADTTOTO,5)

AC_Outbound__Dwell_Time_center = NORMAL(AC_MOADTC,10)

AC_Outbound__Dwell_Time_Departure = NORMAL(AC_MOADTD,2)

AC_Outbound__Dwell_Time_Preflight = NORMAL(AC_MOADTP,5)

AC_SATS_Scaling_Factor = if AC_SATS_Switch = 1 then

1.60

else

1.0

AC_SATS_Switch = 1

AC_Scaling_Factor_for_Enroute_Flights = 1.9

AC_Year_of_Analysis = 2020

AC_IADF = GRAPH(time)

(0.00, 0.2), (60.0, 0.7), (120, 1.00), (180, 1.50), (240, 2.40), (300, 3.50), (360, 5.15), (420, 6.00), (480, 5.45), (540, 4.85), (600, 4.25), (660, 3.80), (720, 3.85), (780, 3.65), (840, 3.75), (900, 4.30), (960, 5.50), (1020, 5.95), (1080, 5.40), (1140, 3.70), (1200, 3.20), (1260, 2.80), (1320, 3.20), (1380, 2.70), (1440, 1.20)

AC_Inbound__Dwell_Time_Idle = GRAPH(TIME)

(0.00, 300), (60.0, 260), (120, 227), (180, 207), (240, 182), (300, 155), (360, 122), (420, 105), (480, 75.0), (540, 57.0), (600, 51.0), (660, 42.0), (720, 40.5), (780, 42.0), (840, 43.5), (900, 48.0), (960, 57.0), (1020, 78.0), (1080, 225), (1140, 284), (1200, 300), (1260, 300), (1320, 300), (1380, 300), (1440, 300)

AC_Time_Scale_Factor = GRAPH(AC_Year_of_Analysis)

(1999, 0.46), (2001, 0.51), (2004, 0.582), (2006, 0.648), (2008, 0.708), (2011, 0.774), (2013, 0.851), (2016, 0.923), (2018, 0.96), (2020, 1.00), (2023, 1.06), (2025, 1.09)

Dwell_Time_at_Airport = GRAPH(time)

(0.00, 300), (60.0, 300), (120, 300), (180, 250), (240, 250), (300, 250), (360, 250), (420, 120), (480, 120), (540, 120), (600, 75.0), (660, 60.0), (720, 60.0), (780, 60.0), (840, 60.0), (900, 69.0), (960, 90.0), (1020, 111), (1080, 146), (1140, 200), (1200, 243), (1260, 285), (1320, 700), (1380, 700), (1440, 1000)

TC_Inbound__Dwell_Time_Idle_2 = GRAPH(TIME)

(0.00, 300), (60.0, 251), (120, 240), (180, 221), (240, 173), (300, 156), (360, 120), (420, 105), (480, 90.0), (540, 72.0), (600, 42.0), (660, 33.0), (720, 28.5), (780, 27.0), (840, 31.5), (900, 34.5), (960, 45.0), (1020, 61.5), (1080, 96.0), (1140, 143), (1200, 224), (1260, 237), (1320, 480), (1380, 560), (1440, 600)

Part II: Tactical Weather Information Requirement

There are nine tactical weather products in AWINRM model. Each product is modeled by four aircraft category - Air carrier, Air taxi/Commuter, General Aviation, and Military seperately. They have the similar source codes. The following source codes are an example of a tactical weather product - METAR/SPECI for Air carrier aircraft.

METAR/SPECI for Air Carrier

```
AC_Aircraft_in_Approach_Operation = AC_NIAA
AC_Aircraft_in_Outbound_Criuse = AC_NOAC
AC_Aircraft_in_Preflight_Planning = AC_NOAPP
AC_Aircraft_in_Taxi_In_and_Parking = AC_NIATIP
AC_Aircraft_in_Taxi_Out_and_Take_Off = AC_NOATOTO
AC_Aircraft_in__Initial_Climb_Segment = AC_NOAICS
AC_Aircraft__in_Departure = AC_NOAD
AC_Aircraft__in_Inbound_Cruise = AC_NIAC
AC_Aircraft__in_Initial_Cruise = AC_NOAIC
AC_Aircraft__in_Landing_Operation = AC_NIAL
AC_Aircraft__in_Post = AC_NIAP
AC_Aircraft__in_Preflight = AC_NOAP
AC_Aircraft__in_Transient = AC_TACA
AC_Inbound_Dwell_Time_at_I_to_II = AC_Inbound__Dwell_Time_Approach+AC_Inbound__Dwell_Time_Cruise
AC_Inbound_Dwell_Time_at_I_to_III = AC_Inbound_Dwell_Time_at_I_to_II+AC_Inbound__Dwell_Time_Landing
AC_Inbound_Dwell_Time_at_I_to_IV = AC_Inbound_Dwell_Time_at_I_to_III+AC_Inbound_Dwell_Time_Taxi_In_and_Parking
AC_Inbound_Dwell_Time_at_I_to_V = AC_Inbound_Dwell_Time_at_I_to_IV+AC_Inbound__Dwell_Time_Post
AC_Inbound_Dwell_Time_Taxi_In_and_Parking = NORMAL(AC_MIADTTIP,5)
AC_Inbound__Dwell_Time_Approach = NORMAL(AC_MIADTA,5)
AC_Inbound__Dwell_Time_Cruise = NORMAL(AC_MIADTC,10)
AC_Inbound__Dwell_Time_Landing = NORMAL(AC_MIADTL,2)
AC_Inbound__Dwell_Time_Post = NORMAL(AC_MIADTP,10)
AC_MADTTA = 40
AC_METAR_Sampling_Times_at_Approach = IF((INT(AC_Inbound_Dwell_Time_at_I_to_II/METAR_SPECI_Sampling_Rate)-
AC_METAR_Sampling_Times_at_Inbound_Cruise)>=1 or METAR_Time_Factor=1) THEN (1) ELSE (0)
AC_METAR_Sampling_Times_at_Departure = IF((INT(AC_Outbound_Dwell_Time_at_I_to_IV/METAR_SPECI_Sampling_Rate)-
AC_METAR_Sanpling_Times_at_I_to_III+1)>=1 or METAR_Time_Factor=1)THEN(1)ELSE(0)
AC_METAR_Sampling_Times_at_Inbound_Cruise = IF((INT(AC_Inbound__Dwell_Time_Cruise/METAR_SPECI_Sampling_Rate))>=1 or
METAR_Time_Factor=1) THEN (1) ELSE (0)
AC_METAR_Sampling_Times_at_Inbound_I_to_II = AC_METAR_Sampling_Times_at_Approach+AC_METAR_Sampling_Times_at_Inbound_Cruise
AC_METAR_Sampling_Times_at_Inbound_I_to_III = AC_METAR_Sampling_Times_at_Inbound_I_to_II+AC_METAR_Sampling_Times_at_Landing
AC_METAR_Sampling_Times_at_Inbound_I_to_IV=
AC_METAR_Sampling_Times_at_Inbound_I_to_III+AC_METAR_Sampling_Times_at_Taxi_In_and_Parking
AC_METAR_Sampling_Times_at_Initial_Climb_Segment = IF((INT(AC_Outbound_Dwell__Time_at_I_to_V/METAR_SPECI_Sampling_Rate)-
```

AC_METAR_Sampling_Times_at_I_to_IV+1)>=1 or METAR_Time_Factor=1) THEN (1) ELSE (0)

AC_METAR_Sampling_Times_at_Initia_Cruise = IF((INT(AC_Outbound_Dwell_Time_at_I_to_VI/METAR_SPECI_Sampling_Rate)-AC_METAR_Sampling_Times_at_I_to_V+1)>=1 or METAR_Time_Factor=1) THEN (1) ELSE (0)

AC_METAR_Sampling_Times_at_I_to_II = AC_METAR_Sampling_Times_at_Preflight+AC_METAR_Sampling_Times_at_Preflight_Planning

AC_METAR_Sampling_Times_at_I_to_IV = AC_METAR_Sampling_Times_at_Departure+AC_METAR_Sanpling_Times_at_I_to_III

AC_METAR_Sampling_Times_at_I_to_V = AC_METAR_Sampling_Times_at_Initial_Climb_Segment+AC_METAR_Sampling_Times_at_I_to_IV

AC_METAR_Sampling_Times_at_I_to_VI = AC_METAR_Sampling_Times_at_Initia_Cruise+AC_METAR_Sampling_Times_at_I_to_V

AC_METAR_Sampling_Times_at_Landing = IF((INT(AC_Inbound_Dwell_Time_at_I_to_III/METAR_SPECI_Sampling_Rate)-AC_METAR_Sampling_Times_at_Inbound_I_to_II)>=1 or METAR_Time_Factor=1) THEN (1) ELSE (0)

AC_METAR_Sampling_Times_at_Outbound_Cruise = IF((INT(AC_Outbound_Dwell_Time_at_I_to_VII/METAR_SPECI_Sampling_Rate)-AC_METAR_Sampling_Times_at_I_to_VI+1)>=1 or METAR_Time_Factor=1) THEN (1) ELSE (0)

AC_METAR_Sampling_Times_at_Post = IF((INT(AC_Inbound_Dwell_Time_at_I_to_V/METAR_SPECI_Sampling_Rate)-AC_METAR_Sampling_Times_at_Inbound_I_to_IV)>=1 or METAR_Time_Factor=1) THEN (1) ELSE (0)

AC_METAR_Sampling_Times_at_Preflight = IF((INT(AC_Outbound_Dwell_Time_at_I_to_II/METAR_SPECI_Sampling_Rate)-AC_METAR_Sampling_Times_at_Preflight_Planning+1)>=1 or METAR_Time_Factor=1) THEN (1) ELSE (0)

AC_METAR_Sampling_Times_at_Preflight_Planning = IF((INT(AC_Outbound_Dwell_Time_Preflight_Planning/ METAR_SPECI_Sampling_Rate)+1)>=1 or METAR_Time_Factor=1) THEN(0) ELSE(0)

AC_METAR_Sampling_Times_at_Taxi_In_and_Parking = IF((INT(AC_Inbound_Dwell_Time_at_I_to_IV/METAR_SPECI_Sampling_Rate)-AC_METAR_Sampling_Times_at_Inbound_I_to_III)>=1 or METAR_Time_Factor=1) THEN (1) ELSE (0)

AC_METAR_Sampling_Times_at_Taxi_Out_and_Take_Off = IF((INT(AC_Outbound_Dwell_Time_at_I_to_III/METAR_SPECI_Sampling_Rate)-AC_METAR_Sampling_Times_at_I_to_II+1)>=1 or METAR_Time_Factor=1) THEN (1) ELSE (0)

AC_METAR_Sampling_Times_at_Transient = IF((INT(AC_MADTTA/METAR_SPECI_Sampling_Rate))>=1 or METAR_Time_Factor=1) THEN (1) ELSE (0)

AC_METAR_Sanpling_Times_at_I_to_III = AC_METAR_Sampling_Times_at_I_to_II+AC_METAR_Sampling_Times_at_Taxi_Out_and_Take_Off

AC_METAR_SPECI_Size_at_Approach= AC_Aircraft_in_Approach_Operation*(AC_METAR_Sampling_Times_at_Approach+SPECI_Rate)*Number_of_METAR_at_AC_Approach*Update_Unit__MEATR_SPECI_Size

AC_METAR_SPECI_Size_at_Cruise= AC_METAR_SPECI_Size_at_Inbound_Cruise+AC_METAR_SPECI_Size_at_Outbound_Cruise+AC_METAR_SPECI_Size_at_Transient

AC_METAR_SPECI_Size_at_Departure= AC_Aircraft__in_Departure*(AC_METAR_Sampling_Times_at_Departure+SPECI_Rate)*Number_of_METAR_at_AC_Departuer*Update_Unit__MEATR_SPECI_Size

AC_METAR_SPECI_Size_at_Inbound_Cruise= AC_Aircraft__in_Inbound_Cruise*(AC_METAR_Sampling_Times_at_Inbound_Cruise+SPECI_Rate)*Number_of_METAR_at_AC_Inbound_Cruise*Update_Unit__MEATR_SPECI_Size

AC_METAR_SPECI_Size_at_Landing= AC_Aircraft__in_Landing_Operation*(AC_METAR_Sampling_Times_at_Landing+SPECI_Rate)*Number_of_METAR_at_AC_Landing*Update_Unit__MEATR_SPECI_Size

AC_METAR_SPECI_Size_at_Outbound_Cruise= AC_Aircraft_in_Outbound_Criuse*(AC_METAR_Sampling_Times_at_Outbound_Cruise+SPECI_Rate)*Number_of_METAR_at_AC_Outbound_Cruise*Update_Unit__MEATR_SPECI_Size

AC_METAR_SPECI_Size_at_Post= AC_Aircraft__in_Post*(AC_METAR_Sampling_Times_at_Post+SPECI_Rate)*Number_of_METAR_at_AC_Post*Update_Unit__MEATR_SPECI_Size

AC_METAR_SPECI_Size_at_Preflight= AC_Aircraft__in_Preflight*(AC_METAR_Sampling_Times_at_Preflight+SPECI_Rate)*Update_Unit__MEATR_SPECI_Size*Number_of_META_at_AC_Preflight_Planning*AC_Past_METAR_Fator

AC_METAR_SPECI_Size_at_Taxi_In_and_Parking= AC_Aircraft_in_Taxi_In_and_Parking*(AC_METAR_Sampling_Times_at_Taxi_In_and_Parking+SPECI_Rate)*Number_of_METAR_at_AC_Taxi_In_and_Parking*Update_Unit__MEATR_SPECI_Size

AC_METAR_SPECI_Size_at_Taxi_Out_and_Take_Off=

AC_Aircraft_in_Taxi_Out_and_Take_Off*(AC_METAR_Sampling_Times_at_Taxi_Out_and_Take_Off+SPECI_Rate)*Update_Unit__MEATR_SPECI_Size

AC_METAR_SPECI_Size_at_Transient= AC_Aircraft__in_Transient*(AC_METAR_Sampling_Times_at_Transient+SPECI_Rate)*Number_of_METAR_at_AC_Transient*Update_Unit__MEATR_SPECI_Size

AC_METAR_SPECI_Size__at_Initial_Climb_Segment= AC_Aircraft_in__Initial_Climb_Segment*(AC_METAR_Sampling_Times_at_Initial_Climb_Segment+SPECI_Rate)*Number_of_METAR_at_AC_Initia_Climb_Segment*Update_Unit__MEATR_SPECI_Size

AC_METAR_SPECI_Size__at_Initial_Cruise= AC_Aircraft__in_Initial_Cruise*(AC_METAR_Sampling_Times_at_Initia_Cruise+SPECI_Rate)*Number_of_METAR_at_AC_Initia_Cruise*Update_Unit__MEATR_SPECI_Size

AC_METAR_SPECI_Size__at_Preflight_Planning= AC_Aircraft_in_Preflight_Planning*Number_of_META_at_AC_Preflight_Planning*Update_Unit__MEATR_SPECI_Size*AC_Past_METAR_Fator*(AC_METAR_Sampling_Times_at_Preflight_Planning+SPECI_Rate)

AC_Outbound_Dwell_Time_at_I_to_II = AC_Outbound_Dwell_Time_Preflight_Planning+AC_Outbound__Dwell_Time_Preflight

AC_Outbound_Dwell_Time_at_I_to_III = AC_Outbound_Dwell_Time_at_I_to_II+AC_Outbound_Dwell_Time_Taxi_Out_and_Take_Off

AC_Outbound_Dwell_Time_at_I_to_IV = AC_Outbound_Dwell_Time_at_I_to_III+AC_Outbound__Dwell_Time_Departure

AC_Outbound_Dwell_Time_at_I_to_VI = AC_Outbound_Dwell_Time_Initial_Cruise+AC_Outbound_Dwell__Time_at_I_to_V

AC_Outbound_Dwell_Time_at_I_to_VII = AC_Outbound_Dwell_Time_at_I_to_VI+AC_Outbound__Dwell_Time_center

AC_Outbound_Dwell_Time_Initial_Climb_Segment = NORMAL(AC_MOADTICS,5)

AC_Outbound_Dwell_Time_Initial_Cruise = NORMAL(AC_MOADTIC,5)

AC_Outbound_Dwell_Time_Preflight_Planning = NORMAL(AC_MOADTPP,10)

AC_Outbound_Dwell_Time_Taxi_Out_and_Take_Off = NORMAL(AC_MOADTTOTO,5)

AC_Outbound_Dwell__Time_at_I_to_V = AC_Outbound_Dwell_Time_at_I_to_IV+AC_Outbound_Dwell_Time_Initial_Climb_Segment

AC_Outbound__Dwell_Time_center = NORMAL(AC_MOADTC,10)

AC_Outbound__Dwell_Time_Departure = NORMAL(AC_MOADTD,2)

AC_Outbound__Dwell_Time_Preflight = NORMAL(AC_MOADTP,5)

AC_Past_METAR_Fator = 3*METAR_Sampling_Rate_Factor

Mean_unit_METAR_Size = 800

METAR_Graphical_Factor = 1

METAR_Sampling_Rate_Factor = Original_METAR_Sampling_Rate/METAR_Update_Sampling_Rate

METAR_SPECI_Sampling_Rate = Original_METAR_Sampling_Rate/METAR_Sampling_Rate_Factor

METAR_Uncode_Factor = 2

METAR_Update_Sampling_Rate = 60

Number_of_METAR_at_AC_Approach = 6

Number_of_METAR_at_AC_Departuer = 5

Number_of_METAR_at_AC_Inbound_Cruise = 6

Number_of_METAR_at_AC_Initia_Climb_Segment = 5

Number_of_METAR_at_AC_Initia_Cruise = 6

Number_of_METAR_at_AC_Landing = 6

Number_of_METAR_at_AC_Outbound_Cruise = 6

Number_of_METAR_at_AC_Post = 6

Number_of_METAR_at_AC_Taxi_In_and_Parking = 6

Number_of_METAR_at_AC_Transient = 10

Number_of_META_at_AC_Preflight_Planning = 20

Original_METAR_Sampling_Rate = 60

SPECI_Rate = MONTECARLO(5,999)

Unit_METAR_Size = NORMAL(Mean_unit_METAR_Size, 200)

Update_Unit__MEATR_SPECI_Size = Unit_METAR_Size*METAR_Uncode_Factor*METAR_Graphical_Factor

METAR_Time_Factor = GRAPH(TIME)

(0.00, 1.00),(1.00, 0.00),(2.00, 0.00), (3.00, 0.00), (4.00, 0.00), (5.00, 0.00), (6.00, 0.00), (7.00, 0.00), (8.00, 0.00), (9.00, 0.00), (10.0, 0.00), (11.0, 0.00), (12.0, 0.00), (13.0, 0.00), (14.0, 0.00), (15.0, 0.00), (16.0, 0.00), (17.0, 0.00), (18.0, 0.00), (19.0, 0.00), (20.0, 0.00), (21.0, 0.00), (22.0, 0.00), (23.0, 0.00), (24.0, 0.00), (25.0, 0.00), (26.0, 0.00), (27.0, 0.00), (28.0, 0.00), (29.0, 0.00), (30.0, 0.00), (31.0, 0.00), (32.0, 0.00), (33.0, 0.00), (34.0, 0.00), (35.0, 0.00), (36.0, 0.00), (37.0, 0.00), (38.0, 0.00), (39.0, 0.00), (40.0, 0.00), (41.0, 0.00), (42.0, 0.00), (43.0, 0.00), (44.0, 0.00), (45.0, 0.00), (46.0, 0.00), (47.0, 0.00), (48.0, 0.00), (49.0, 0.00), (50.0, 0.00), (51.0, 0.00), (52.0, 0.00), (53.0, 0.00), (54.0, 0.00), (55.0, 0.00), (56.0, 0.00), (57.0, 0.00), (58.0, 0.00), (59.0, 0.00), (60.0, 1.00), (61.0, 0.00), (62.0, 0.00), (63.0, 0.00), (64.0, 0.00), (65.0, 0.00), (66.0, 0.00), (67.0, 0.00), (68.0, 0.00), (69.0, 0.00), (70.0, 0.00), (71.0, 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(1367, 0.00), (1368, 0.00), (1369, 0.00), (1370, 0.00), (1371, 0.00), (1372, 0.00), (1373, 0.00), (1374, 0.00), (1375, 0.00), (1376, 0.00), (1377, 0.00), (1378, 0.00), (1379, 0.00), (1380, 1.00), (1381, 0.00), (1382, 0.00), (1383, 0.00), (1384, 0.00), (1385, 0.00), (1386, 0.00), (1387, 0.00), (1388, 0.00), (1389, 0.00), (1390, 0.00), (1391, 0.00), (1392, 0.00), (1393, 0.00), (1394, 0.00), (1395, 0.00), (1396, 0.00), (1397, 0.00), (1398, 0.00), (1399, 0.00), (1400, 0.00), (1401, 0.00), (1402, 0.00), (1403, 0.00), (1404, 0.00), (1405, 0.00), (1406, 0.00), (1407, 0.00), (1408, 0.00), (1409, 0.00), (1410, 0.00), (1411, 0.00), (1412, 0.00), (1413, 0.00), (1414, 0.00), (1415, 0.00), (1416, 0.00), (1417, 0.00), (1418, 0.00), (1419, 0.00), (1420, 0.00), (1421, 0.00), (1422, 0.00), (1423, 0.00), (1424, 0.00), (1425, 0.00), (1426, 0.00), (1427, 0.00), (1428, 0.00), (1429, 0.00), (1430, 0.00), (1431, 0.00), (1432, 0.00), (1433, 0.00), (1434, 0.00), (1435, 0.00), (1436, 0.00), (1437, 0.00), (1438, 0.00), (1439, 0.00), (1440, 1.00)

Part III: Strategic Weather Information Requirement

There are fourteen strategic weather products in AWINRM model. Each product is modeled by four aircraft category - Air carrier, Air taxi/Commuter, General Aviation, and Military seperately. They have the similar source codes. The following source codes are an example of a strategic weather product - Radiosonde Additional Data (RA) for Air carrier aircraft.

Radiosonde Additional Data (RA) for Air Carrier

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AC_Aircraft_in_Approach_Operation = AC_NIAA
AC_Aircraft_in_Outbound_Criuse = AC_NOAC
AC_Aircraft_in_Preflight_Planning = AC_NOAPP
AC_Aircraft_in_Taxi_In_and_Parking = AC_NIATIP
AC_Aircraft_in_Taxi_Out_and_Take_Off = AC_NOATOTO
AC_Aircraft_in__Initial_Climb_Segment = AC_NOAICS
AC_Aircraft__in_Departure = AC_NOAD
AC_Aircraft__in_Inbound_Cruise = AC_NIAC
AC_Aircraft__in_Initial_Cruise = AC_NOAIC
AC_Aircraft__in_Landing_Operation = AC_NIAL
AC_Aircraft__in_Post = AC_NIAP
AC_Aircraft__in_Preflight = AC_NOAP
AC_Aircraft__in_Transient = AC_TACA
AC_Inbound_Dwell_Time_at_I_to_II = AC_Inbound__Dwell_Time_Approach+AC_Inbound__Dwell_Time_Cruise
AC_Inbound_Dwell_Time_at_I_to_III = AC_Inbound_Dwell_Time_at_I_to_II+AC_Inbound__Dwell_Time_Landing
AC_Inbound_Dwell_Time_at_I_to_IV = AC_Inbound_Dwell_Time_at_I_to_III+AC_Inbound_Dwell_Time_Taxi_In_and_Parking
AC_Inbound_Dwell_Time_at_I_to_V = AC_Inbound_Dwell_Time_at_I_to_IV+AC_Inbound__Dwell_Time_Post
AC_Inbound__Dwell_Time_Cruise = NORMAL(AC_MIADTC,10)
AC_MADTTA = 40
AC_Outbound_Dwell_Time_at_I_to_II = AC_Outbound_Dwell_Time_Preflight_Planning+AC_Outbound__Dwell_Time_Preflight
AC_Outbound_Dwell_Time_at_I_to_III = AC_Outbound_Dwell_Time_at_I_to_II+AC_Outbound_Dwell_Time_Taxi_Out_and_Take_Off
AC_Outbound_Dwell_Time_at_I_to_IV = AC_Outbound_Dwell_Time_at_I_to_III+AC_Outbound__Dwell_Time_Departure
AC_Outbound_Dwell_Time_at_I_to_VI = AC_Outbound_Dwell_Time_Initial_Cruise+AC_Outbound_Dwell__Time_at_I_to_V
AC_Outbound_Dwell_Time_at_I_to_VII = AC_Outbound_Dwell_Time_at_I_to_VI+AC_Outbound__Dwell_Time_center
AC_Outbound_Dwell_Time_Preflight_Planning = NORMAL(AC_MOADTPP,10)
AC_Outbound_Dwell__Time_at_I_to_V = AC_Outbound_Dwell_Time_at_I_to_IV+AC_Outbound_Dwell_Time_Initial_Climb_Segment
AC_Past_RA_Fator = 3*RA_Sampling_Rate_Factor
AC_RA_Sampling_Times_at_Approach = IF((INT(AC_Inbound_Dwell_Time_at_I_to_II/RA_Sampling_Rate)-
AC_RA_Sampling_Times_at_Inbound_Cruise+1)>=1 or RA_Time_Factor=1) THEN (1) ELSE (0)
AC_RA_Sampling_Times_at_Departure = IF((INT(AC_Outbound_Dwell_Time_at_I_to_IV/RA_Sampling_Rate)-
AC_RA_Sanpling_Times_at_I_to_III+1)>=1 or RA_Time_Factor=1) THEN (1) ELSE (0)
AC_RA_Sampling_Times_at_Inbound_Cruise = IF((INT(AC_Inbound__Dwell_Time_Cruise/RA_Sampling_Rate)+1)>=1 or RA_Time_Factor=1)
THEN (1) ELSE (0)
AC_RA_Sampling_Times_at_Inbound_I_to_II = AC_RA_Sampling_Times_at_Approach+AC_RA_Sampling_Times_at_Inbound_Cruise
AC_RA_Sampling_Times_at_Inbound_I_to_III = AC_RA_Sampling_Times_at_Inbound_I_to_II+AC_RA_Sampling_Times_at_Landing
AC_RA_Sampling_Times_at_Inbound_I_to_IV = AC_RA_Sampling_Times_at_Inbound_I_to_III+AC_RA_Sampling_Times_at_Taxi_In_and_Parking
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AC_RA_Sampling_Times_at_Initial_Climb_Segment = IF((INT(AC_Outbound_Dwell__Time_at_I_to_V/RA_Sampling_Rate)-AC_RA_Sampling_Times_at_I_to_IV+1)>=1 or RA_Time_Factor=1) THEN (1) ELSE (0)

AC_RA_Sampling_Times_at_Initia_Cruise = IF((INT(AC_Outbound_Dwell_Time_at_I_to_VI/RA_Sampling_Rate)-AC_RA_Sampling_Times_at_I_to_V+1)>=1 or RA_Time_Factor=1) THEN (1) ELSE (0)

AC_RA_Sampling_Times_at_I_to_II = AC_RA_Sampling_Times_at_Preflight+AC_RA_Sampling_Times_at_Preflight_Planning

AC_RA_Sampling_Times_at_I_to_IV = AC_RA_Sampling_Times_at_Departure+AC_RA_Sanpling_Times_at_I_to_III

AC_RA_Sampling_Times_at_I_to_V = AC_RA_Sampling_Times_at_Initial_Climb_Segment+AC_RA_Sampling_Times_at_I_to_IV

AC_RA_Sampling_Times_at_I_to_VI = AC_RA_Sampling_Times_at_Initia_Cruise+AC_RA_Sampling_Times_at_I_to_V

AC_RA_Sampling_Times_at_Landing = IF((INT(AC_Inbound_Dwell_Time_at_I_to_III/RA_Sampling_Rate)-AC_RA_Sampling_Times_at_Inbound_I_to_II+1)>=1 or RA_Time_Factor=1) THEN (1) ELSE (0)

AC_RA_Sampling_Times_at_Outbound_Cruise = IF((INT(AC_Outbound_Dwell_Time_at_I_to_VII/RA_Sampling_Rate)-AC_RA_Sampling_Times_at_I_to_VI+1)>=1 or RA_Time_Factor=1) THEN (1) ELSE (0)

AC_RA_Sampling_Times_at_Post = IF((INT(AC_Inbound_Dwell_Time_at_I_to_V/RA_Sampling_Rate)-AC_RA_Sampling_Times_at_Inbound_I_to_IV+1)>=1 or RA_Time_Factor=1) THEN (1) ELSE (0)

AC_RA_Sampling_Times_at_Preflight = IF((INT(AC_Outbound_Dwell_Time_at_I_to_II/RA_Sampling_Rate)-AC_RA_Sampling_Times_at_Preflight_Planning+1)>=1 or RA_Time_Factor=1) THEN (1) ELSE (0)

AC_RA_Sampling_Times_at_Preflight_Planning = IF((INT(AC_Outbound_Dwell_Time_Preflight_Planning/RA_Sampling_Rate)+1)>=1 or RA_Time_Factor=1) THEN (1) ELSE (0)

AC_RA_Sampling_Times_at_Taxi_In_and_Parking = IF((INT(AC_Inbound_Dwell_Time_at_I_to_IV/RA_Sampling_Rate)-AC_RA_Sampling_Times_at_Inbound_I_to_III+1)>=1 or RA_Time_Factor=1) THEN (1) ELSE (0)

AC_RA_Sampling_Times_at_Taxi_Out_and_Take_Off = IF((INT(AC_Outbound_Dwell_Time_at_I_to_III/RA_Sampling_Rate)-AC_RA_Sampling_Times_at_I_to_II+1)>=1 or RA_Time_Factor=1) THEN (1) ELSE (0)

AC_RA_Sampling_Times_at_Transient = IF((INT(AC_MADTTA/RA_Sampling_Rate))>=1 or RA_Time_Factor=1) THEN (1) ELSE (0)

AC_RA_Sanpling_Times_at_I_to_III = AC_RA_Sampling_Times_at_I_to_II+AC_RA_Sampling_Times_at_Taxi_Out_and_Take_Off

AC_RA_Size_at_Approach= AC_Aircraft_in_Approach_Operation*AC_RA_Sampling_Times_at_Approach*Number_of_RA_at_AC_Approach*Update_Unit_RA_Size

AC_RA_Size_at_Cruise = AC_RA_Size_at_Inbound_Cruise+AC_RA_Size_at_Outbound_Cruise+AC_RA_Size_at_Transient

AC_RA_Size_at_Departure= AC_Aircraft__in_Departure*AC_RA_Sampling_Times_at_Departure*Number_of_RA_at_AC_Departuer*Update_Unit_RA_Size

AC_RA_Size_at_Inbound_Cruise= AC_Aircraft__in_Inbound_Cruise*AC_RA_Sampling_Times_at_Inbound_Cruise*Number_of_RA_at_AC_Inbound_Cruise_*Update_Unit_RA_Size

AC_RA_Size_at_Landing= AC_Aircraft__in_Landing_Operation*AC_RA_Sampling_Times_at_Landing*Number_of_RA_at_AC_Landing*Update_Unit_RA_Size

AC_RA_Size_at_Outbound_Cruise= AC_Aircraft_in_Outbound_Criuse*AC_RA_Sampling_Times_at_Outbound_Cruise*Number_of_RA_at_AC_Outbound_Cruise*Update_Unit_RA_Size

AC_RA_Size_at_Post = AC_Aircraft__in_Post*AC_RA_Sampling_Times_at_Post*Number_of_RA_at_AC_Post*Update_Unit_RA_Size

AC_RA_Size_at_Preflight= AC_Aircraft__in_Preflight*AC_RA_Sampling_Times_at_Preflight*Update_Unit_RA_Size*Number_of_RA_at_AC_Preflight_Planning*AC_Past_RA_Fator

AC_RA_Size_at_Taxi_In_and_Parking= AC_Aircraft_in_Taxi_In_and_Parking*AC_RA_Sampling_Times_at_Taxi_In_and_Parking*Number_of_RA_at_AC_Taxi_In_and_Parking*Update_Unit_RA_Size

AC_RA_Size_at_Taxi_Out_and_Take_Off= AC_Aircraft_in_Taxi_Out_and_Take_Off*AC_RA_Sampling_Times_at_Taxi_Out_and_Take_Off*Update_Unit_RA_Size

AC_RA_Size_at_Transient= AC_Aircraft__in_Transient*AC_RA_Sampling_Times_at_Transient*Number_of_RA_at_AC_Transient*Update_Unit_RA_Size

AC_RA_Size__at_Initial_Climb_Segment= AC_Aircraft_in__Initial_Climb_Segment*AC_RA_Sampling_Times_at_Initial_Climb_Segment*Number_of_RA_at_AC_Initia_Climb_Segment*Update_Unit_RA_Size

AC_RA_Size__at_Initial_Cruise= AC_Aircraft__in_Initial_Cruise*AC_RA_Sampling_Times_at_Initia_Cruise*Number_of_RA_at_AC_Initia_Cruise*Update_Unit_RA_Size

AC_RA_Size__at_Preflight_Planning= AC_Aircraft_in_Preflight_Planning*AC_RA_Sampling_Times_at_Preflight_Planning*Number_of_RA_at_AC_Preflight_Planning*Update_Unit_RA_Size*AC_Past_RA_Fator

Mean_unit_RA_Size = 800

Number_of_RA_at_AC_Approach = 6

Number_of_RA_at_AC_Departuer = 5

Number_of_RA_at_AC_Inbound_Cruise_ = 6

Number_of_RA_at_AC_Initia_Climb_Segment = 5

Number_of_RA_at_AC_Initia_Cruise = 6

Number_of_RA_at_AC_Landing = 6

Number_of_RA_at_AC_Outbound_Cruise = 6

Number_of_RA_at_AC_Post = 6

Number_of_RA_at_AC_Preflight_Planning = 20

Number_of_RA_at_AC_Taxi_In_and_Parking = 6

Number_of_RA_at_AC_Transient = 10

Original_RA_Sampling_Rate = 720

RA_Graphical_Factor = 1

RA_Sampling_Rate = Original_RA_Sampling_Rate/RA_Sampling_Rate_Factor

RA_Sampling_Rate_Factor = Original_RA_Sampling_Rate/RA_Update_Sampling_Rate

RA_Uncode_Factor = 2

RA_Update_Sampling_Rate = 720

Unit_RA_Size = NORMAL(Mean_unit_RA_Size, 200)

Update_Unit_RA_Size = Unit_RA_Size*RA_Uncode_Factor*RA_Graphical_Factor

RA_Time_Factor = GRAPH(TIME)

(0.00, 1.00),(1.00, 0.00),(2.00, 0.00), (3.00, 0.00), (4.00, 0.00), (5.00, 0.00), (6.00, 0.00), (7.00, 0.00), (8.00, 0.00), (9.00, 0.00), (10.0, 0.00), (11.0, 0.00), (12.0, 0.00), (13.0, 0.00), (14.0, 0.00), (15.0, 0.00), (16.0, 0.00), (17.0, 0.00), (18.0, 0.00), (19.0, 0.00), (20.0, 0.00), (21.0, 0.00), (22.0, 0.00), (23.0, 0.00), (24.0, 0.00), (25.0, 0.00), (26.0, 0.00), (27.0, 0.00), (28.0, 0.00), (29.0, 0.00), (30.0, 0.00), (31.0, 0.00), (32.0, 0.00), (33.0, 0.00), (34.0, 0.00), (35.0, 0.00), (36.0, 0.00), (37.0, 0.00), (38.0, 0.00), (39.0, 0.00), (40.0, 0.00), (41.0, 0.00), (42.0, 0.00), (43.0, 0.00), (44.0, 0.00), (45.0, 0.00), (46.0, 0.00), (47.0, 0.00), (48.0, 0.00), (49.0, 0.00), (50.0, 0.00), (51.0, 0.00), (52.0, 0.00), (53.0, 0.00), (54.0, 0.00), (55.0, 0.00), (56.0, 0.00), (57.0, 0.00), (58.0, 0.00), (59.0, 0.00), (60.0, 0.00), (61.0, 0.00), (62.0, 0.00), (63.0, 0.00), (64.0, 0.00), (65.0, 0.00), (66.0, 0.00), (67.0, 0.00), (68.0, 0.00), (69.0, 0.00), (70.0, 0.00), (71.0, 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0.00), (839, 0.00), (840, 0.00), (841, 0.00), (842, 0.00), (843, 0.00), (844, 0.00), (845, 0.00), (846, 0.00), (847, 0.00), (848, 0.00), (849, 0.00), (850, 0.00), (851, 0.00), (852, 0.00), (853, 0.00), (854, 0.00), (855, 0.00), (856, 0.00), (857, 0.00), (858, 0.00), (859, 0.00), (860, 0.00), (861, 0.00), (862, 0.00), (863, 0.00), (864, 0.00), (865, 0.00), (866, 0.00), (867, 0.00), (868, 0.00), (869, 0.00), (870, 0.00), (871, 0.00), (872, 0.00), (873, 0.00), (874, 0.00), (875, 0.00), (876, 0.00), (877, 0.00), (878, 0.00), (879, 0.00), (880, 0.00), (881, 0.00), (882, 0.00), (883, 0.00), (884, 0.00), (885, 0.00), (886, 0.00), (887, 0.00), (888, 0.00), (889, 0.00), (890, 0.00), (891, 0.00), (892, 0.00), (893, 0.00), (894, 0.00), (895, 0.00), (896, 0.00), (897, 0.00), (898, 0.00), (899, 0.00), (900, 0.00), (901, 0.00), (902, 0.00), (903, 0.00), (904, 0.00), (905, 0.00), (906, 0.00), (907, 0.00), (908, 0.00), (909, 0.00), (910, 0.00), (911, 0.00), (912, 0.00), (913, 0.00), (914, 0.00), (915, 0.00), (916, 0.00), (917, 0.00), (918, 0.00), (919, 0.00), (920, 0.00), (921, 0.00), (922, 0.00), (923, 0.00), (924, 0.00), (925, 0.00), (926, 0.00), (927, 0.00), (928, 0.00), (929, 0.00), (930, 0.00), (931, 0.00), (932, 0.00), (933, 0.00), (934, 0.00), (935, 0.00), (936, 0.00), (937, 0.00), (938, 0.00), (939, 0.00), (940, 0.00), (941, 0.00), (942, 0.00), (943, 0.00), (944, 0.00), (945, 0.00), (946, 0.00), (947, 0.00), (948, 0.00), (949, 0.00), (950, 0.00), (951, 0.00), (952, 0.00), (953, 0.00), (954, 0.00), (955, 0.00), (956, 0.00), (957, 0.00), (958, 0.00), (959, 0.00), (960, 0.00), (961, 0.00), (962, 0.00), (963, 0.00), (964, 0.00), (965, 0.00), (966, 0.00), (967, 0.00), (968, 0.00), (969, 0.00), (970, 0.00), (971, 0.00), (972, 0.00), (973, 0.00), (974, 0.00), (975, 0.00), (976, 0.00), (977, 0.00), (978, 0.00), (979, 0.00), (980, 0.00), (981, 0.00), (982, 0.00), (983, 0.00), (984, 0.00), (985, 0.00), (986, 0.00), (987, 0.00), (988, 0.00), (989, 0.00), (990, 0.00), (991, 0.00), (992, 0.00), (993, 0.00), (994, 0.00), (995, 0.00), (996, 0.00), (997, 0.00), (998, 0.00), (999, 0.00), (1000, 0.00), (1001, 0.00), (1002, 0.00), (1003, 0.00), (1004, 0.00), (1005, 0.00), (1006, 0.00), (1007, 0.00), (1008, 0.00), (1009, 0.00), (1010, 0.00), (1011, 0.00), (1012, 0.00), (1013, 0.00), (1014, 0.00), (1015, 0.00), (1016, 0.00), (1017, 0.00), (1018, 0.00), (1019, 0.00), (1020, 0.00), (1021, 0.00), (1022, 0.00), (1023, 0.00), (1024, 0.00), (1025, 0.00), (1026, 0.00), (1027, 0.00), (1028, 0.00), (1029, 0.00), (1030, 0.00), (1031, 0.00), (1032, 0.00), (1033, 0.00), (1034, 0.00), (1035, 0.00), (1036, 0.00), (1037, 0.00), (1038, 0.00), (1039, 0.00), (1040, 0.00), (1041, 0.00), (1042, 0.00), (1043, 0.00), (1044, 0.00), (1045, 0.00), (1046, 0.00), (1047, 0.00), (1048, 0.00), (1049, 0.00), (1050, 0.00), (1051, 0.00), (1052, 0.00), (1053, 0.00), (1054, 0.00), (1055, 0.00), (1056, 0.00), (1057, 0.00), (1058, 0.00), (1059, 0.00), (1060, 0.00), (1061, 0.00), (1062, 0.00), (1063, 0.00), (1064, 0.00), (1065, 0.00), (1066, 0.00), (1067, 0.00), (1068, 0.00), (1069, 0.00), (1070, 0.00), (1071, 0.00), (1072, 0.00), (1073, 0.00), (1074, 0.00), (1075, 0.00), (1076, 0.00), (1077, 0.00), (1078, 0.00), (1079, 0.00), (1080, 0.00), (1081, 0.00), (1082, 0.00), (1083, 0.00), (1084, 0.00), (1085, 0.00), (1086, 0.00), (1087, 0.00), (1088, 0.00), (1089, 0.00), (1090, 0.00), (1091,*

0.00), (1092, 0.00), (1093, 0.00), (1094, 0.00), (1095, 0.00), (1096, 0.00), (1097, 0.00), (1098, 0.00), (1099, 0.00), (1100, 0.00), (1101, 0.00), (1102, 0.00), (1103, 0.00), (1104, 0.00), (1105, 0.00), (1106, 0.00), (1107, 0.00), (1108, 0.00), (1109, 0.00), (1110, 0.00), (1111, 0.00), (1112, 0.00), (1113, 0.00), (1114, 0.00), (1115, 0.00), (1116, 0.00), (1117, 0.00), (1118, 0.00), (1119, 0.00), (1120, 0.00), (1121, 0.00), (1122, 0.00), (1123, 0.00), (1124, 0.00), (1125, 0.00), (1126, 0.00), (1127, 0.00), (1128, 0.00), (1129, 0.00), (1130, 0.00), (1131, 0.00), (1132, 0.00), (1133, 0.00), (1134, 0.00), (1135, 0.00), (1136, 0.00), (1137, 0.00), (1138, 0.00), (1139, 0.00), (1140, 0.00), (1141, 0.00), (1142, 0.00), (1143, 0.00), (1144, 0.00), (1145, 0.00), (1146, 0.00), (1147, 0.00), (1148, 0.00), (1149, 0.00), (1150, 0.00), (1151, 0.00), (1152, 0.00), (1153, 0.00), (1154, 0.00), (1155, 0.00), (1156, 0.00), (1157, 0.00), (1158, 0.00), (1159, 0.00), (1160, 0.00), (1161, 0.00), (1162, 0.00), (1163, 0.00), (1164, 0.00), (1165, 0.00), (1166, 0.00), (1167, 0.00), (1168, 0.00), (1169, 0.00), (1170, 0.00), (1171, 0.00), (1172, 0.00), (1173, 0.00), (1174, 0.00), (1175, 0.00), (1176, 0.00), (1177, 0.00), (1178, 0.00), (1179, 0.00), (1180, 0.00), (1181, 0.00), (1182, 0.00), (1183, 0.00), (1184, 0.00), (1185, 0.00), (1186, 0.00), (1187, 0.00), (1188, 0.00), (1189, 0.00), (1190, 0.00), (1191, 0.00), (1192, 0.00), (1193, 0.00), (1194, 0.00), (1195, 0.00), (1196, 0.00), (1197, 0.00), (1198, 0.00), (1199, 0.00), (1200, 0.00), (1201, 0.00), (1202, 0.00), (1203, 0.00), (1204, 0.00), (1205, 0.00), (1206, 0.00), (1207, 0.00), (1208, 0.00), (1209, 0.00), (1210, 0.00), (1211, 0.00), (1212, 0.00), (1213, 0.00), (1214, 0.00), (1215, 0.00), (1216, 0.00), (1217, 0.00), (1218, 0.00), (1219, 0.00), (1220, 0.00), (1221, 0.00), (1222, 0.00), (1223, 0.00), (1224, 0.00), (1225, 0.00), (1226, 0.00), (1227, 0.00), (1228, 0.00), (1229, 0.00), (1230, 0.00), (1231, 0.00), (1232, 0.00), (1233, 0.00), (1234, 0.00), (1235, 0.00), (1236, 0.00), (1237, 0.00), (1238, 0.00), (1239, 0.00), (1240, 0.00), (1241, 0.00), (1242, 0.00), (1243, 0.00), (1244, 0.00), (1245, 0.00), (1246, 0.00), (1247, 0.00), (1248, 0.00), (1249, 0.00), (1250, 0.00), (1251, 0.00), (1252, 0.00), (1253, 0.00), (1254, 0.00), (1255, 0.00), (1256, 0.00), (1257, 0.00), (1258, 0.00), (1259, 0.00), (1260, 0.00), (1261, 0.00), (1262, 0.00), (1263, 0.00), (1264, 0.00), (1265, 0.00), (1266, 0.00), (1267, 0.00), (1268, 0.00), (1269, 0.00), (1270, 0.00), (1271, 0.00), (1272, 0.00), (1273, 0.00), (1274, 0.00), (1275, 0.00), (1276, 0.00), (1277, 0.00), (1278, 0.00), (1279, 0.00), (1280, 0.00), (1281, 0.00), (1282, 0.00), (1283, 0.00), (1284, 0.00), (1285, 0.00), (1286, 0.00), (1287, 0.00), (1288, 0.00), (1289, 0.00), (1290, 0.00), (1291, 0.00), (1292, 0.00), (1293, 0.00), (1294, 0.00), (1295, 0.00), (1296, 0.00), (1297, 0.00), (1298, 0.00), (1299, 0.00), (1300, 0.00), (1301, 0.00), (1302, 0.00), (1303, 0.00), (1304, 0.00), (1305, 0.00), (1306, 0.00), (1307, 0.00), (1308, 0.00), (1309, 0.00), (1310, 0.00), (1311, 0.00), (1312, 0.00), (1313, 0.00), (1314, 0.00), (1315, 0.00), (1316, 0.00), (1317, 0.00), (1318, 0.00), (1319, 0.00), (1320, 0.00), (1321, 0.00), (1322, 0.00), (1323, 0.00), (1324, 0.00), (1325, 0.00), (1326, 0.00), (1327, 0.00), (1328, 0.00), (1329, 0.00), (1330, 0.00), (1331, 0.00), (1332, 0.00), (1333, 0.00), (1334, 0.00), (1335, 0.00), (1336, 0.00), (1337, 0.00), (1338, 0.00), (1339, 0.00), (1340, 0.00), (1341, 0.00), (1342, 0.00), (1343, 0.00), (1344, 0.00), (1345, 0.00), (1346, 0.00), (1347, 0.00), (1348, 0.00), (1349, 0.00), (1350, 0.00), (1351, 0.00), (1352, 0.00), (1353, 0.00), (1354, 0.00), (1355, 0.00), (1356, 0.00), (1357, 0.00), (1358, 0.00), (1359, 0.00), (1360, 0.00), (1361, 0.00), (1362, 0.00), (1363, 0.00), (1364, 0.00), (1365, 0.00), (1366, 0.00), (1367, 0.00), (1368, 0.00), (1369, 0.00), (1370, 0.00), (1371, 0.00), (1372, 0.00), (1373, 0.00), (1374, 0.00), (1375, 0.00), (1376, 0.00), (1377, 0.00), (1378, 0.00), (1379, 0.00), (1380, 0.00), (1381, 0.00), (1382, 0.00), (1383, 0.00), (1384, 0.00), (1385, 0.00), (1386, 0.00), (1387, 0.00), (1388, 0.00), (1389, 0.00), (1390, 0.00), (1391, 0.00), (1392, 0.00), (1393, 0.00), (1394, 0.00), (1395, 0.00), (1396, 0.00), (1397, 0.00), (1398, 0.00), (1399, 0.00), (1400, 0.00), (1401, 0.00), (1402, 0.00), (1403, 0.00), (1404, 0.00), (1405, 0.00), (1406, 0.00), (1407, 0.00), (1408, 0.00), (1409, 0.00), (1410, 0.00), (1411, 0.00), (1412, 0.00), (1413, 0.00), (1414, 0.00), (1415, 0.00), (1416, 0.00), (1417, 0.00), (1418, 0.00), (1419, 0.00), (1420, 0.00), (1421, 0.00), (1422, 0.00), (1423, 0.00), (1424, 0.00), (1425, 0.00), (1426, 0.00), (1427, 0.00), (1428, 0.00), (1429, 0.00), (1430, 0.00), (1431, 0.00), (1432, 0.00), (1433, 0.00), (1434, 0.00), (1435, 0.00), (1436, 0.00), (1437, 0.00), (1438, 0.00), (1439, 0.00), (1440, 1.00)

Part IV: Aircraft as Aviation weather Sensor

Aircraft_Weather_Sampling_Rate = 60

Aircraft__in_Enroute= AC_Aircraft_in_Outbound_Criuse+AC_Aircraft__in_Inbound_Cruise+AC_Aircraft__in_Initial_Cruise+AC_Aircraft__in_Transient+TC_Aircraft_in_Inbound_Cruise+TC_Aircraft_in_Transient+TC_Aircraft__in_Initial_Cruise+TC_Aircraft__in_Outbound_Cruise

Aircraft__in_Terminal= AC_Aircraft_in_Approach_Operation+AC_Aircraft_in__Initial_Climb_Segment+AC_Aircraft__in_Departure+AC_Aircraft__in_Landing_Operation+TC_Aircraft_in__Initial_Climb_Segment+TC_Aircraft__in_Approach_Operation+TC_Aircraft__in_Departure+TC_Aircraft__in_Landing_Operation

Bytes_per_Area_FST = Total_Bytes_FST_Service/Far_Strategic_Area

Bytes_per_Area_NST = Total_Bytes_NST_Service/Near_Strategic_Area

Bytes_per_Area_TAC = Total_Bytes_TAC_Service/Tactical_Area

Convective_Wx_Info_per_AC = 128/8

Convective_Wx_Info_Sampling_rate = Aircraft_Weather_Sampling_Rate

Far_Strategic_Area = 1.2e6

Icing_Info_per_AC = 16

Icing_Info_Sampling_Rate = Aircraft_Weather_Sampling_Rate

Near_Strategic_Area = 7.2e5

No_of_Bytes_per_Cell = 2

Sampling_Rate_of_Aircraft_Sensor= MAX(Convective_Wx_Info_Sampling_rate,Icing_Info_Sampling_Rate,Turbulence_Info_Sampling_Rate,Winds_Aloft_and_Temperature_Info_Sampling_Rate)

Tactical_Area = 9e4

Total_Aircarf_Weather_Load_in_ENR= Total_Convective_Wx_in_ENR+Total_Icing_Info_in_ENR+Total_Turbulence_Info_in_ENR+Total_Winds_Aloft_and_Temperature_in_ENR

Total_Aircraft_Weather_Load_in_TERM= Total_Convective_Wx_in_TERM+Total_Icing_Info_in_TERM+Total_Turbulence_Info_in_TERM+Total_Winds_Aloft_and_Temperature_in_TERM

Total_Bytes_FST_Service = No_of_Cells_in_FST*No_of_Bytes_per_Cell

Total_Bytes_NST_Service = No_of_Bytes_per_Cell*No_of_Cells_in_NST

Total_Bytes_TAC_Service = No_of_Bytes_per_Cell*No_of_Cells_in_TAC

Total_Convective_Wx_in_ENR = Aircraft__in_Enroute*Convective_Wx_Info_per_AC*Convective_Wx_Info_Sampling_rate

Total_Convective_Wx_in_TERM = Aircraft__in_Terminal*Convective_Wx_Info_per_AC*Convective_Wx_Info_Sampling_rate

Total_Icing_Info_in_ENR = Aircraft__in_Enroute*Icing_Info_per_AC*Icing_Info_Sampling_Rate

Total_Icing_Info_in_TERM = Aircraft__in_Terminal*Icing_Info_per_AC*Icing_Info_Sampling_Rate

Total_Turbulence_Info_in_ENR = Aircraft__in_Enroute*Turbulence_Info_per_AC*Turbulence_Info_Sampling_Rate

Total_Turbulence_Info_in_TERM = Aircraft__in_Terminal*Turbulence_Info_per_AC*Turbulence_Info_Sampling_Rate

Total_Winds_Aloft_and_Temperature_in_ENR= Aircraft__in_Enroute*Winds_Aloft_and_Temperature_Info_per_AC*Winds_Aloft_and_Temperature_Info_Sampling_Rate

Total_Winds_Aloft_and_Temperature_in_TERM= Aircraft__in_Terminal*Winds_Aloft_and_Temperature_Info_per_AC*Winds_Aloft_and_Temperature_Info_Sampling_Rate

Turbulence_Info_per_AC = 16

Turbulence_Info_Sampling_Rate = Aircraft_Weather_Sampling_Rate

Winds_Aloft_and_Temperature_Info_per_AC = 64

Winds_Aloft_and_Temperature_Info_Sampling_Rate = Aircraft_Weather_Sampling_Rate

Grid_Size_of_Cell_Map = GRAPH(Sampling_Rate_of_Aircraft_Sensor)

(6.00, 1.00), (15.0, 0.85), (24.0, 0.7), (33.0, 0.55), (42.0, 0.4), (51.0, 0.25), (60.0, 0.1)

No_of_Cells_in_FST = GRAPH(Grid_Size_of_Cell_Map)

(0.1, 2e+006), (0.25, 1.2e+006), (0.4, 0.00), (0.55, 0.00), (0.7, 315000), (0.85, 0.00), (1.00, 123000)

No_of_Cells_in_NST = GRAPH(Grid_Size_of_Cell_Map)

(0.1, 7.2e+007), (0.25, 1.6e+007), (0.4, 6e+006), (0.55, 3e+006), (0.7, 1.5e+006), (0.85, 1e+006), (1.00, 720000)

No_of_Cells_in_TAC = GRAPH(Grid_Size_of_Cell_Map)

(0.1, 9e+006), (0.25, 2e+006), (0.4, 900000), (0.55, 500000), (0.7, 183000), (0.85, 100000), (1.00, 90000)

Appendix C: MATLAB Source Code

Read ETMS Data Function

```
function Fp=readetms_flights(filename)

tic
f1=fopen(filename,'r')
f=0;
fname=fscanf(f1,'%s',1);

while(feof(f1)==0)
    fname=fname;
    move=fscanf(f1,'%s',1);
    clear move;
    fmodel=fscanf(f1,'%s',1);
    move=fscanf(f1,'%s',[1 4]);
    clear move;
    origin=fscanf(f1,'%s',1);
    dest=fscanf(f1,'%s',1);
        f=f+1;
        Fp(f).fname=fname;
        Fp(f).fmodel=fmodel;
        Fp(f).origin=origin;
        Fp(f).dest=dest;
        move=fscanf(f1,'%s',[1 10]);
        clear move;
        num=fscanf(f1,'%d',1);
        Fp(f).n=num;

        for(i=1:num)
            move=fscanf(f1,'%s',1);
            clear move;
            temp_wp(i, 1:6)=fscanf(f1,'%f',[1 6]);
        end
        Fp(f).wp(:,1:3)=temp_wp(:, 1:3);
        Fp(f).twp(:,1)=temp_wp(:, 4);
        clear temp_wp;
        temp=Fp(f).wp(:, 1);
```

```
        Fp(f).wp(:, 1)=-Fp(f).wp(:, 2);
        Fp(f).wp(:, 2)=temp;
        clear temp;
    fname=fscanf(f1,'%s',1);
end
fclose(f1);
toc
```

Read SDAT Data Function

```
function fp=readsdat(filename)
tic
f1=fopen(filename, 'r')
f=0;
move=fscanf(f1,'%s',1);
clear move;
fname=fscanf(f1,'%s',1);

while(feof(f1)==0)
%while(f<=100)
   f=f+1;
   fp(f).fname=fname;
   fp(f).origin=fscanf(f1,'%s',1);
   fp(f).dest=fscanf(f1,'%s',1);
   fp(f).fmodel=fscanf(f1,'%s',1);
   move=fscanf(f1,'%s',[1 2]);
   clear move;
   num1=fscanf(f1,'%d',1);
   num2=fscanf(f1,'%d',1);
   fp(f).n1=num1;
   fp(f).n2=num2;

   for(i=1:num1)
      sector =fscanf(f1,'%s',1);
      fp(f).sector(i,1:2)=sector;
      lat=fscanf(f1,'%s',1);
      fp(f).latnum(i,1)=str2num(lat(1:6));
      long =fscanf(f1,'%s',1);
      fp(f).longnum(i,1)=str2num(long(1:7));
```

```
      fp(f).wp(i, 1:2)=fscanf(f1,'%f', [1 2]);
   end

   if(num2>0)
      move=fscanf(f1,'%s',[1 4]);
      clear move;
   end

      for(i=1:num2)
         move=fscanf(f1,'%s',1);
         clear move;
         move=fscanf(f1,'%f',[1 4]);
         clear move;
      end

    move=fscanf(f1,'%s',1);
    clear move;
    fname=fscanf(f1,'%s',1);

end
fclose(f1);
toc
```

Read SDAT Node Data Function

```
function Node=read_sdat_node(filename)

lf=length(filename);

filename(lf+1:lf+13)='.export.nodes';

f1=fopen(filename,'r');
Node=struct('N',[],'name',[]);
i=0;
move=fgets(f1)

N_name=fscanf(f1,'%s',1);

while(feof(f1)==0)
```

```
    i=i+1;
    lat=fscanf(f1,'%s',1);
    lat=getdeg( str2num(lat(1:6)) );
    long=fscanf(f1,'%s',1);
    long=getdeg( str2num(long(1:7)) );
    Node.N(i,:)=[ long lat];
    Node.name(i,:)=N_name;
    N_name=fscanf(f1,'%s',1);
end
fclose(f1);
```

Read SDAT Sector Data Function

```
function out=read_sdat_sect(filename,Node)

lf=length(filename);

filename(lf+1:lf+15)='.export.sectors';

f1=fopen(filename,'r')
sect_num=0;
newsect=0;
move=fgets(f1)
S=struct('ver',[],'lat',[],'long',[]);

while(feof(f1)==0)
    value=fscanf(f1,'%s',1);
    if( length( findstr('M-',value) ) >0 )
        newsect=1;
        sect_num=sect_num+1;
        num=0;
        h(sect_num,:)=[ str2num(value(3:5))  str2num(value(7:9))+1 ];
    end

    while( newsect==1)
        value=fscanf(f1,'%s',1);
        nodenum=get_sdat_nodenum(Node.name,value);
        if(nodenum==0)
```

```
            newsect=0;
            S(sect_num).long(num+1,1)=S(sect_num).long(1,1);
            S(sect_num).lat(num+1,1)=S(sect_num).lat(1,1);
        else
            num=num+1;
            S(sect_num).ver(1,num)=nodenum;
            S(sect_num).long(num,1)=-Node.N(nodenum,1);
            S(sect_num).lat(num,1)=Node.N(nodenum,2);
        end
    end
end
out.S=S;
out.h=h;
fclose(f1);
```

Find Weather System Centroid Function

```
function C=find_centroid(weather_filename)

tic
f1=fopen(werather_filename, 'r')
n=50;
A=[0100 0200 0300 0400 0500 0600 0700 0800 0900 1000 1100 1200 1300 1400 ...
   1500 1600 1700 1800 1900 2000 2100 2200 2300 2400 2500 2600 2700 2800 ...
   2900 3000 3100 3200 3300 3400 3500 3600 3700 3800 3900 4000 4100 4200];

for(i=1:42)
  C(i).total_lat=0;
  C(i).total_long=0;
  C(i).maxR=0;
   for(j=1:n)
    C(i).Cp(j).long=fscanf(f1,'%f',1);
      if(C(i).Cp(j).long==A(i))
         C(i).Cp(j).long=0;
         %C(i).Cp(j).lat=0;
         if(C(i).Cp(1).long==0)
                C(i).Cp_long=0;
                C(i).Cp_lat=0;
         end
         break;
      end

    C(i).Cp(j).lat=fscanf(f1,'%f',1);
```

```
   C(i).Cp(j).ceiling=fscanf(f1,'%f',1);
   C(i).Cp(j).floor=fscanf(f1,'%f',1);
   C(i).total_long=C(i).total_long + C(i).Cp(j).long;
   C(i).total_lat=C(i).total_lat + C(i).Cp(j).lat;
   C(i).Cp_long=C(i).total_long/(length(C(i).Cp));
   C(i).Cp_lat =C(i).total_lat/(length(C(i).Cp));

  end

  for(k=1:length(C(i).Cp))
    if(length(C(i).Cp)==1)
      C(i).d(k).distance=0;
    else
      C(i).d(k).distance=((C(i).Cp_long-C(i).Cp(k).long)^2+(C(i).Cp_lat-C(i).Cp(k).lat)^2)^(1/2);
    end
  end
  for(k=1:length(C(i).Cp))
    if(length(C(i).Cp)==1)
      C(i).maxR=0;
    else
      if (C(i).d(k).distance>C(i).maxR)
         C(i).maxR=C(i).d(k).distance;
      else
         C(i).maxR=C(i).maxR;
      end
    end
   end
end
tic;
```

Draw Weather System Function

```
function draw_circle(xc, yc, R)

n=xc-R;
m=xc+R;

for(i=1:49)
  x(1)=xc-R;
  y(1)=yc;
  z(1)=yc;
  x(i+1)=n+((m-n)/49)*i;
  y(i+1)=yc+(R^2-(x(i+1)-xc)^2)^(1/2);
  z(i+1)=yc-(R^2-(x(i+1)-xc)^2)^(1/2);
end
```

```
usmap;
hold;
axis equal;
axis([-130 -60 20 55]);
grid on;
for(i=1:50)
    plot(x,y,'r',x,z,'r');
end
```

Find Impacted Flight Function

```
function IF=impact_flight(flight_filename,sua_filename)

tic;
f=0;
k=0;
number=0;
   f1=fopen(flight_filename,'r');
   fname=fscanf(f1,'%s',1);

   while(feof(f1)==0 );
   %while(f<=300 );
     fname=fname;
     %name=fname(1:3);
     move=fscanf(f1,'%s',1);
     clear move;
     fmodel=fscanf(f1,'%s',1);
     move=fscanf(f1,'%s',[1 4]);
     clear move;
        origin=fscanf(f1,'%s',1);
        dest=fscanf(f1,'%s',1);
        f=f+1;
        Fp(f).fname=fname;
        Fp(f).fmodel=fmodel;
        Fp(f).origin=origin;
        Fp(f).dest=dest;
        move=fscanf(f1,'%s',[1 10]);
            clear move;
            num=fscanf(f1,'%d',1);
            Fp(f).n=num;
```

```
    for(i=1:num)
      move=fscanf(f1,'%s',1);
      clear move;
      temp_wp(i, 1:6)=fscanf(f1,'%f',[1 6]);
    end

  Fp(f).wp(:,1:3)=temp_wp(:, 1:3);
  Fp(f).twp(:,1)=temp_wp(:, 4);
  Fp(f).speed(:,1)=temp_wp(:, 5);
  clear temp_wp;

  temp=Fp(f).wp(:, 1);
    Fp(f).wp(:, 1)=-Fp(f).wp(:, 2);
    Fp(f).wp(:, 2)=temp;
    clear temp;

B=[1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 ...
    23 24 25 26 27 28 29 30 32 33 34 35 36 37 38 39 40 41 42];
C=[1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 ...
    23 24 25 26 27 28 29 30 32 33 34 35 36 37 38 39 40 41 42];
D=[1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 ...
    23 24 25 26 27 28 29 30 32 33 34 35 36 37 38 39 40 41 42];
 tstart=Fp(f).twp(1,1);
 tend=Fp(f).twp(num,1);

 if(tstart<100)
   tstart=100;
 end

 for(i=0:100:4200)

    if (tstart>i & tstart<(100+i))
      tstart=B(i/100);
    end
    if (tend>i & tend<(100+i))
     tend=C(i/100)+1;
   end
  end
```

```
  find_centroid(sua_filename);
  C=ans;
  for(i=tstart:tend)

      for(j=1:num)
          Fp(f).F(i).d(j)=((Fp(f).wp(j,1)-C(i).Cp_long)^2 + (Fp(f).wp(j,2)-C(i).Cp_lat)^2)^(1/2);
          Fp(f).d(i)=min(Fp(f).F(i).d);
      end
  end
  %d=min(IF(f).d(i));
  %R =max(C(i).maxR);
  for(i=tstart:tend)
      if(Fp(f).d(i)<=C(i).maxR)
         number=number+1;
         k=k+1;
         IF(k).number=number;
         IF(k).fname=Fp(f).fname;
         IF(k).fmodel=Fp(f).fmodel;
         IF(k).origin=Fp(f).origin;
         IF(k).dest=Fp(f).dest;
         IF(k).n=Fp(f).n;
         IF(k).wp=Fp(f).wp;
         IF(k).twp=Fp(f).twp;
         IF(k).speed=Fp(f).speed;
         break;
      end
  end

  fname=fscanf(f1,'%s',1);
end

fclose(f1);

toc;
```

Generate Detour Flight Path Function

```
function Fp=generatesurrogate

tic
load impact_flight_k_R;
m=length(IF);
sua_filename='sua_k_data.m';
number_surrogate=1;
RR=1;
f=0;
for(number=1:number_surrogate)
  for(f=1:20)
      Fp=IF;
      Fp(f).flp(number)=f;
      num=Fp(f).n;
      Fp(f).original_travel_time=(IF(f).twp(num,1) - IF(f).twp(1,1))/60;
      B=[1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 ...
          23 24 25 26 27 28 29 30 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50];
      C=[1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 ...
          23 24 25 26 27 28 29 30 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50];
      D=[1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 ...
          23 24 25 26 27 28 29 30 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50];
      tstart=Fp(f).twp(1,1);
      tend=Fp(f).twp(num,1);
      if(tstart<100)
        tstart=100;
      end
      for(i=0:100:5000)
          if (tstart>i & tstart<(100+i))
            tstart=B(i/100);
          end
          if (tend>i & tend<(100+i))
           tend=C(i/100)+1;
          end
      end
      C=find_centroid(sua_filename);
      for(i=tstart:tend)
          if(sua_filename=='sua_k_data.m')
            longitude=C(i).Cp_long+0.2;
```

```
   latitude=C(i).Cp_lat;
   if(RR==1)
     R=C(i).maxR-0.42;
   elseif(RR==2)
     R=(C(i).maxR-0.42)/2;
   else
     R=(C(i).maxR-0.42)/4;
   end
 end
 if(sua_filename=='sua_n_data.m')
   longitude=C(i).Cp_long;
   latitude=C(i).Cp_lat;
   if(RR==1)
     RR=C(i).maxR;
   elseif(R==2)
     R=(C(i).maxR)/2;
   else
     R=(C(i).maxR)/4;
   end
 end
 if(sua_filename=='sua_v_data.m')
    longitude=C(i).Cp_long-0.6;
    latitude=C(i).Cp_lat-0.6;
    if(RR==1)
     R=C(i).maxR-0.4;
    elseif(RR==2)
     R=(C(i).maxR-0.4)/2;
    else
     R=(C(i).maxR-0.4)/4;
    end
 end
 for(j=1:num)
  d(j)=((Fp(f).wp(j,1)-longitude)^2 + (Fp(f).wp(j,2)-latitude)^2)^(1/2);
    if(d(j)<=R)
     time=Fp(f).twp(j,1);
     for(k=0:100:4200)
         if (time>k & time<(100+k))
         time=D(k/100)+1;
         break;
```

```
          end
        end
        if(time==i)
         time_value=i;
         break;
        end
      end
  end
end
C=find_centroid(sua_filename);
if(sua_filename=='sua_k_data.m')
     xc=C(time_value).Cp_long+0.2;
     yc=C(time_value).Cp_lat;
       if(RR==1)
          R=C(time_value).maxR-0.42;
       elseif(RR==2)
          R=(C(time_value).maxR-0.42)/2;
       else
          R=(C(time_value).maxR-0.42)/4;
       end
  end
  if(sua_filename=='sua_n_data.m')
       xc=C(time_value).Cp_long;
       yc=C(time_value).Cp_lat;
       if(RR==1)
          R=C(time_value).maxR;
       elseif(RR==2)
          R=(C(time_value).maxR)/2;
       else
          R=(C(time_value).maxR)/4;
       end
  end
  if(sua_filename=='sua_v_data.m')
        xc=C(time_value).Cp_long-0.6;
       yc=C(time_value).Cp_lat-0.6;
        if(RR==1)
          R=C(time_value).maxR-0.4;
       elseif(RR==2)
          R=(C(time_value).maxR-0.4)/2;
```

```
      else
         R=(C(time_value).maxR-0.4)/4;
      end
   end
for(j=1:num)
 xworigin=Fp(f).wp(1,1); %first flight waypoints
 yworigin=Fp(f).wp(1,2); %first flight waypoints
 xwdestination=Fp(f).wp(num,1);%last flight waypoints
 ywdestination=Fp(f).wp(num,2);%last flight waypoints
 xw=Fp(f).wp(j,1);
 yw=Fp(f).wp(j,2);
 r(j)=two_points_distance(xc,yc,xw,yw);
end
for(j=1:num-1)
 xw=Fp(f).wp(j,1);
 yw=Fp(f).wp(j,2);
 xw1=Fp(f).wp((j+1),1);
 yw1=Fp(f).wp((j+1),2);
 if((r(j+1)>R & r(j)>R)|(r(j+1)<R & r(j)<R))
    Fp(f).wp(j,1)=Fp(f).wp(j,1);
    Fp(f).wp(j,2)=Fp(f).wp(j,2);
 elseif(r(j+1)<R & r(j)>R)
    k_A=((yw1)-yw)/((xw1)-xw);
    %y-yw=k_A(x-xw)
    A=k_A;
    B=-1;
    C=-k_A*xw+yw;
    [x1,y1,x2,y2]=intersection_circle_line(A,B,C,xc,yc,R);
    if(xw<xc)
       A_point=[x2,y2];
    else
       A_point=[x1,y1];
    end
    k_A_tangent=-(yc-A_point(2))/(xc-A_point(1));
    %y-y2=k_A_tangent*(x-x2) the tangent line through point A
 elseif(r(j+1)>R & r(j)<R)
    k_B=((yw1)-yw)/((xw1)-xw);
    %y-yw=k_A(x-xw)
    A=k_B;
```

```
      B=-1;
      C=-k_B*xw+yw;
      [x1,y1,x2,y2]=intersection_circle_line(A,B,C,xc,yc,R);
      if(xw1>xc)
        B_point=[x1,y1];
      else
        B_point=[x2,y2];
      end
      k_B_tangent=-(yc-B_point(2))/(xc-B_point(1));
      %y-y1=k_B_tangent*(x-x1) the tangent line through point B
    end
  end

  if(r(1)<R)
    A_point=[Fp(f).wp(1,1),Fp(f).wp(1,2)];
    k_A_tangent=-(yc-A_point(2))/(xc-A_point(1));
  end

  if(r(num)<R)
    B_point=[Fp(f).wp(num,1),Fp(f).wp(num,2)];
    k_B_tangent=-(yc-B_point(2))/(xc-B_point(1));
  end
  %Calculate C point
   k_A_tangent=(1/k_A_tangent);
   A1=k_A_tangent;
   B1=-1;
   C1=-k_A_tangent*A_point(1)+A_point(2);
   k_B_tangent=(1/k_B_tangent);
   A2=k_B_tangent;
   B2=-1;
   C2=-k_B_tangent*B_point(1)+B_point(2);
   x,y]=two_lines_intersection_point(A1,B1,C1,A2,B2,C2);
   C_point=[x,y];
   %Calculate D point
   k_D=(yc-C_point(2))/(xc-C_point(1));
   %y-yc=k_D*(x-xc)
   A=k_D;
   B=-1;
   C=-k_D*xc+yc;
```

```
 [x1,y1,x2,y2]=intersection_circle_line(A,B,C,xc,yc,R);
 D1_point=[x1,y1];
 D2_point=[x2,y2];
 d1=two_points_distance(C_point(1),C_point(2),D1_point(1),D1_point(2));
 d2=two_points_distance(C_point(1),C_point(2),D2_point(1),D2_point(2));
 if (d1>d2)
   D_point=D2_point;
 else
  D_point=D1_point;
 end
%Calculate E point
k_D_tangent=-(1/k_D);
%the tangent line through D_point
%y-D_point(2)=K_D_tangent*(x-D_point(1))
%y-A_point(2)=K_A_tangent*(x-A_point(1))
A1=k_D_tangent;
B1=-1;
C1=-k_D_tangent*(D_point(1))+D_point(2);
A2=k_A_tangent;
B2=-1;
C2=-k_A_tangent*(A_point(1))+A_point(2);
[x,y]=two_lines_intersection_point(A1,B1,C1,A2,B2,C2);
E_point=[x,y];
%Calculate F point
k_D_tangent=-(1/k_D);
%the tangent line through D_point
%y-D_point(2)=K_D_tangent*(x-D_point(1))
%y-B_point(2)=K_B_tangent*(x-B_point(1))
A1=k_D_tangent;
B1=-1;
C1=-k_D_tangent*(D_point(1))+D_point(2);
A2=k_B_tangent;
B2=-1;
C2=-k_B_tangent*(B_point(1))+B_point(2);
[x,y]=two_lines_intersection_point(A1,B1,C1,A2,B2,C2);
F_point=[x,y];
k=0;
v=1;
for(j=1:num)
```

```
  xw=Fp(f).wp(j,1);
  yw=Fp(f).wp(j,2);
  r(j)=two_points_distance(xc,yc,xw,yw);
  if (r(j)<R)
    if (number==1)
         P=[A_point,E_point,D_point,F_point,B_point];
    else
         if((j+1-number)<1)
            A_point=[Fp(f).wp(1,1),Fp(f).wp(1,2)];
         else
            A_point=[Fp(f).wp((j+1-number),1),Fp(f).wp((j+1-number),2)];
         end
         if((j+number-1)<=num)
            B_point1=[Fp(f).wp((j+number-1),1),Fp(f).wp((j+number-1),2)];
         else
            B_point1=[Fp(f).wp((num),1),Fp(f).wp((num),2)];
         end
         P=[A_point,E_point,D_point,F_point,B_point];
    end
    w=j;
    k=k+1;
    if (k<=5)
      Fp(f).wp(j,1)=P(v);
      Fp(f).wp(j,2)=P(v+1);
      v=v+2;
    else
      Fp(f).wp(j,1)=P(9);
      Fp(f).wp(j,2)=P(10);
    end
  else

    Fp(f).wp(j,1)=Fp(f).wp(j,1);
    Fp(f).wp(j,2)=Fp(f).wp(j,2);

  end
end
% This part is used to calculate the distance, travel time and cost between two waypoints
total_distance=0;
total_travel_time=0;
```

```
        total_cost=0;
         for (i=1:num-1)

             if (Fp(f).wp((i+1),3)>Fp(f).wp((i),3))
                 wp1=[Fp(f).wp((i+1),1),Fp(f).wp((i+1),2)];
                 wp2=[Fp(f).wp((i),1),Fp(f).wp((i),2)];
                 d=waypoints_distance(wp1,wp2);
                 Fp(f).travel_time(i,1)=d/((Fp(f).speed((i+1),1)+Fp(f).speed((i),1))/2);
                 Fp(f).cost(i,1)=Fp(f).travel_time(i,1)*climb_fuel_value(Fp(f).fmodel);
             elseif (Fp(f).wp((i+1),3)==Fp(f).wp((i),3))
                 wp1=[Fp(f).wp((i+1),1),Fp(f).wp((i+1),2)];
                 wp2=[Fp(f).wp((i),1),Fp(f).wp((i),2)];
                 d=waypoints_distance(wp1,wp2);
                 Fp(f).travel_time(i,1)=d/((Fp(f).speed((i+1),1)+Fp(f).speed((i),1))/2);
                 Fp(f).cost(i,1)=Fp(f).travel_time(i,1)*cruise_fuel_value(Fp(f).fmodel);
             else
                 wp1=[Fp(f).wp((i+1),1),Fp(f).wp((i+1),2)];
                 wp2=[Fp(f).wp((i),1),Fp(f).wp((i),2)];
                 d=waypoints_distance(wp1,wp2);
                 Fp(f).travel_time(i,1)=d/((Fp(f).speed((i+1),1)+Fp(f).speed((i),1))/2);
                 Fp(f).cost(i,1)=Fp(f).travel_time(i,1)*descent_fuel_value(Fp(f).fmodel);
             end
                 total_travel_time=total_travel_time + Fp(f).travel_time(i,1);
                 Fp(f).total_travel_time=total_travel_time;
                 Fp(f).delay=(Fp(f).total_travel_time-Fp(f).original_travel_time)*60;
                 total_cost=total_cost+Fp(f).cost(i,1);
                 Fp(f).cost=total_cost*60*(0.8)/3.78;
         end
     end % end while
end

toc
```

Reference

I Documents and Articles

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Vita

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