# AIR SURVEILLANCE FOR SMART LANDING FACILITIES IN THE SMALL AIRCRAFT TRANSPORATION SYSTEM

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(ABSTRACT)

The Small Aircraft Transportation System (SATS) is a partnership among various organizations including NASA, the FAA, US aviation industry, state and local aviation officials, and universities. The program objectives are intend to reduce travel times by providing high-speed, safe travel alternatives by making use of small aircraft and underused small airports throughout the nation. A major component of the SATS program is the Smart Landing Facility (SLF). The SLF is a small airport that has been upgraded to handle SATS traffic. One of the services needed at SLFs is air surveillance of the airspace surrounding it.

This thesis researches the different surveillance techniques available for use at the SLFs. The main focuses of this paper are an evaluation of the Traffic Alert and Collision Avoidance System (TCAS) when used as a ground sensor at SLFs and the design of a Position and Identification Reporting Beacon (PIRB). The use of the TCAS ground sensor is modeled in Matlab and the results of that model are discussed. The PIRB is a new system that can be used in conjunction with the Automatic Dependent Surveillance-Broadcast (ADS-B) system or independently to provide position information for all aircraft using GPS based positioning.

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# Chapter 1 - Introduction

An integral part of the Small Aircraft Transportation System (SATS) is the Smart Landing Facility (SLF). It is envisioned that SATS pilots will be able to self-separate from each other and need either minimal or no Air Traffic Control (ATC) while in flight. For this to occur, traffic information must be made available to the pilots at all times, in all weather conditions. This research investigates the different options for surveillance at SLFs, and evaluates the performance of those systems. This research also involves evaluating the different ATC issues that arise from the specific surveillance options.

## 1.1 SATS and SLF Information

The Small Aircraft Transportation System (SATS) program is a partnership of the Federal Aviation Administration, the National Aeronautics and Space Administration, the United States aviation industry, and many universities. The partnership's goals are to help satisfy the emerging public demand for safe, higher-speed mobility and increased accessibility.

The current air traffic system consists mainly of passenger airlines that operate in a hub and spoke fashion. The thirty major airports in the United States represent the hubs of the system. In most cases, if one currently wants to travel from a small city or town one must travel via car or small aircraft to one of the hubs first. From that hub one can then travel to other hubs in different regions and then out to other small cities or towns which are considered spokes off of that hub. This system leads to the underutilization of many of the smaller spoke airports and the overuse of the hub airports. The SATS program goals are to allow more direct flights from small airports directly to other small airports. Allowing for more of these direct flights would reduce the total door to door travel time currently experienced.

A direct consequence of having more direct flights from small airports to other small airports is the need for more small aircraft. To accommodate these needs, the SATS program is also developing advanced aircraft that will be easier to pilot under both Instrument Meteorological Conditions (IMC) and Visual Meteorological Conditions (VMC). This will also increase the need for trained, small aircraft pilots. In a SATS scenario, the new aircraft will make single pilot operation safer than ever before. As more people are able to fly by small aircraft, it will become more affordable to do so. Trips in the 100 to 300 mile range will be able to be accomplished much quicker by flying than by driving.

As flying small aircraft becomes easier and safer, there will be an increase in the number of flights leaving and entering small airports. To allow these small airports to accommodate the larger traffic volume, the concept of Smart Landing Facilities was developed. Smart Landing Facilities (SLFs) are envisioned to provide many different services to the pilots, which include: traffic sequencing and separation, landing and take-off clearances, taxi clearances, weather observations, and airport operation information. Many of these services require the ability to track aircraft in and around the SLFs.

Current surveillance techniques, which include using Primary and Secondary Radar, are highly desirable for the SLFs. The cost of installing and maintaining Primary and Secondary Radars at all SLF make the use of those systems impractical. Since there are over 2000 small airports that could possibly be transformed into SLFs, the cost and maintenance at the SLFs must be kept to a minimum. Instead of the current surveillance techniques, the SLF will make use of a new type of surveillance that uses different technology.

## 1.2 Research Overview

This thesis examines the different surveillance techniques that can be used for Smart Landing Facilities that make use of current technology. One of the systems that is explored for surveillance at SLFs includes the Traffic Alert and Collision Avoidance System (TCAS) ground sensor. A Matlab simulation was constructed to test the TCAS ground sensor, in theory, for the systems limitations in providing air surveillance. The

ATC considerations that are needed for the TCAS ground sensor to work successfully are also discussed.

The second system that is explored for use at the SLFs for surveillance is the Automated Dependent Surveillance-Broadcast (ADS-B) system. Since the ADS-B system is not compatible with the current SSR system, a low-cost way to equip aircraft with an ADS-B like system is investigated. A Position and Identification Reporting Beacon (PIRB) is a design which broadcasts GPS position and aircraft identification information in the same format that the ADS-B does. Options for using the PIRB in conjunction with ADS-B and for using the PIRB independently are discussed. As with the TCAS ground sensor, the ATC issues that arise from using the ADS-B and PIRB systems are investigated.

## 1.3 Thesis Outline

This thesis is divided into 7 chapters. Background information on aircraft surveillance techniques and systems is found in Chapter 2. This chapter gives a detailed description of the operations of Primary Radar, Secondary Surveillance Radar, Mode A/C and S transponders, TCAS, and ADS-B. Chapter 3 outlines the different possible surveillance techniques that are available for use at the SLFs. The use of Secondary Surveillance Radar, multi-lateration techniques, TCAS ground sensors, and GPS based surveillance such as ADS-B and the PIRB system are discussed.

Chapter 4 is an in depth evaluation of the use of TCAS as a ground sensor at SLFs. The design of a Matlab simulation for testing the TCAS ground sensor is described. The results and analysis of the simulation are also reviewed in Chapter 4. Chapter 5 presents the design and analysis of the Position and Identification Report Beacon (PIRB). The PIRB is a low cost system that broadcasts GPS position information and a flight identification number for use by the ADS-B system or for collection by a ground sensor.

Chapter 6 discusses different Air Traffic Control (ATC) issues that must be addressed depending on the surveillance system that is chosen. The advantages and disadvantages of the TCAS ground sensor, the ADS-B system and the PIRB system are investigated concerning ATC. Chapter 7 is a summary of the thesis and suggests future work concerning these topics.

# Chapter 2 - Aviation Surveillance

Since aircraft started flying, people have been trying to track those aircraft for both military and civil purposes. The systems used for aircraft surveillance fall into three categories: primary radar, secondary radar, and GPS based positing such as the Automated Dependent Surveillance-Broadcast system. Primary radars emit high power electromagnetic energy and rely on the aircraft's outer coating or 'skin' to reflect some of that energy back to the radar which in turn uses that energy to detect the presence of an aircraft. The term radar actually comes from this process, RAdio Detection And Ranging.

Secondary Radar, despite its name, is more of a combination of radar and a communication system rather than a pure radar system. The ground station in a secondary radar system transmits a specific set of pulses. The aircraft carry devices called transponders that receive the interrogation from the ground station and then respond to it with an encoded message. The ground station uses those responses to track the aircraft.

The invention and commercialization of the Global Positioning System, GPS, provides yet another way for aircraft surveillance to be maintained. The Automatic Dependent Surveillance-Broadcast system, known as ADS-B, uses GPS receivers aboard aircraft to determine each individual aircraft's position, and then broadcasts that information to receiving stations. Each of these different methods of tracking aircraft will be discussed and the advantages and disadvantages of each system will be explored.

## 2.1 Primary Radar

Primary Radar was first used at the onset of World War II. Throughout the 1920s and 1930s work had been done in the United States, Great Britain, and Germany concerning high frequency radio wave transmissions. The theory of radar detection had initially been proven by Heinrich Hertz in 1886 when he showed that radio waves were reflected by metallic and other dielectric bodies [1]. In 1922, A. H. Taylor and L. C. Young working for the Naval Research Laboratory showed that a ship could be detected using a continuous wave transmitter and separate receiver. The two scientists showed that wave interference caused by the passing ship between the transmitter and receiver could be detected [2]. Today such a radar would be called a bistatic CW (continuous wave) radar. Later similar systems were proved to be able to detect aircraft as well. These first radars left much to be desired. Though they could detect the presence of objects, they could not give a position of the target.

Great Britain, needing protection from the Nazi war-machine, expended a larger amount of effort in the development of radar. In 1935, the British had shown that by pulsing the transmitted signal, the range of the target could be detected. By 1938 the British had deployed a series of radars which operated at 25 MHz knows as Chain Home to guard against German air attacks [1].

In the fall of 1940, the first meeting between American and British scientist concerning the development of radar took place. The major British contribution was the disclosure of the magnetron, which made high-powered microwave transmission possible. The American scientists shared the radar duplexer that they had developed which allowed the rapid switching of an antenna from the transmission phase of operation to the receive phase while not allowing the high-powered transmitted pulse to destroy the sensitive receiving hardware. The sharing of these two inventions led to rapid advances in radar by both countries [3].

These early radars led to the development of the primary radars that we use today. The primary radar that we use for air traffic control (ATC) can not only detect aircraft, but the range and bearing from the radar, the relative size of the target, and by using multiple returns can determine the heading and speed of the target. A typical primary radar consists of a large antenna which is connected to a high-speed switch known as a Transmit/Receive (T/R) cell that in turn is connected to both the transmission and receiving hardware. The antenna is rotated, normally at a rate of six to ten rotations a minute, so that the entire sky can be searched. By using a highly directional antenna, the energy that is transmitted by the radar is pointed in a specific direction that is known to the radar thus giving the bearing to any possible targets. The narrow beam is rotated through a complete circle, allowing for coverage of all angles. The radar does not have the ability to detect directly above its antenna, but the area directly above the radar is very small by comparison to the area that is visible. Short pulses of energy are transmitted, and when that energy travels to and is reflected by a target, the same directional antenna receives the returned pulse. By measuring the time it takes the pulse to travel out and back, and by knowing the speed at which the pulse travels through the air, the range to the target can be calculated. The amplitude of the returned pulse is proportional to the reflectivity of the target, which can be equated to its size.

However, primary radar is not sufficient for air traffic control purposes. Identification of individual aircraft is not possible with the radar alone, nor is altitude information obtained. Radar returns from the ground, called ground clutter, can also interfere with the returns from valid targets, as can rain between the target and the radar.

## 2.2 IFF

The precursor to today's civilian secondary radar systems was the military Identification, Friend or Foe (IFF). IFF was developed in the build up for World War II. Both the Axis and the Allied powers saw the need to be able to identify whether or not an aircraft was a part of their own forces or of that of the enemy well before visual confirmation could be attained. Equipment was developed that was placed on all friendly aircraft. This equipment would detect friendly ground radar transmissions and then would reply with a transmission of its own. By transmitting a coded signal, the aircraft was able to let the ground radar station know it was a friendly aircraft. This system was later changed from responding to radar transmitters to a separate interrogation on a different frequency.

By the end of World War II, the system in use was utilizing 1030 MHz for interrogation and 1090 MHz for replies. The replies consisted of up to 15 pulses, which allowed for individual aircraft identification. The same system, with a few refinements is still in use today and is known as Secondary Surveillance Radar (SSR) [4].

## 2.3 Secondary Surveillance Radar

Secondary Surveillance Radar is composed of the ground station, or interrogator, the airborne system, or transponder, and the signals the two systems send to each other. SSR is used in conjunction with primary radar to provide surveillance for the air traffic control system. SSR provides airplane identification numbers and altitude data information that cannot be acquired by primary radar. However, SSR can give range and bearing data without primary radar as long as the aircraft are carrying working transponders. Primary radar is still used for air traffic surveillance, though, to ensure that there are no airplanes without working transponders in the airspace.

### *2.1.1 SSR Signals*

The interrogation signal sent by the ground station to the aircraft is centered at 1030 MHz. This signal is shown in Figure 2.1. The signal consists of three different pulses: P1, P2, and P3. Each of these pulses is 0.8 microseconds in duration. There is a spacing of 2 μs between the start of the P1 and of the P2 pulses. The spacing between the start of the P1 and the P3 pulses differs depending on the response that the interrogation is eliciting [5].

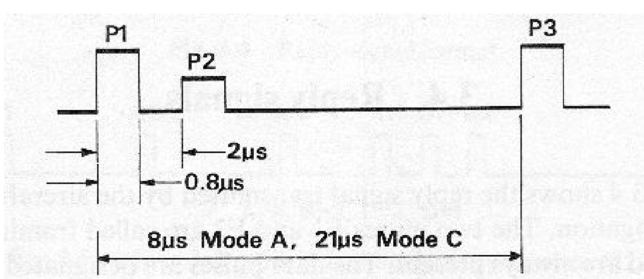


*Figure 2.1 Secondary Radar Interrogation [4]*

The P2 pulse is known as the control pulse. The ground station radiates the control pulse in every direction but that of the main beam. The P1 and P3 pulses are transmitted by the main beam. The radiation patterns of the different pulses is shown in Figure 2.2. The transponder on the aircraft compares the amplitude of the P1 pulse to the P2 pulse. If the P2 pulse has greater amplitude than the P1 pulse, then the transponder knows to suppress its response since it is not in the main beam of the SSR.

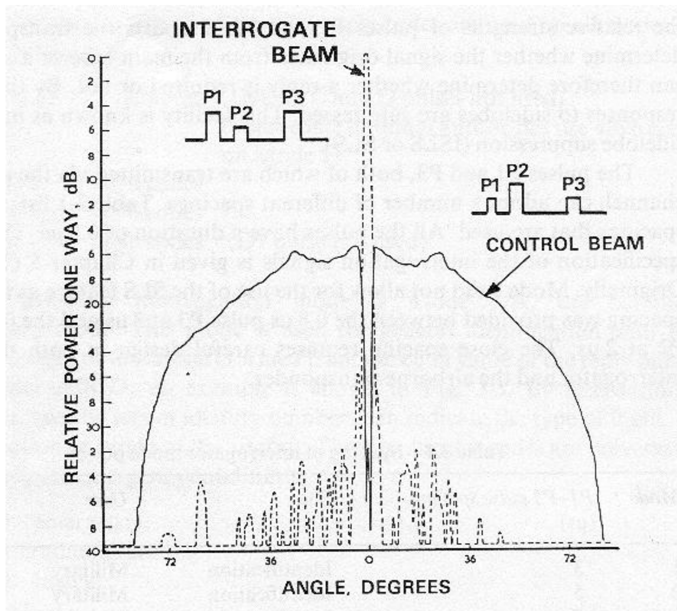


*Figure 2.2 Interrogation and Control Beam Patterns [4]*

As mentioned previously, the spacing between the P1 and P3 pulses determines the type of response generated by the transponder. The different categories of responses are called the mode of the response. Table 2.1 shows the different types of modes that the SSR system is capable of using. Modes A and C are the code types that are used by civil SSR and are the codes are used by General Aviation (GA) aircraft.

| Mode | P1-P3 Spacing in microseconds | Use | User |
|---|---|---|---|
| 1 | 3 | Identification | Military |
| 2 | 5 | Identification | Military |
| 3/A | 8 | Identification | Civil/Military |
| B | 17 | Not Used | Civil |
| C | 21 | Altitude | Civil |

*Table 2.1 Interrogator Modes*

The reply signals generated by the transponders are centered around 1090 MHz. The signal is composed of two framing pulses, F1 and F2, and up to 12 data pulses, designated A, B, C, and D with a suffix 1, 2, or 4. The signal can also contain a special position indicator or SPI pulse. The middle pulse in the signal, called the X pulse, is currently not used. Figure 2.3 shows the arrangement of the pulses in the reply signal. The A, B, C, and D pulses are in octal format providing identification numbers in decimal format 0000 through 7777.

Each pulse in the reply signal is 0.45 μs in duration and each pulse is separated by 1.0 μs, with the exception of the SPI pulse, which is separated by 3.9 μs. A typical response, which does not include the SPI pulse, is 20.75 μs in duration. The 12 data pulses allow for up to 4096 permutations that are used to supply data to the SSR.

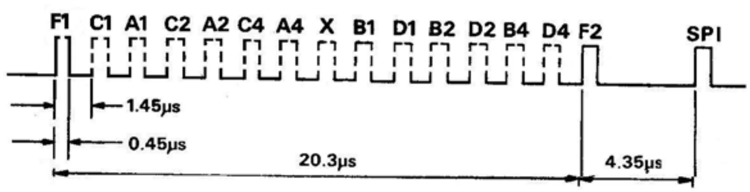


*Figure 2.3 Reply Signal Format [4]*

For a Mode A response, which is the identity of the aircraft, all 4096 permutations of the code are used. The identity number is extracted from the signal by taking the octal value of the reply pulses in the order ABCD. In an aircraft, the transponder has dials, which allows the pilot to input the code that the transponder will reply with when interrogated. Normally this code is assigned to the aircraft by the air traffic controller when the flight plan for the aircraft is filed. If the plane is operating under visual flight rules, no flight plan is required, and the pilot uses a transponder code of 1200. Other reserved codes are: 7700 for emergency, 7600 for radio failure, and 7500 for hijack. During a flight, the pilot may be asked to dial in a different code as he or she enters different controlled airspaces. The pilot might also be asked to press the “Ident” button on the transponder. The pressing of the “Ident” button activates the transmission of the SPI pulse in the Mode A response for approximately 20 seconds [4].

For a Mode C response, which is the altitude of the aircraft, only 2048 permutations of code are used, as the D1 pulse is not utilized. This allows for the transmission of all altitudes from –1000 feet to 121,000 feet in 100-foot increments. The altitude of the aircraft is obtained by the transponder from a piezzo electric barometer.

### *2.1.2 SSR Radars*

The ground station of a SSR system is very similar to that of primary radar. In the case of SSR, the antenna is very wide, on the order of 8-10 meters, which gives an azimuth beamwidth of 2-2.75° [1]. This allows the SSR to have very good angular resolution on the targets. The antenna has a vertical length of only approximately a meter, allowing for a wider beam in the vertical plane. This allows the SSR to have more total coverage area at higher elevations. This antenna is normally mounted on top of the primary radar at most airfields.

Though the antenna used for SSR has a relatively small azimuth beamwidth, the possibility of an aircraft close to the SSR might receive a strong enough interrogation in one of the antenna side lobes to elicit a response is a very real problem with the system. Since the path loss suffered by a signal is a function of range, a close in aircraft receives a much stronger signal. Even if that aircraft is not in the main lobe of the antenna, the signal strength in the side lobes of the antenna could be strong enough to elicit a response. To overcome this, the SSR creates both a sum and a difference pattern with the antenna. The sum pattern creates certain pulses, the P1 and P3 pulses, of the interrogation and the difference pattern, also called the control beam, creates another distinct pulse, the P2 pulse, which allows for the limiting of responses. This is shown in Figure 2.2.

Another component of the ground station is the receiver. The receiving portion of the system times the delay between the transmitted pulse and reception of a response and from that information can give a range to the target. The bearing to the target is known from the bearing in which the interrogation is made. The receiver then decodes the Mode

A and Mode C responses to extract the identification number and altitude of the target. The information is then displayed on a radar display terminal, which plots a vector at the correct range and bearing and labels that vector with the identity number and the aircraft's altitude. The vector length is determined by the velocity of the aircraft and the direction the vector points is the heading of the aircraft. Velocity and heading information is gained by compiling multiple SSR responses.

Two major problems can occur while trying to decode responses. One problem is *fruit* appearing and the second problem is *garbling*. Fruit is when a reply is received at a ground station from an aircraft that is responding to a different ground station's interrogation. Fruit could cause the appearance of a false target on the radar screen. Garbling occurs when two or more replies from different aircraft to the interrogation from a single ground station overlap. Garbling can cause wanted replies to be suppressed.

Fruit is dealt with in two separate ways. First, reply-path side-lobe suppression (RSLS) is used. In this process a second, omni-directional antenna is set up at the ground station that feeds a second channel in the receiver. The two channels, one from the main SSR antenna and one from the omni-directional antenna, are then connected to an amplitude comparator. Only those signals with greater amplitude in the channel from the main SSR antenna are kept. By suppressing any replies picked up in the side lobe of the receiving antenna, any nearby aircraft's reply that is being generated by a separate interrogator will be ignored [4].

The second way fruit is removed is by gain-time control (GTC), which is also known as sensitivity time control (STC), at the receiver. By knowing that the power received at the ground station is inversely proportional to the square of the range of the aircraft and by knowing the minimum power output required in a transponder, a threshold can be established for the power that must be received as a function of time. This allows weaker responses to be ignored. Many fruit responses that are picked up in the main beam will be suppressed in this way [4].

Garbling occurs when the slant paths for two separate aircraft to the ground station are within 3.7 kilometers, or half the distance electromagnetic waves can travel in 25.1 μs, of each other. 25.1 μs is the length of the Mode A/C reply with the SPI pulse included. This close proximity of aircraft is common when the aircraft are "stacked" vertically. Since the SSR has a wide beam in the vertical direction, any "stacked" aircraft will be interrogated at the same time. When two or more replies are overlapped, they can be classified as synchronous or non-synchronous reply-code overlap [4]. Synchronous reply-code overlap is considered to have occurred when the pulses from two or more signals overlap. In this case the signal is suppressed. Non-synchronous reply-code overlap is when the pulses of one code fall into the gaps of the second code. When this occurs, the two codes can be separated.

### *2.1.3 Transponders*

The transponders used for General Aviation aircraft and those used in commercial aircraft differ in complexity and power ratings. In this section, the discussion will be limited to transponders used in General Aviation. Typically the transponder is connected to an omni-directional antenna mounted on the underside of the fuselage. The system has a receiver sensitivity of approximately –70 to –75 dBm [5]. To keep the transmitter of the system from overloading, the sensitivity of the receiver is reduced by 3 dB when the system is being interrogated at a rate over 1000 interrogations per second. This reduces the effective interrogation range by half. By reducing the sensitivity of the receiver during these overloads, the system will still respond to the closer SSR, which is normally the more important SSR as far as air traffic control is concerned.

When an interrogation is received, the amplitude of the P2 pulse is compared to the amplitude of the P1 pulse. If the amplitude of the P2 pulse is 9 dB below the P1 pulse, then the transponder will respond. If the amplitude of the P2 pulse is between 0 dB and 9 dB below the P1 pulse, then the transponder may or may not respond. If the amplitude of the P2 pulses is larger than the P1 pulse the system will not respond. The system also has a built in suppression period of up to 125 μs after a successful interrogation before it will allow another interrogation of the system [4].

Once a successful interrogation is received, the transponder has a built in delay before it responds to a given interrogation. The delay is 3.0 ± 0.5 μs between the leading edge of the P3 pulse and the leading edge of the framing pulse F1. This variation of delay leads to a range ambiguity of ±150 meters. Based on the interrogation type received, the correct reply is produced. If an aircraft is not equipped with an altimeter, and a mode C response is requested, the transponder replies with just the framing pulses [5].

## 2.4 Mode S Transponders

Potential saturation of the current SSR system caused the development of the Mode S transponder. This new transponder allows for special individual interrogations and also combines the height and identification number, the normal Mode A and Mode C replies, into just one reply. The new transponder was designed to be compatible with the older transponder versions so that each aircraft would not have to carry two systems in order to be visible to SSR.

The interrogation of the Mode S transponder is very similar to the interrogation of the Mode A/C transponders. Mode S requires two different types of interrogation: an individual call and an all call. In the all call, the P1, P2, and P3 pulses are still present along with a new P4 pulse that begins 2 μs after the leading edge of the P3 pulse. The P4 pulse lasts for a duration of 1.6 μs and does not interfere with the interrogation of the Mode A/C transponders. If the P4 pulse is not present, the transponder knows that it must make its reply in the Mode A/C format [4].

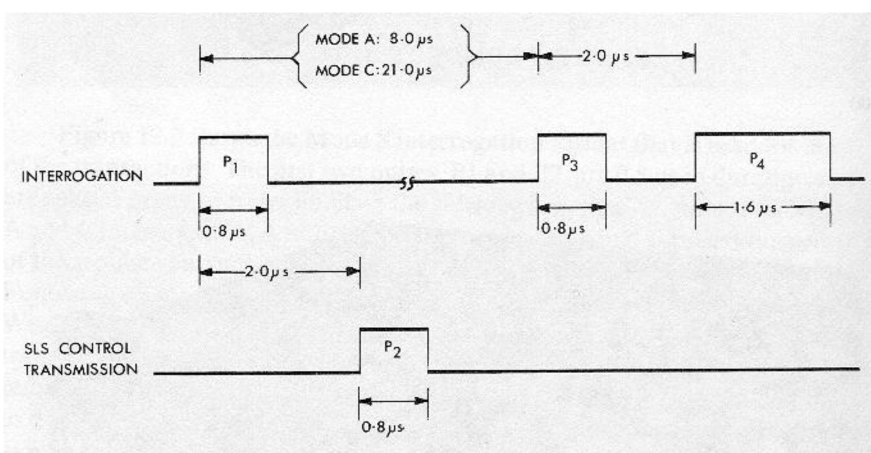


*Figure 2.4 Mode A/C/S All Call [4]*

The individual call again consists of the P1 and P2 pulses. The P2 pulse in this case has greater amplitude than the P1 pulse so that Mode A/C transponders will no longer attempt to decode the interrogation. The P2 pulse is followed by a P6 pulse that is either 16.25 or 30.25 μs in length. The P6 pulse contains data in differential phase shift keying (DPSK) format and either contains 56 or 112 bits of data along with a synchronization pulse. This number of data bits allows for a multitude of different types of interrogation and also by reserving the final 24 bits of every interrogation for an aircraft identification number, the interrogation can be made specifically to one aircraft with the remainder of the aircraft ignoring the request. The Mode S individual call also contains a sidelobe suppression bit that is used in a similar to the way that the P2 pulse was used in Mode A/C transponders. The pulse is called the P5 pulse and is transmitted in the difference beam of the interrogator and the pulse is generated so that it will coincide with the synchronization pulse in P6. By interfering with the synchronization bit, the P5 pulse keeps aircraft in the side lobes of the transmission antenna from being able to syncronize and thus decode the DPSK signal [4].

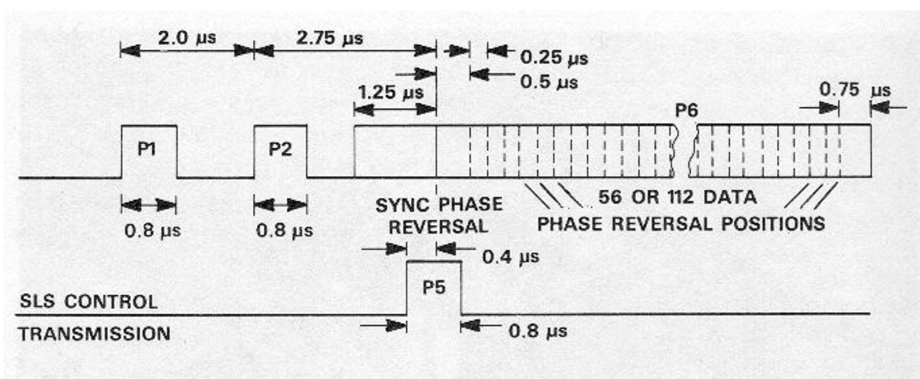


*Figure 2.5 Mode S Interrogation[4]*

The reply format for a Mode S interrogation is very similar to that of its interrogation. First the reply contains four ASK bits that are spaced in such a way that no two overlapping Mode A/C responses could generate them. Following these preamble bits is a block of either 56 or 112 data pulses, depending on the reply that is requested. The data pulses are sent in ASK format with Manchester encoding so that each data pulse lasts 1.0 μs but each pulse is constructed of two 0.5 μs pulses, one high and one low. This helps make the signal very resistant to noise interference and reduces the number of replies needed for Mode S to operate safely. Again the final 24 bits of each reply contain the aircraft's identification number and a parity check of the data bits so that errors caused by noise can be detected and false information is not generated [4].

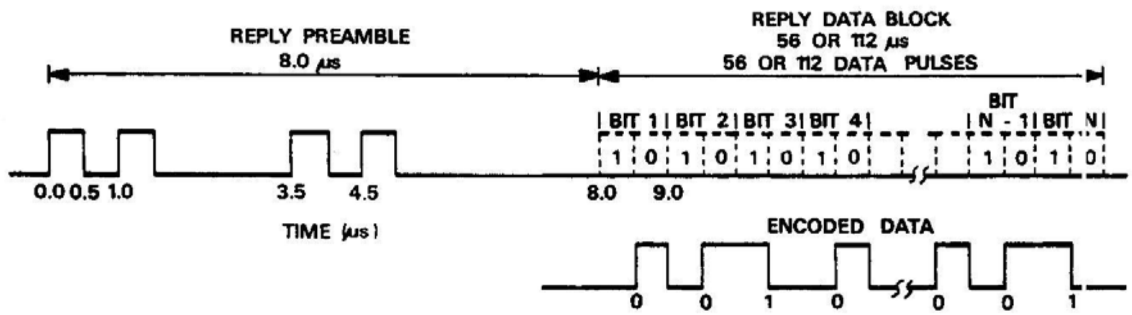


*Figure 2.6 Mode S Reply Format [4]*

The Mode S transponder is also designed to make transmissions without being interrogated. This transmission is called a "squitter." The squitter contains the shorter 56-bit transmission and is made to inform surrounding receivers of the aircraft' identification number. This is done so that individual calls can be made to that aircraft from that point forward.

The Mode S transponder was designed to help reduce the congestion caused in the 1030 and 1090 MHz bands. This was needed because of potential saturation of the SSR systems around busy airports. The Mode S transponder never became widely used though because of the higher costs, that is until a second system called the Traffic Advisory and Collision Avoidance System (TCAS) was developed. TCAS makes use of Mode S and became a government-mandated system on all commercial carriers. Still, virtually no general aviation (GA) aircraft is equipped with a Mode S Transponder [6].

## 2.5 Traffic Advisory and Collision Avoidance System

The Traffic Advisory and Collision Avoidance system (TCAS) is an airborne system used to give pilots information about other aircraft that are in close proximity to their aircraft. TCAS is used mainly today as a safety backup to positive air traffic control. The system works much in the same way as ground based SSR to determine the range and bearing to other aircraft. TCAS has been developed in three separate models designated by TCAS I, TCAS II, and TCAS III. Another purpose of TCAS is to spread the use of Mode S transponders to help reduce the congestion of the 1030-1090 MHz bands.

TCAS I is the most rudimentary of the TCAS systems and was designed for small aircraft. TCAS I determines the locations of all aircraft in close proximity to it which are near its own flight level, and displays that information to the pilot. It is then the pilot's job to keep proper separation. TCAS II is a more sophisticated system that is intended for use on larger commercial aircraft. This system is able to track aircraft in both the vertical and horizontal planes. The system also can give verbal warnings of approaching aircraft and actually gives directions on how to avoid the potential hazard by either climbing or descending. TCAS III is very similar to TCAS II but can also give collision avoidance directions in the lateral plane [7].

TCAS I assumes that the other aircraft near it will be equipped with only a Mode A/C transponder. The TCAS system makes a Mode C interrogation to elicit the response of the altitude information from the surrounding aircraft. In an effort to collect data on only a few aircraft at one time, TCAS employs the whisper-shout interrogation method. By starting off with low power interrogations, the TCAS system receives responses from nearby aircraft. TCAS then increases the interrogation power in order to receive replies from aircraft that are at greater ranges. In order to suppress the responses from the closer aircraft, the second Mode C interrogation is preceded by 2 μs with a pulse of the amplitude of the first interrogation. In this way, the closer aircraft that were interrogated by the first, lower power, interrogation will see the first pulse and assume it is a P1 pulse and then the second pulse, at the higher power, will be seen as a P2 pulse and this will suppress responses in that transponder. Aircraft that are farther out will not see the first pulse. The second pulse will be seen and will be assumed to be the P1 pulse and then the third pulse will be seen as the P3 pulse because it has the proper spacing. This process can be repeated if necessary to increase the range of the TCAS [8].

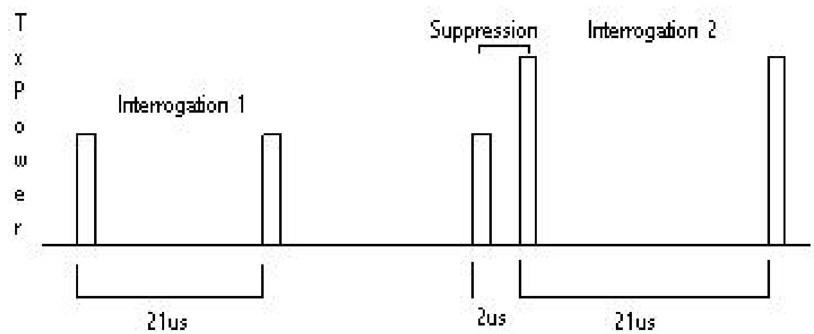


*Figure 2.7 Whisper-Shout Interrogation*

Another way that the TCAS system can locate aircraft is by use of the Mode S squitter. By listening for squitters from other Mode S transponders, the TCAS system can learn the identification numbers of those aircraft. Then the TCAS system can make individual calls to those aircraft using the Mode S transponder to acquire the information on location and altitude needed without activating responses from other Mode A/C or S transponders [9].

TCAS II and TCAS III make use of the extra data bits in the Mode S transponder reply to co-ordinate maneuvers between the aircraft. If both aircraft are equipped with TCAS, when one TCAS unit decides that an evasive maneuver must be undertaken, the TCAS unit tells the other aircraft, in a special Mode S reply, which maneuver it will undertake. In this way, the second TCAS unit can ensure that it is not giving the mirror image maneuver to its pilot.

Another advance that can be seen in the TCAS III unit is the use of directional antennas. This version of TCAS uses eight top-loaded monopoles that are arranged in a circular pattern. This antenna allows for the subdivision of the main beam into 22.5° increments. A P2 pulse is then transmitted in the difference pattern, as occurred in SSR, to limit the number of responding aircraft. This increased number of elements in the antenna also allows for a better bearing measurement. An accuracy of ±4° is normal in a TCAS III [4].

## 2.6 Automatic Dependent Surveillance-Broadcast

The Automatic Dependent Surveillance-Broadcast (ADS-B) system differs from the other surveillance techniques discussed. ADS-B contains a Global Positioning System (GPS) receiver that allows the ADS-B equipped aircraft to determine its own location. This location information, along with the aircraft's identification number is then broadcast. Any aircraft or ground station in the vicinity can then receive the broadcast and then know the exact location and identity of that aircraft without having to interrogate it.

The basic principle of ADS-B is to simplify air surveillance by making use of GPS. Since GPS receivers have become readily available and extremely accurate, making use of GPS for surveillance became an obvious choice. With this system, each aircraft would be able to broadcast its position and this would replace the need for directional antennas for bearing and exact timing for range information. Also the number of broadcasts needed for each ADS-B system would be on the order of one or two a second. Current transponders are interrogated at a rate approaching 1000 times a second in high-density airspaces where there are numerous SSR and TCAS equipped aircraft. The reduction in channel congestion is obvious in such a system.

ADS-B is designed to make use of the Mode-S transponder. By setting the transponder in the squitter mode and increasing the rate of the squitter from 1 Hz to 2 Hz, the transponder then broadcasts given information using the 112 data bits in the long Mode S reply. Three different broadcasts are designed to be made in succession. The first is intended for ground stations and contains latitude, longitude, transmission time, heading, and movement. The second transmission contains information for airborne receivers and contains latitude, longitude, transmission time, barometric altitude, and turning information. The third transmission contains more specific identification information of the aircraft [10].

The Mode S transponder is used in this system in hopes of making ADS-B more compatible with the current SSR system. Despite this fact, the ADS-B system is a relatively new system that has not been accepted yet for general use by the FAA.

# Chapter 3 - Smart Landing Facility Surveillance Options

One of the main goals of the Small Aircraft Transportation System (SATS) program is to increase the number of small aircraft that are used. To accommodate more aircraft, many of our nation's 5000 airports will have to be upgraded to be able to accommodate a higher volume of air traffic while at the same time increasing the safety levels that are present today in General Aviation (GA).

Currently, many of the smaller airports do not have a tower or Secondary Surveillance Radar (SSR). The pilot maintains separation between aircraft when under Visual Meteorological Conditions (VMC) by just visually searching for other aircraft. When under Instrument Meteorological Conditions (IMC), only one aircraft is allowed in the airspace at a time. This separation is maintained by the nearest Air Traffic Control (ATC) center. For example, in the case of the Blacksburg Airport, under IMC Roanoke ATC allows one aircraft to enter Blacksburg's airspace and keeps all others out until the first aircraft has landed. This means that only two or three aircraft can land at Blacksburg over the course of an hour under IMC.

In order to make SATS a viable transportation option, the number of arrivals and departures under IMC should not be drastically different from the number in VMC. To increase traffic at these airports, but to remain without a tower or conventional ATC, a Smart Landing Facility (SLF) must be developed in order to maintain the safety requirements mandated by the Federal Aviation Administration (FAA) and the public.

A major component of the SLF will be surveillance of the airspace. For pilots to keep self separation under IMC where visual separation is impossible, some sort of tracking system must be employed so that the locations of all aircraft in the airspace can be made known to all other aircraft in that airspace. To accomplish this, the exact location and altitude of each aircraft must be known. Primary Radar cannot find altitude information accurately so it is not an option for the SLF surveillance. The current systems that could obtain the required information are Secondary Surveillance Radar (SSR), multi-lateration of transponder replies, the Traffic Alert and Collision Avoidance System (TCAS), and ADS-B or other GPS based location systems.

## 3.1 Secondary Surveillance Radar

One option for maintaining surveillance at Smart Landing Facilities is to use Secondary Surveillance Radar. The SSR is currently used at major airports to maintain positive air traffic control. By using a SSR to locate all the aircraft in the airspace, the information can then be broadcast by a ground unit via a data link back to all the aircraft in the airspace. In this manner, each pilot will be aware of the air traffic situation and be able to maintain separation.

By using SSR, the airborne equipment required in SATS aircraft so that each aircraft will be detectable by the Smart Landing Facility will only be a Mode A/C transponder. Most General Aviation aircraft are already equipped with this type of transponder, which means that most aircraft will be seen by the SSR and thus be able to use the SLF. Obviously SATS aircraft will need to be equipped with the proper data link and display so that the information obtained by the SSR can be up-linked to the aircraft. This will allow the pilots to keep proper separation from the other aircraft solely by using the up-linked data from the SLF. The fact that even non-SATS aircraft can be seen using such a system means that these non-SATS aircraft can be more smoothly integrated into the SLF.

Secondary Surveillance Radar is a very costly system. Each ground unit costs over one million dollars, and this does not include the equipment needed to process the data and retransmit that data back to the aircraft. Another problem with using SSR is that fact that is involves the use of a rotating antenna. This means that the antenna will need constant maintenance and repair. Cost and maintenance concerns make the use of SSR for surveillance at Smart Landing Facilities a poor choice.

## 3.2 Multi-Lateration of Mode A/C Transponder Replies

Since the rotating antenna of a Secondary Surveillance Radar unit is primary reason for not using that system, the question arises is there another way to create a system similar to SSR without the rotating antenna. One way of accomplishing this is to have a single omni-directional interrogator and three or more omni-directional receiving stations. Since the rotating antenna is needed only to determine the bearing to each aircraft, the use of at least three receiving stations and multi-lateration can give the same result.

In such a system the ground unit interrogates all the transponders in the airspace. The time delay of each response at each receiving station can be calculated. The time delay gives the range of each aircraft from each receiving station. By using the ranges from at least three of the receiving stations, the location of each aircraft can be determined by using multi-lateration. Since the three ranges give three distinct overlapping spheres that the aircraft must lie on, and only one of the two intersections of the three spheres is above the surface of the earth, the location of the aircraft can be determined. Once the location of each aircraft is determined by the ground station, that information will have to be transmitted to the aircraft via a data-link.

This multi-lateration system has the same advantages as the SSR system, but the drawbacks of this system are more numerous. One problem will occur because of the omni-directional interrogation. By interrogating all aircraft, instead of only those in a 2.75° sector, as SSR does, more garbling of responses will occur. The increased number of reply collisions will mean lower reliability of the system, which is not acceptable.

Yet another problem with using this type of system is the need for three or more widely spread receiving stations. The baseline between stations must be longer than the individual responses in space to help limit the collisions between responses and to allow for better resolution in the multi-lateration calculations. This means baseline distances of over three miles. Since the typical small airport is nowhere near three miles wide or long, the receiving sensors must be placed outside the airport's limits. This requires the leasing or buying of land to place these sensors and could also lead to security issues around those sensors.

Multi-lateration using Mode A/C transponder replies, though a very simplistic idea, does not seem to meet the requirements of the Smart Landing Facility. Reliability of the system cannot be ensured, especially as air traffic volume increases. The overall cost of this system also appears to be comparable to the SSR system, which was considered too expensive.

## 3.3 Traffic Alert and Collision Avoidance System

The advantages of making use of the Mode A/C transponders already aboard the majority of General Aviation aircraft leads to the examination of the possibilities of using other surveillance systems that make use of those transponders. One such system is the Traffic Alert and Collision Avoidance System. Though the TCAS system is currently only used as an airborne system, the idea of using TCAS as a ground system has been proposed and the idea has been dubbed *TCAS on a stick*.

A TCAS would have many advantages over the multi-lateration system in tracking aircraft by their transponder replies. If a system similar to TCAS III were used, the antennas needed would simply be eight monopoles in a twelve-inch, circular array. Using this array, TCAS can interrogate in 45-90° sectors. Interrogating sections of the airspace at a time helps reduce the amount of garbling received at the ground station. Garbling is when two or more replies overlap at the receiver. The ground station could also make use of the Whisper-Shout technique that TCAS uses to help reduce garbling even further.

Using a TCAS system, there are two ways that each individual aircraft can get the overall radar picture of the airspace for separation purposes. The first way is to use a data link from the ground station to the aircraft, as described in the previous systems. The second way is to have each aircraft outfitted with a TCAS unit. Each aircraft can then independently display the radar picture around itself and does not have to rely on a ground station.

The advantage of having a TCAS on each aircraft is it eliminates the need for a special data link from the ground station to each aircraft. A TCAS on each aircraft also allows the aircraft to have situational awareness of the traffic around it even when away from the Smart Landing Facility. If a data link is required, then there would have to be ground stations covering all the airways that SATS traffic would travel so that the pilots can maintain self-separation, or there would simply be no data supplied to the pilots about surrounding traffic. A disadvantage of having a TCAS unit on each aircraft is that the 1090 MHz channel will become more congested with replies than if there is only one TCAS unit on the ground.

Before TCAS can be used for surveillance at the proposed Smart Landing Facilities, there are a few issues that must be resolved. First, does a TCAS unit, using the phase difference of the replies at the different antennas of the unit, have enough bearing resolution to accurately track aircraft at the outer limits of the surveillance range of the airport? Another issue will be adapting TCAS to receive both the altitude and the identification information from each aircraft. Currently TCAS receives only altitude information from Mode A/C transponders. Lastly, the issue of traffic congestion on the 1090 MHz channel must be addressed. Can a TCAS unit track all the aircraft that will be in an airspace around a Smart Landing Facility without dropping any of the tracks? What will occur in such a system if each aircraft is also equipped with TCAS and is interrogating all other aircraft? These questions will be studied in Chapter 4.

## 3.4 Automatic Dependent Surveillance-Broadcast

Another option for surveillance around Smart Landing Facilities is to make use of the ADS-B system. Instead of using the Mode A/C transponders on aircraft, this system relies on the use of GPS positioning. The need to interrogate other aircraft is eliminated when each aircraft is able to determine its own position by using GPS, and broadcasts that information. Eliminating the need to interrogate transponders, and timing those responses, greatly simplifies the ground systems needed for surveillance around the SLF.

The ground system at SLFs that rely on ADS-B would only need an omni-direction antenna. Since each aircraft broadcasts its identification and its exact three-dimensional location every half second, the ground station needs only to listen to these broadcasts to compile a complete picture of the airspace traffic. There would be no need for a data link from the ground to the aircraft for the purposes of surveillance in this system. Each aircraft needs to have an omni-directional antenna and a receiver and it too can compile a complete picture of the airspace traffic.

Since ADS-B relies on GPS for position information, increasing the number of aircraft in an airspace will increase the congestion on the 1090 MHz channel at a much slower pace than if each aircraft has a TCAS system. ADS-B requires only one transmission per aircraft, no matter the number of receiving stations, for every other aircraft and ground station to learn its position and identity. TCAS requires one transmission by each aircraft for each individual receiving station.

Another advantage of the ADS-B system is that by broadcasting responses, the 1090 MHz channel is turned into a random access channel. In a TCAS system, garbling occurs when the difference in slant path length between two aircraft is too small. In an ADS-B system, garbling will be a random occurrence that depends only on the total number of broadcasts, not on the relative location of the aircraft.

For all the advantages that ADS-B has, there is one major disadvantage; the only current General Aviation aircraft that have ADS-B are the small number of aircraft participating in FAA evaluations of the system. This means that any aircraft that would want to use of a SLF must buy the new ADS-B system. Since there are over 250,000 aircraft in this country, complete switching to ADS-B is a very expensive proposition. Chapter 5 will investigate a cheaper alternative to a full ADS-B system that can make the use of a GPS based system for the separation of traffic around a SLF.

# Chapter 4 - Traffic Alert and Collision Avoidance System as a Ground Based Sensor

This chapter is an in-depth look at the use of the Traffic Alert and Collision Avoidance System (TCAS) in its proposed use as a ground sensor for Smart Landing Facilities (SLFs). Issues to be addressed include maximum traffic able to be supported by a “TCAS on a stick”, the complexity of the antenna needed for the TCAS ground sensor, and the ability of the system to cope with non-cooperative targets.

A Matlab simulation was designed to test different variables with the TCAS ground sensor. The design of the simulation, along with the assumptions made in the simulation, is reviewed. The data gained from the simulation is presented and discussed. Chapter 6 further discusses the results of this chapter and those results’ effect on Air Traffic issues that must be addressed for such a system to be implemented.

## 4.1 Methodology

The first step in evaluating the performance of a TCAS ground sensor is to choose a methodology to follow in that evaluation. This chapter uses a ten-step methodology that is presented by Jain that is a method of systematic performance evaluation [11]. Jain’s ten steps are:

1. State goals and define the system
2. List services and outcomes
3. Select metrics
4. List parameters
5. Select factors to study
6. Select evaluation technique

7. Select workload
8. Design experiment
9. Analyze and interpret data
10. Present results

This methodology allows for a very systematic look at the use of a TCAS ground sensor for surveillance at Smart Landing Facilities and allows for the discovery of the strengths and weaknesses of such a system.

## 4.2 System Definition and Goals

The TCAS ground sensor consists of an interrogator transmitter, an antenna, and a receiver. The system operates by transmitting an interrogation signal that consists of a number of pulses. This is the same interrogation that is used for Secondary Surveillance Radar. Aircraft carry a transponder that receives this interrogation. Once the interrogation is received, the transponder replies with a signal that either includes altitude information or identity information. Figure 4.1 depicts the Mode A/C transponder reply, which is the transponder found on the majority of GA aircraft. The F1 and F2 pulses are framing pulses that are always present. The A1 through D4 are used for encoding the identity information in the Mode A reply and the altitude information in the Mode C reply. The X pulses is not used and the SPI pulse is a special identification pulse that is added to the reply when the IDENT button is depressed on the transponder unit that is found in the cockpit of the aircraft.

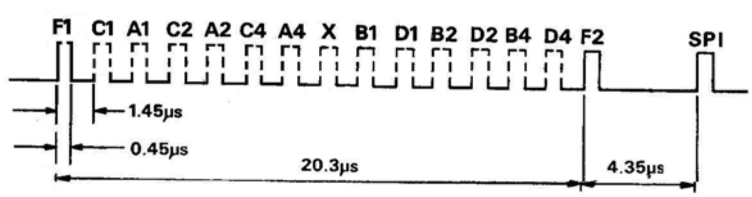


*Figure 4.1 Mode A/C Reply Signal Format [4]*

TCAS is designed to be used in conjunction with the Mode S transponder that makes use of the Mode S squitter. The Mode S transponder periodically broadcasts its identity without being interrogated. This allows the TCAS to listen for aircraft in the area without making an all call interrogation. The Mode S transponder allows for both an all-call interrogation and individual interrogation. By allowing for individual interrogation, the TCAS system can interrogate one aircraft at a time, greatly reducing the probability of a collision between two responses. When TCAS is used as a ground sensor at SLFs, the system must be able to track Mode A/C transponders since that is the type of transponder carried by the majority of General Aviation (GA) aircraft. Since the Mode A/C transponder does not allow for individual interrogation the probability of collisions at the receiver increases. The analysis throughout this chapter is based on Mode A/C responses.

For this evaluation, the whisper-shout interrogation method is not used. The whisper-shout technique is when the TCAS unit starts with a low power interrogation to receive replies from only the closest aircraft. The TCAS unit then increases the power of the interrogation to receive replies from aircraft at greater ranges. By preceding the second, greater strength interrogation by 2 μs with a pulse the strength of the previous interrogation, the closer aircraft's transponder replies are suppressed. For a more detailed explanation of this process, refer to Section 2.5.

The whisper-shout technique works best at close ranges when the path changes more quickly with small distance changes. At greater distances, the path losses differ less and the whisper-shout technique becomes much less effective. For example, the path loss difference for 30 km to 40 km is only 2.5 dB and the whisper-shout method would have no effect over these ranges.

The goal of this evaluation of TCAS as a ground sensor is to find how well the system works with only Mode A/C transponders. This evaluation is needed to determine whether, once actual Smart Land Facilities are in place, General Aviation can use those airports without the need for any additional airborne systems.

## 4.3 System Services

The TCAS as a ground system must provide surveillance of the airspace around a Smart Landing Facility. The system must not lose the track on any given aircraft for any length of time longer than what is deemed safe. For this analysis, safe is determined by the separation between aircraft and the maximum velocity at which the aircraft travel. The system must work not only in ideal situations but also in the case of non-cooperative targets. Ideally, the system would allow for Free Flight, which means that the system would allow pilots to choose their own best course to the airport and not have to fly on specific airways.

## 4.4 Metrics

The TCAS ground sensor is evaluated using two metrics. Since the system works by receiving replies from the aircraft transponders, the reception of a reply without interference allows the system to properly track aircraft. The only interference that has a major effect on the system is interference caused by other replies that overlap. This being the case, the first metric is the percentage of total replies that result in a collision between two or more replies.

Collisions between replies are not random. Collisions occur when the distance from the ground sensor to any one aircraft is within 3.1 kilometers of the distance of any other aircraft from the ground sensor within the same antenna sector. Since the collisions do not occur in a random fashion another metric is required to properly gauge the effectiveness of the TCAS ground sensor. The second metric is the maximum number of consecutive replies from one aircraft that are not received due to collisions. This metric allows calculation of maximum length of time that any one aircraft can be in the airspace and not be detected by the TCAS ground sensor.

## 4.5 Parameters

There are many parameters in the TCAS ground sensor that have a bearing on the effectiveness of the system. Most of these parameters for this evaluation have been set so that a worst-case scenario occurs. Since the TCAS ground sensor relies on specific geometry between aircraft to ensure clear reception of replies, the worst-case situation for the system is when the aircraft follow no specific flight path in the airspace. For this evaluation, aircraft will operate under the restricted Free Flight scenario, shown in Figure 4.2, where the aircraft can follow any direct path to the Arrival Point as long as those aircraft enter the airspace North of the Arrival Point. In the same fashion, departing aircraft will be able to take any flight path out of the airspace once those aircraft have reached a certain altitude. The orientation of the airport is for evaluation purposes only; not all runways are oriented North and South. The altitude ceiling for the restricted airspace depicted in Figure 4.2 is 4000 feet above the surface of the airport.

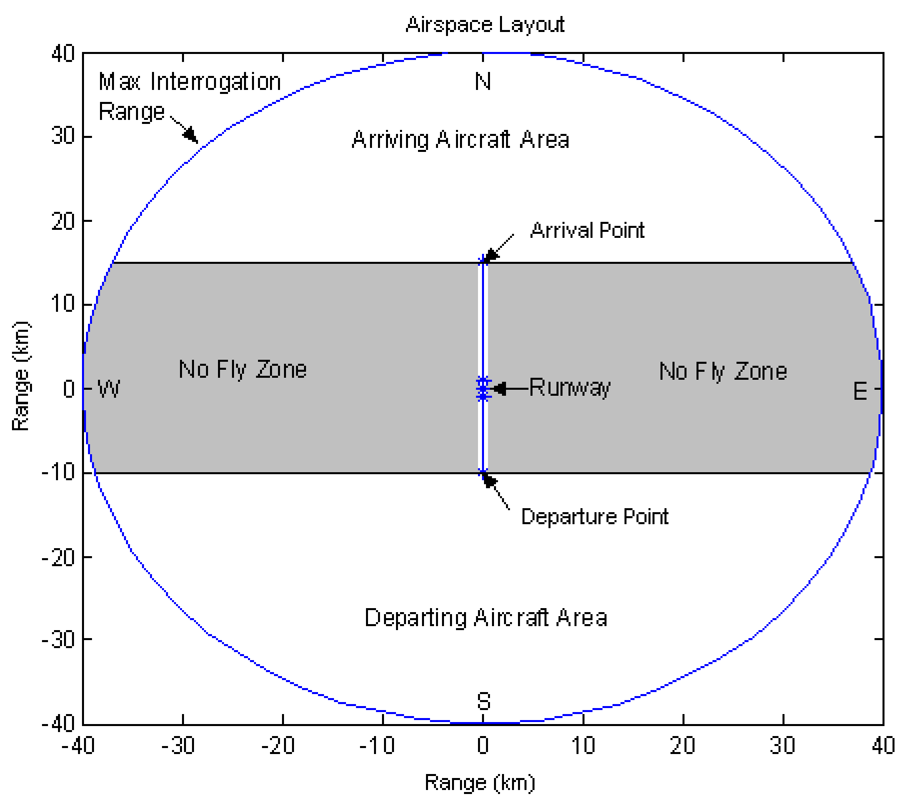


*Figure 4.2 Airspace Layout*

Another way to ensure that the geometry between aircraft is always changing is by varying the velocities of the aircraft that are in the airspace. For this evaluation, the aircraft use velocities ranging from the minimum approach airspeed for typical General Aviation aircraft, approximately 80 knots, and the maximum allowed airspeed in Class C, D, and E airspace, which is 200 knots.

The interrogation rate at which the TCAS unit operates also has an effect on the number of collisions that occur between responses. In this evaluation, an interrogation rate of 1 Hz was chosen. This is the same rate that the airborne TCAS unit uses and was chosen for that reason.

## 4.6 Factors Studied

There are three main factors in this evaluation. Those factors are (1) the number of aircraft a TCAS ground sensor can successfully track, (2) the effects of sectored antennas on the number of aircraft a TCAS ground sensor can successfully track, and (3) the effects of having the air traffic properly self-separate when on final approach and departure. Each of these three factors is examined in combination with each other in the evaluation.

The maximum number of aircraft that are envisioned to use a Smart Landing Facility per hour is 20 aircraft. This evaluation finds how successfully a number of aircraft that can be tracked by the TCAS ground sensor with a given antenna up to that maximum limit. Different antenna configurations are explored in this evaluation to minimize the cost and complexity of the ground sensor. These reasons make it necessary to find the most elementary antenna design that can maintain surveillance around the Smart Landing Facility.

The evaluation of the system is done both with traffic self-separating on final approach and departure and with totally uncooperative traffic for one overriding reason. Normal air traffic will always have to keep a certain separation distance from each other when landing and taking off. This separation is greater than 3.1km, which is the minimum range difference needed to ensure that there is no collision between replies of two aircraft. It seems that this is an assumption that can be made in the evaluation and is referred to as cooperating traffic. In the case of an aircraft not following the proper separation though, it is still necessary to maintain surveillance on that aircraft. For this reason, the worst-case scenario of all aircraft being non-cooperative and not following the separation standards is also investigated.

## 4.7 Evaluation Technique

Simulation techniques were used to investigate the use of TCAS as a ground sensor. Actual experimentation using a TCAS sensor on the ground at an airport was ruled out because of cost and time constraints. Analytical evaluation of the system was not chosen because of the complexity of the system and the fact that the TCAS ground sensor is used to track aircraft that move in a very fluid and dynamic way.

The simulation approach to evaluation was chosen so that many trials could be done while changing the factors to be studied. Simulation also enabled this initial evaluation to make assumptions about aircraft tracks and to move aircraft in close proximity to each other that could be dangerous for real aircraft. Another benefit of using the simulation is that future Air Traffic Control rules that might be applied to Smart Landing Facilities can be added to the simulation to allow for testing of the system under those new circumstances.

## 4.8 Select Workload

This simulation was designed to test three different antenna configurations on the TCAS ground sensor. The antenna configurations were: (1) one omni-directional, (2) two 180° sectors, and (3) four 90° sectors. These antenna sectors were considered to have no overlap and were oriented in relation to the airport runway to minimize collisions in replies. In Figure 4.3 the different sectors that the antenna configurations can cover are shown. The omni-directional antenna covers all four sectors. In the case of the 180° sector antennas, one antenna covers Sectors 1 and 2 and the other antenna covers Sectors 3 and 4. With the four 90° sectors, one covers Sector 1, the second antenna covers Sector 2, including the boundary with Sector 1, the third antenna covers Sector 3, including the boundary with Sector 4, and the fourth antenna covers Sector 4.

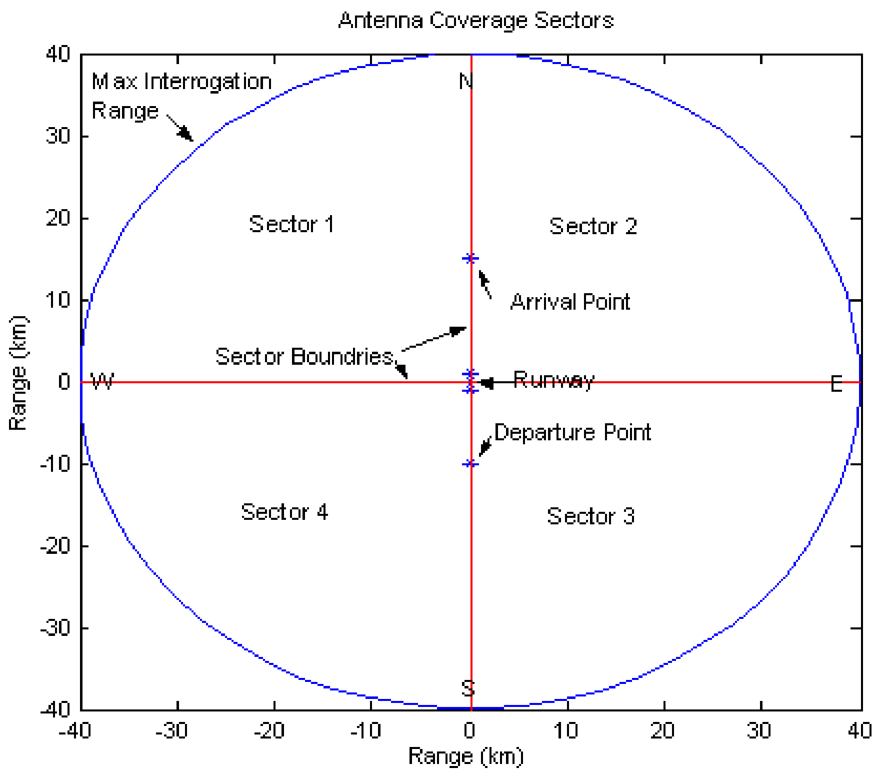


*Figure 4.3 Antenna Sectors and Layout*

The simulation was also designed for the introduction of any number of aircraft into the airspace of the course of an hour. For this evaluation, the number of aircraft entering and exiting the airspace will be limited to 1, 2, 3, 4, 5, 10, 15, and 20 aircraft per hour for the given trials. This allowed for the evaluation of the system with both low numbers of aircraft and also the maximum number of aircraft envisioned using the Smart Landing Facility.

The simulation was designed to run in simulated one-hour increments. Since the arrival and departure times along with the flight paths are generated by a random number generator, by running multiple shorter trials the seed numbers that are used in the random number generator change from simulation to simulation. This prevents the overall results from being dependent on the seed numbers.

## 4.9 Simulation Description

This simulation was designed to detect the number of collisions that would occur between responses to a TCAS ground sensor interrogations with varying traffic levels and varying sector patterns of interrogation. For detection of collisions to occur, first the location of the replying aircraft must be determined over the course of the simulation. This means that aircraft must move in a realistic manner through out the airspace. To accomplish this, aircraft were broken into two groups: arriving aircraft, and departing aircraft.

The simulation enters into the airspace, shown in Figure 4.2, the given number of arriving aircraft at the maximum range of the TCAS ground sensor, which was set at 40 kilometers, at any point north of the arrival point. The time that the aircraft first arrives in the airspace is a random time, to the nearest second, over the course of the hour. The aircraft in the simulation start to reply to interrogations once the aircraft enters the airspace. Once the arriving aircraft is in the airspace, it travels at a designated speed that is randomly chosen between the minimum of 80 knots and the maximum of 200 knots (41 and 102 meters per second) towards the arrival point. All aircraft that enter the airspace are at an altitude of approximately 4430 ft or 1350 meters mean sea level. This allows the aircraft to fly level heading to the arrival point. Once at arrival point the aircraft turn toward the runway, slow to 80 kts and follow a glide slope of approximately 3° to the runway surface. The runway surface is located at approximately 2000 ft or 610 meters mean sea level, which is the approximate altitude of the runway at Blacksburg, VA. Once the arriving aircraft are on the runway surface, it no longer replies to interrogations.

The number of departing aircraft in the simulation is set to equal the number of arriving aircraft. The departing aircraft are assigned random departure times over the course of the hour, to the nearest second. Departing aircraft are also assigned a velocity that is in the same range of velocities as those used for the arriving aircraft. Departing aircraft do not start replying to interrogations until the departure time for that aircraft. All departing aircraft fly along a steady slope of approximately 4.5° leaving the airport at the assigned velocity of the aircraft until it is at a range of 10 km from the airport, which in the simulation is referred to as the departure point. Once at the departure point, the aircraft are at an altitude of approximately 4430 ft or 1350 m mean sea level. At this point the aircraft are given a random heading of any bearing south of the departure point. The aircraft follow this new heading until out of the 40 km range of the TCAS interrogations. Once out of the 40 km airspace, the aircraft stop replying to interrogations.

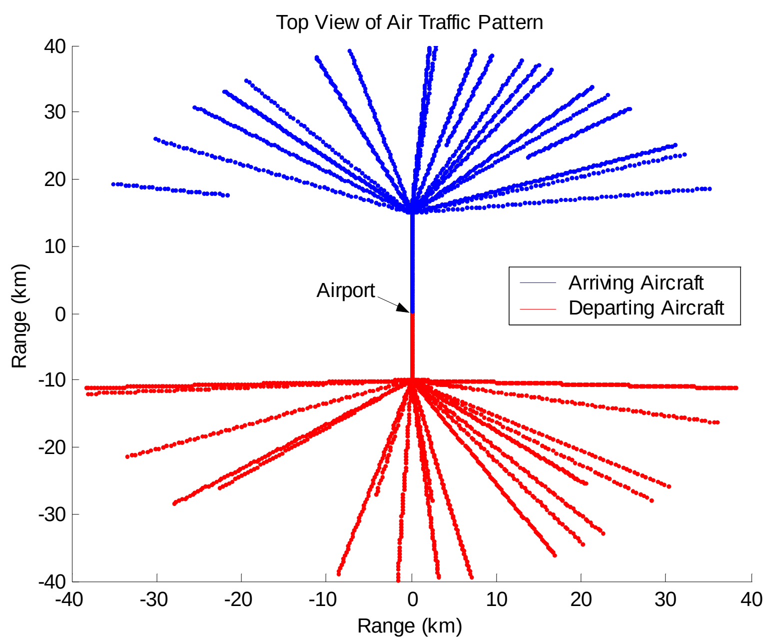


*Figure 4.4 Typical Airspace with 20 Arrivals and Departures per Hour*

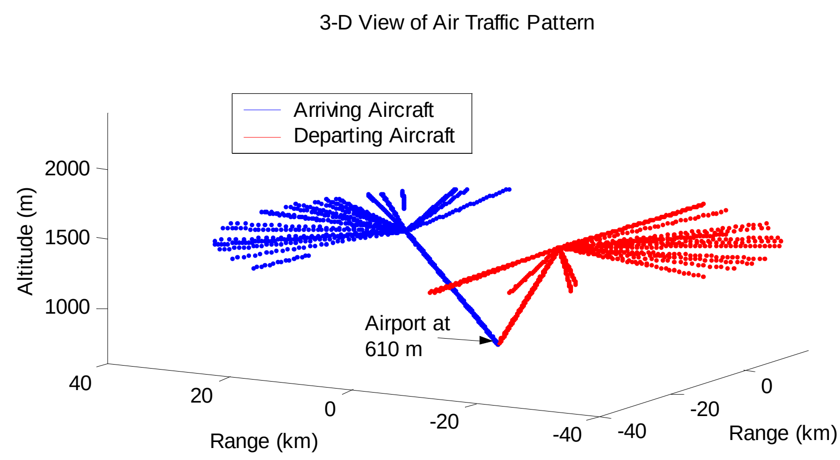


*Figure 4.5 Typical Airspace with 20 Arrivals and Departures per Hour*

In the simulation, aircraft position is updated once a second. For every update, a simulated interrogation is sent out to each aircraft. A collision between replies is determined by finding the range from the TCAS ground sensor to each aircraft. This range in compared to the ranges of all other aircraft that are within the same sector of the ground sensor. If the separation between any two aircraft is less than 3111 meters, which is half the distance occupied by the 20.75 μs transponder reply, then a collision is assumed to have occurred between those two replies. This geometry is illustrated in Figure 4.6.

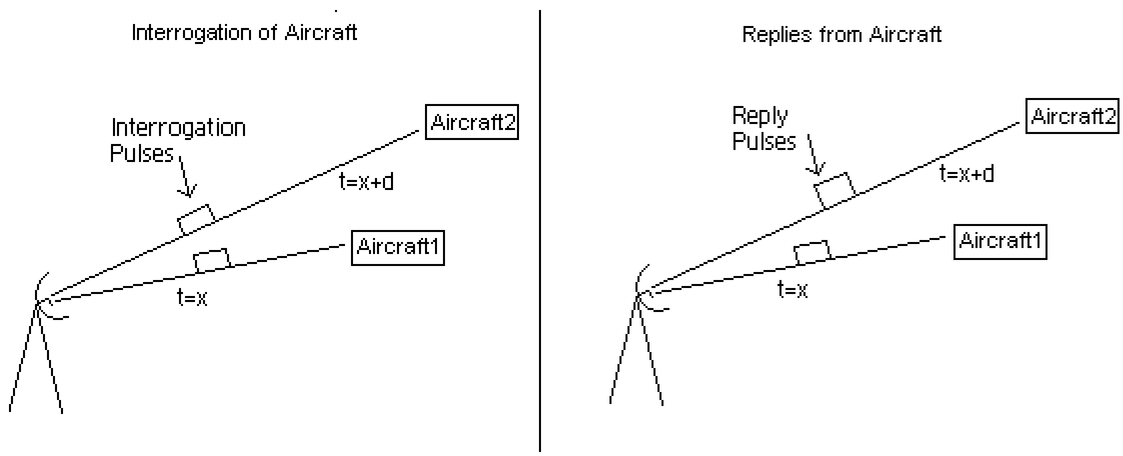


*Figure 4.6 Reply Timing Diagram*

For no collision to occur between the responses from Aircraft 1 and Aircraft 2, the entire reply from Aircraft 1 must be received before the start of the reply from Aircraft 2 is received. The interrogation pulses for both planes are transmitted at the same time. In Equation 4.1, if the interrogation takes time X to arrive at the aircraft, delay is the processing time required by the transponder, and message is the length of the reply message in time, then the end of the reply from Aircraft 1 will be received at time EndMessage1. In Equation 4.2, if the interrogation takes time X + δ to arrive at the aircraft, and delay is equal to the processing time required by the transponder, then the start of the reply from Aircraft 2 will be received by the ground sensor at time StartMessage2. For no collision to occur between these two replies, the time that the end of the reply from Aircraft 1 reaches the ground sensor, End Message1, must be earlier than the time that the start of the reply from Aircraft 2 reaches the ground sensor, StartMessage2. Solving for Equations 4.3 and 4.4, the separation between the two aircraft in time, δ, must be greater than half the message length. This means that the aircraft must be separated by 3111 m, or the distance occupied by a 10.375 μs pulse.

$$EndMessage1 = 2 \times X + delay + message \quad (4.1)$$

$$StartMessage2 = 2 \times (X + \delta) + delay \quad (4.2)$$

$$EndMessage1 < StartMessage2 \quad (4.3)$$

$$2 \times X + delay + message < 2 \times (X + \delta) + delay \quad (4.4)$$

$$\delta > message / 2 \quad (4.5)$$

The simulation was constructed in such a way that it could also simulate scenarios with different antenna configurations. There were three choices for the antenna configuration. The first was an omni-directional antenna pattern, and in this case the responses from any one aircraft could collide with responses from any other aircraft. The second antenna pattern consisted of two 180° sectors. In this case, only arriving aircraft responses could collide with other arriving aircraft responses, and similarly for departing aircraft responses. The third antenna pattern consisted of four 90° sectors. In this design, the aircraft were still separated into arriving and departing aircraft, but also into aircraft in the left and right sides of the Cartesian plot (East and West sectors in Figure 4.3).

One last option built into the simulation allows for the separation of aircraft while on final approach and while on the departure path from the airport. The first simulation design did not guarantee separation during these two parts of the flight. Instead the aircraft randomly entered the final approach and randomly departed the airport. This allowed for a worst-case scenario where none of the aircraft operations were coordinated. The second option of mandating separation on the final approach and departing path allows for the evaluation of the TCAS ground sensor where Free Flight is still occurring but the aircraft are self-separating when they reach the final approach fix and when departing the airport until they reach the departure fix.

## 4.10 Model Verification

Once the Matlab simulation was written, the model had to be tested to ensure that it was properly working. The verification was done by running the simulation with test cases where the results were already known. First, to ensure that the aircraft were moving properly in the simulation, a number of simulations were run and plotted so that the flight paths of the aircraft could be visually inspected.

Once aircraft motion was correct, the calculation of collisions had to be verified. First the omni-directional antenna was tested. By having only one aircraft arrive and one aircraft depart in the course of an hour, the possibility of collisions of responses is limited to the number of responses that can be made by two aircraft based on the speed that they are traveling. The maximum number of collisions will occur when the two aircraft are flying at the minimum velocity. As shown in Figure 4.7, the replies from the aircraft will collide when both aircraft enter the 3111 m wide ring shown. The maximum amount of collisions will occur when the two aircraft spend the maximum amount of time in the 3111 m wide ring. This will occur when the aircraft are flying at the minimum velocity, as shown in Equation 4.6. Equation 4.7 shows that each aircraft will be in the ring for 76 s. With one interrogation and reply per second, each aircraft will make 76 replies. Since the 76 replies from both aircraft collide together, the total number of collisions would be 152, as shown in Equation 4.8.

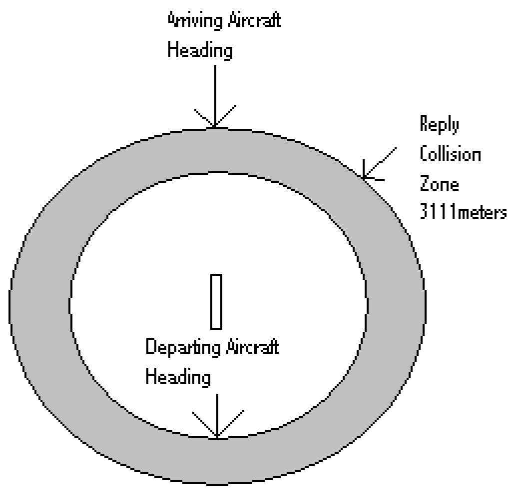


*Figure 4.7 Reply Collision Zone*

$$SlantRange \div Velocity_{Min} = CollisionTime_{Max} \tag{4.6}$$

$$3111m \div 41m/s \cong 76s \tag{4.7}$$

$$TotalCollisions = CollisionTime_{\max} \times 2 = 152 \tag{4.8}$$

The minimum number of collisions for the omni-direction antenna with one aircraft arriving and departing in the course of an hour is zero. This would occur when the arriving aircraft lands and stops making replies by the time that the departing aircraft takes off. All the tests of the omni-directional antenna fell within these limits.

The 180°-sectored antenna was tested next for proper collision calculation. Again the test case of one aircraft arriving and departing per hour was chosen. Since the antenna sectors are oriented in such a way that arriving aircraft replies cannot collide with departing aircraft replies, this trial had a minimum and maximum number of collisions of zero. The tests of the 180°-sectored antenna showed these results. Lastly the 90°-sectored antenna was tested in the same manner and those tests proved successful.

Verification of the simulation when more aircraft were entered into the system was done by comparison of the flight paths of the different aircraft. The aircraft position data, which is calculated every second, was sampled at different times throughout the simulation for each aircraft. That data was then manually inspected for collision scenarios and compared with the collision data generated by the simulation over that time interval. In all cases the simulation generated the correct results.

## 4.11 Statistical Accuracy

Once the results of the all the trials were tabulated, the results were analyzed for their statistical accuracy. Eighty trials were run for each antenna configuration, ten trials for each of the eight different numbers of aircraft that were studied. These eighty trials were repeated with both no separation guaranteed and separation guaranteed while on final approach and departure.

For each set of ten identical trials, the mean and standard deviation of those trials were calculated. Using the mean and standard deviation, a confidence interval for the population mean was obtained using the Student's t-Distribution [11]. The confidence interval is found by

$$100(1-\alpha)\% = (\bar{x} - t_{[1-\alpha/2;n-1]} s/\sqrt{n}, \bar{x} + t_{[1-\alpha/2;n-1]} s/\sqrt{n}) \qquad (4.9)$$

where $\bar{x}$ is the mean, s is the standard deviation, n is the number of trials, α is the significance level, and t represents the Student t-Distribution. The Student t-Distribution allows for the calculation of confidence intervals when not enough trials have been done to allow for the use of the Normal Distribution. The 90% confidence interval was found for all sets of data and can be found in Appendix A. All graphs showing results from this simulation will be of the mean of the trials and will not include the confidence interval.

## 4.12 Results and Analysis

This section presents the results in graphical form of the different trials of the simulation that were run and discusses the significance of those results. The first set of results shown is of the trials where there was no guaranteed separation for any portion of the flight. The second set of results is from the trials when separation on the final approach and departure are guaranteed. The third set of results shows the improvement gained by guaranteeing separation for part of the flight.

### *4.12.1 Case #1, Non-cooperative Targets*

The results in this section are from the trials run with non-cooperative targets and no guaranteed separation for any part of the flights. Figure 4.8 shows the total percentage of replies that resulted in collisions and Figure 4.9 shows the longest consecutive string of replies that resulted in collisions and thus the outage time for the system for that particular aircraft. Both graphs show the results of the trials using the three different antenna configurations for each of the different traffic levels.

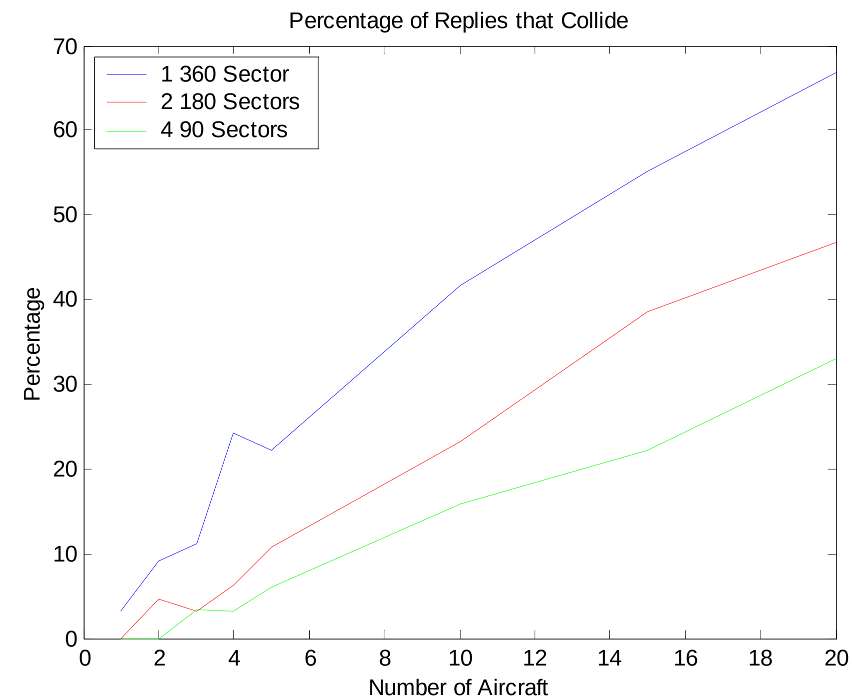


*Figure 4.8 Percentage of Replies Resulting in Collision*

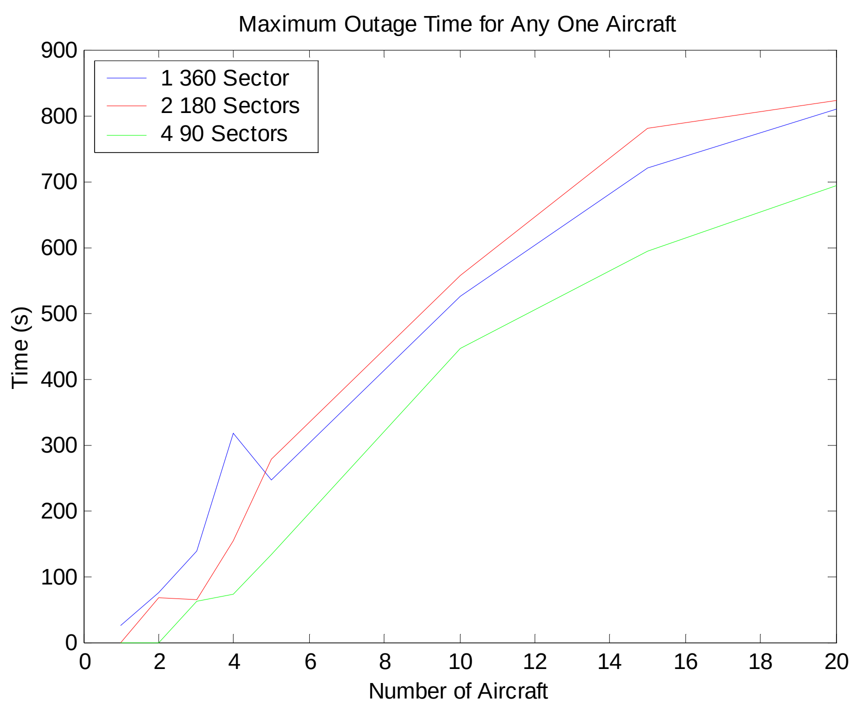


*Figure 4.9 Maximum Outage Time for Any One Aircraft*

Figure 4.8 shows that there is definite improvement in the effectiveness of the TCAS ground sensor when a four-sectored antenna is used. Even with the four-sectored antenna though, almost a third of the overall replies to the TCAS interrogations resulted in a collision when there are 20 arrivals and departures per hour. If collisions were a random occurrence, this level of collisions might be acceptable, but as Figure 4.9 shows, this is not the case. The results in Figure 4.9 show that the maximum outage time for any one aircraft in the system is at an unacceptable level. Even when using a more advanced antenna, there were aircraft in the airspace for an average of almost twelve minutes without being detected. Even at the slowest airspeeds, this means that aircraft would travel for over 18 miles between received replies.

These results show that a TCAS ground sensor cannot be employed for surveillance around a Smart Landing Facility if Free Flight is allowed in the airspace and no separation standards are enforced. Even if a more advanced antenna array were used, the TCAS ground sensor still would have the possibility of long outages if no separation standards were used.

### *4.12.2 Case #2, Separation on Final Approach and Departure*

The results in this section are from the trials run with Free Flight in the airspace, but with separation between aircraft maintained on final approach and departure. This means that all aircraft maintain proper separation between the arrival point and the runway and between the runway and departure point. Figure 4.10 shows the total percentage of replies that resulted in collisions and Figure 4.11 shows the longest consecutive string of replies that resulted in collisions and thus the outage time for the system for that particular aircraft. Both graphs show the results of the trials using the three different antenna designs for each of the different traffic levels.

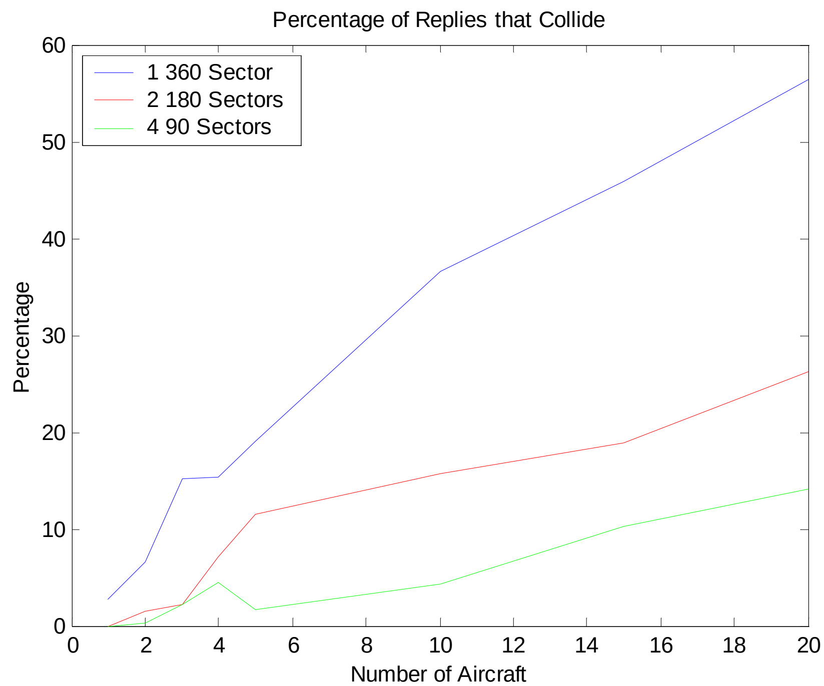


*Figure 4.10 Percentage of Replies Resulting in Collision*

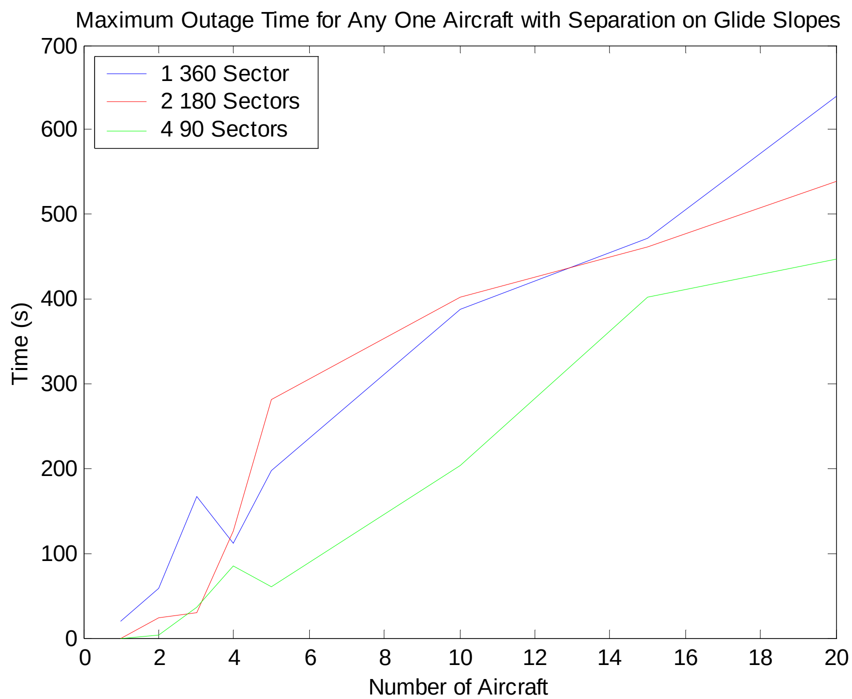


*Figure 4.11 Maximum Outage Time for Any One Aircraft*

Figure 4.10 shows that when using a four sectored antenna and when separation is ensured on the final approach and departure, only approximately 14% of replies result in collision even with 20 aircraft per hour arriving and taking off from the airport. Again, if collisions were a random occurrence, this would allow for acceptable surveillance of the airspace. Figure 4.11 though shows that even with the low percentage of collisions, there are still aircraft in the airspace for over seven minutes without a reply when there is an average of 20 aircraft arriving and departing per hour. This is still at an unacceptable level for the air surveillance needs of the Smart Landing Facility.

### *4.12.3 Comparison of Results*

In this section the data from the two previous cases are compared. The graphs in Figures 412 and 4.13 show the data from both cases when the four-sectored antenna is used.

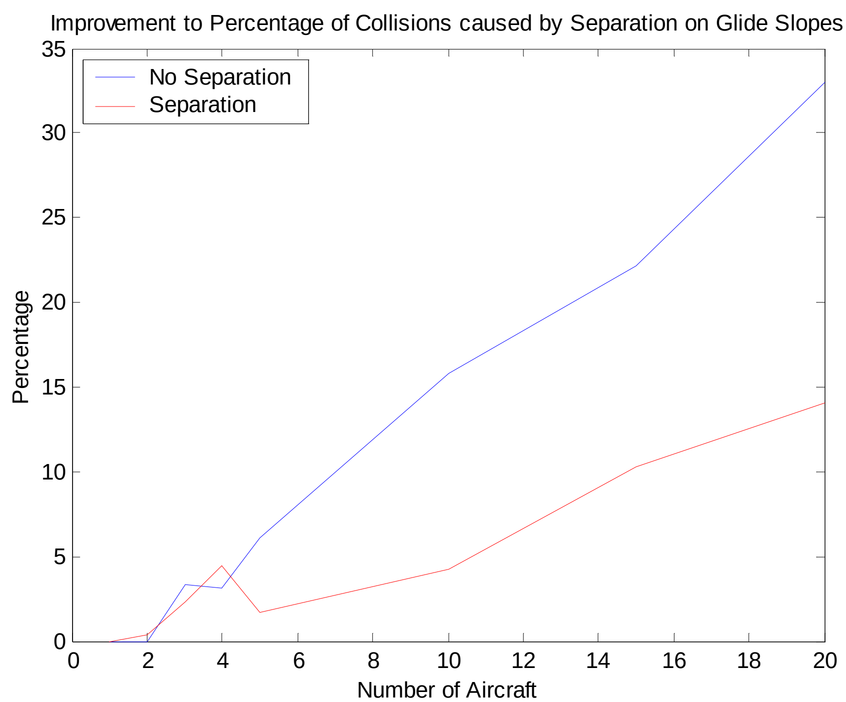


*Figure 4.12 Improvement in Percentage of Collisions*

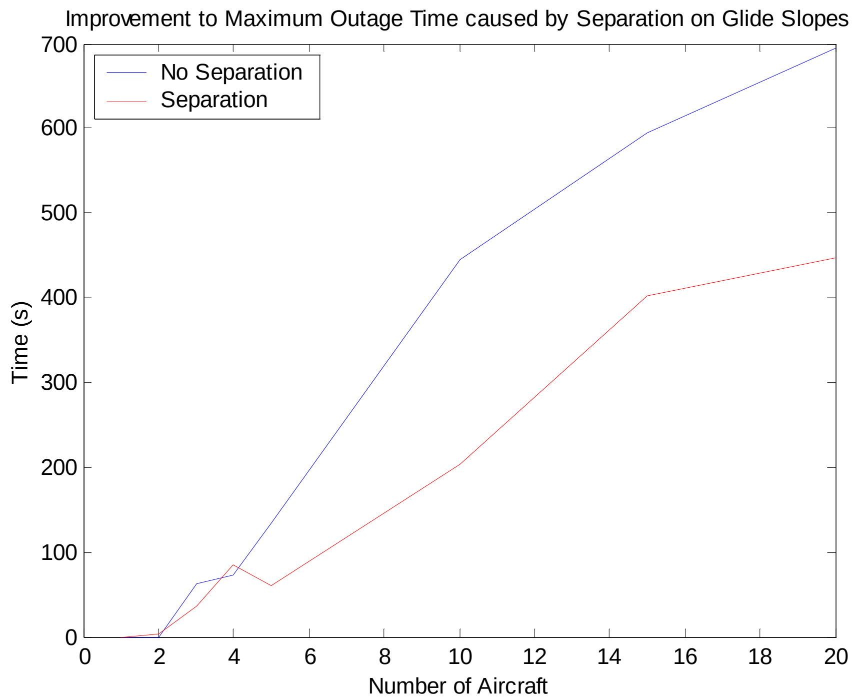


*Figure 4.13 Improvement in Maximum Outage Time for Any One Aircraft*

By comparing the results of the two different cases, a drastic improvement in the percentage of total collisions can be seen when separation is maintained on the final approach and on departure. By ensuring separation on final approach and on departure, the number of collisions was cut in half. The same improvement is not found in the maximum outage time. By ensuring separation during parts of the flight, the aircraft now cannot travel all the way to the runway surface without being detected, but aircraft still can travel to the approach point and away from the departure point without being detected. Table 4.1 shows the maximum outage time for some of the trials with the higher aircraft arrival and departure numbers. The number of aircraft indicated is equal to the number of arrivals and to the number of departures.

| Maximum Outage Time (s) for Any One Aircraft | | | | |
|---|---|---|---|---|
| **# of Aircraft** | 5 | 10 | 15 | 20 |
| **No Separation/Non-Cooperative** | | | | |
| **1 360 degree Sector** | 686 | 768 | 841 | 944 |
| **2 180 degree Sectors** | 513 | 734 | 1073 | 1029 |
| **4 90 degree Sectors** | 413 | 793 | 766 | 930 |
| **Separation/Cooperative** | | | | |
| **1 360 degree Sector** | 359 | 631 | 626 | 775 |
| **2 180 degree Sectors** | 591 | 651 | 768 | 802 |
| **4 90 degree Sectors** | 244 | 459 | 657 | 690 |

*Table 4.1 Maximum Outage Times*

## 4.13 Conclusions

The simulation of the use of a TCAS ground sensor at a Smart Landing Facility proved to be an effective evaluation technique. The simulation showed that uncooperative targets cannot be tracked with any confidence by the TCAS ground sensor. This means that Free Flight operations in an airspace that uses a TCAS ground sensor with the traffic loads foreseen for Smart Landing Facilities are impossible if adequate surveillance is to be maintained. If a TCAS ground sensor is used for surveillance at a Smart Landing Facility, specific antenna designs for the TCAS unit will be needed, and defined flight paths into and out of the airspace must be used. These issues will be discussed in more detail in Chapter 6.

# Chapter 5 - Position and Identification Reporting Beacon

The Automatic Dependant Surveillance-Broadcast (ADS-B) system is a Global Positioning System (GPS) based surveillance system. An ADS-B unit, which includes a GPS receiver and a Mode S transponder, is placed on each airplane. The GPS receiver allows each aircraft to find its own precise location and the Mode S transponder, making use of its squitter function, allows the aircraft to broadcast that location information and the aircraft's identification information. This system, if used solely in the 1090 MHz channel, or any channel, can be a random access system which has major advantages over the current timing based interrogate and reply system.

The lone drawback of the ADS-B system is that it is not widely used today. Practically no General Aviation (GA) aircraft is equipped with an ADS-B system or even a Mode S transponder. In order for the Small Aircraft Transportation System (SATS) to make use of ADS-B, all aircraft that use the Smart Landing Facilities (SLFs) in SATS would have to be visible to all other SATS aircraft. This means that all aircraft would have to broadcast their location and identity. The cost of equipping all current GA aircraft with ADS-B is prohibitive.

An alternative solution to providing all GA aircraft with ADS-B but still making use of GPS for surveillance is to design a low cost beacon that contains a GPS receiver. This beacon can then broadcast the aircraft's identity and position in the same format as ADS-B so that the aircraft would be visible to all ADS-B type receivers. This Position and Identification Reporting Beacon (PIRB) could also be used for airport ground surveillance and could be used as a back-up system in today's current Air Traffic Control (ATC) system.

## 5.1 PIRB Uses

The main use of the PIRB is to allow a low cost upgrade of GA aircraft so that they can make use of SATS Smart Landing Facilities. This is not the only possible use of such a beacon though. The PIRB could also solve the problem of airport ground surveillance, and in light of terrorist attacks of September 11, 2001, could be used to track aircraft in United States airspace.

### *5.1.1 Smart Landing Facility Surveillance*

The PIRB would allow for the use of a single ground monitoring station for aircraft surveillance around Smart Landing Facilities. Since the PIRB produces the same response as an ADS-B transponder, a receiving station for ADS-B messages will also receive the PIRB messages. This also means that aircraft equipped with ADS-B systems that have cockpit displays of the surrounding traffic will be able to see older non-ADS-B aircraft as long as they have an operating beacon. This helps to partially solve the problem of mixed equipage aircraft using the same airport.

Having the PIRB message exactly like the ADS-B message could cause a problem though. If an ADS-B equipped aircraft can detect the PIRB equipped aircraft, the pilot might assume that the PIRB equipped aircraft can detect his or her aircraft as well. Since the PIRB is designed only to allow other aircraft and ground stations to be able to detect it, there must be a way for ADS-B equipped aircraft to differentiate between other ADS-B aircraft and those possessing only a PIRB. One recommendation is to set aside certain known aircraft identification numbers for use in the PIRB. In this manner, when that identification code is received, all the receiving stations will know immediately that the aircraft only has a PIRB and the proper air traffic control procedures can be followed.

### 5.1.2 Airport Ground Surveillance

Another use for the PIRB, besides air surveillance, is ground surveillance at airports. Currently, one of the unsolved problems facing the SATS program is how to maintain clear runways and how to communicate to the pilots wishing to land whether traffic is present on or near the runway. The PIRB could be the solution to this problem as well.

Since the main idea behind the PIRB is to design a low cost alternative to ADS-B, it stands to reason that if the PIRB were mass produced and the cost became low enough, the PIRB could also be placed on ground vehicles at airports. By allocating certain identification numbers to ground vehicles, an aircraft equipped with an ADS-B type receiving unit would be able to receive the messages from the PIRBs on the ground vehicles and identify them as such. This would allow arriving aircraft to determine if the runway is clear while on approach, before the aircraft actually breaks out of the clouds or is committed to a landing.

One of the goals of the SATS program is to lower the landing minimums to allow for the use of small aircraft for a greater portion of the time by reducing the effect that weather has on flights. One of the major concerns with lower landing minimums is whether GA pilots will feel comfortable on an approach with a low minimum descent altitude and poor visibility because of a low ceiling height and fog. By allowing pilots to "see" the ground traffic at the airport by way of PIRBs, the hope is to increase safety of landings that occur under the new lower landing minimums and also to increase the pilot's comfort on such an approach.

### 5.1.3 Back-up Surveillance for All Aircraft

Yet another application for the PIRB is to use the beacons as a back up in the current Air Traffic Control (ATC) system. By using an unused frequency band, such as the 5.1 GHz channel set aside for the Microwave Landing System (MLS), which never came into widespread use, the PIRBs could be placed on all aircraft to act as a second independent system for tracking aircraft. By using a separate frequency for the PIRBs, the transmissions of the beacons would not interfere with the current Secondary Surveillance Radar (SSR) system that makes use of the 1030 and 1090 MHz channels.

After the terrorist attacks of September 11, 2001, the need for an alternate way to track aircraft became apparent. Since SSR depends on a working transponder on the aircraft for it to be visible to air traffic control, the terrorists were able to disable the system by just turning the transponders off from inside the cockpit. This rendered the airplanes invisible to SSR and left primary radar as the only way to track the airplanes. FAA Air Traffic Control (ATC) primary radars are also the air defense system: coverage is complete above a certain altitude, depending on location. The September 11 aircraft were tracked by primary radar.

A PIRB placed on each aircraft, with the beacon designed so that it cannot be turned off from inside the aircraft, would solve the problem of pilots or terrorist being able to disable the surveillance system. One solution is to have the PIRB built into the anti-collision light found near or on the tail of aircraft. By locating the PIRB in the anti-collision light on top of the aircraft, it would be more difficult to manually disable the beacon while the aircraft is on the ground.

For the PIRB to be effective for surveillance it needs to be able to turn itself on when the aircraft is in motion. Since the PIRB would be able to turn on without any manual input from the pilot, the PIRB would always broadcast its position and identification message when the aircraft is in motion. One way to accomplish this is to have the system continuously monitor the GPS data that it receives and to activate its broadcasts when the GPS location information differs. A second way to activate the system is to have a pressure switch in the circuitry that is exposed to the outside air. Since a pressure change develops across the surface of an aircraft while in motion, this pressure change could also activate the system.

The power supply for the PIRB is another concern that must be addressed if the system is to be tamper-proof. Since cutting off the power supply to the beacon would render the system inoperable, a battery backup is needed. To make the system more reliable, the system can operate on both the aircraft’s power supply and from rechargeable battery backup. The system will remain operational if the aircraft’s power

is turned off or disconnected from the beacon and at the same time will not require the replacement of the batteries as often as if the system ran solely on disposable batteries.
A rechargeable battery is also needed if the GPS receiver remains on continuously to monitor aircraft movement.

## 5.2 Random Access Channel

The main reason that the Global Positioning System is used in ADS-B and in the PIRB design is because it allows surveillance information to be transmitted via a random access channel. Interrogations are not required in a broadcast system, so there is no need for precisely timed replies. This means that each aircraft can broadcast its location at a certain repetition rate with no coordination between the different aircraft or the ground stations.

A typical random access system relies on the overall channel loading being kept relatively low, below 18% total capacity. This minimizes collisions between user transmissions on the channel. Normally, the receiving unit in a random access channel will send acknowledgements (ACK) if the information is received properly and it will send a negative acknowledgement (NAK) if the information is not received because of a collision in the channel. This is called Automatic Repeat Request (ARQ). In the case of the PIRB, no acknowledgements will be needed. Since the information will be sent with a certain repetition frequency, if a collision occurs on the channel, the receiving station will just wait until the next message is sent. Since the new message contains the entire positioning and identification information and does not rely on the previous message, there is no reason to have the old message resent. The next section examines the maximum capacity for the randomized transmission time PIRB system as described above.

### *5.2.1 Message Arrival Statistics*

To determine to the probability of a collision between two responses, the probability distribution function for a transmission must be defined. In this analysis we will assume that a PIRB transmission occurs every half second. The start time for the transmission is uniformly distributed over that half second, which means that the transmission is equally likely to start at any time during the half-second interval. This means that the probability distribution function is

$$f(t) = 2 \ \Big|_{x}^{x+0.5} \qquad (5.1)$$

where x is the start of the half second interval. Assuming x = 0 for the first transmission and x = 0.5 for the start of the second transmission, the probability distribution function f(t) is shown in Figure 5.1.

The following probability study of the PIRB transmissions does not take into account any time delay that would be caused by different ranges of the PIRBs from the ground station. This time delay would add to the random nature of the transmission probability distribution function and thus does not need to be included in the probability study of the collisions of responses. This means that that location of the aircraft does not matter when calculating the probability of collisions in this type of uncoordinated random access system.

The probability of collision between two responses can now be defined using the probability distribution function. Given that there are two aircraft in the airspace, both equipped with PIRBs. The first PIRB starts transmission at time $t = t_1$. A collision occurs at the ground station if the second PIRB transmits its message at anytime before the first PIRB finishes transmitting. Collisions also occur if the second PIRB is transmitting when the first PIRB starts. This means that a collision occurs if the second PIRB starts transmitting anytime over the interval

$$t_1-\tau < t < t_1+\tau \qquad (5.2)$$

where $\tau$ is the message length that is being transmitted by both PIRBs. The probability distribution function for the second PIRB is g(t). As Figure 5.1 shows, the probability distribution g(t) is equal to that of f(t) but is shifted on the time axis. This shift is caused by the random start times of the different PIRBs. The random start time does not affect the system in anyway though. Figure 5.1 shows the probability distribution function, f(t), for the start of the first transmission, which is over the interval t = 0 : 0.5. The pdf of the second transmission from the same PIRB is shown over the interval t = 0.5 : 1. The function g(t) represents the pdfs of the transmissions of a second PIRB that was activated 0.25 seconds before the first PIRB. The function h(t) is the pdfs for the transmissions of a third PIRB. As shown in Figure 5.1, the probability of the start of a transmission over any given interval, no matter the start time, is always the same.

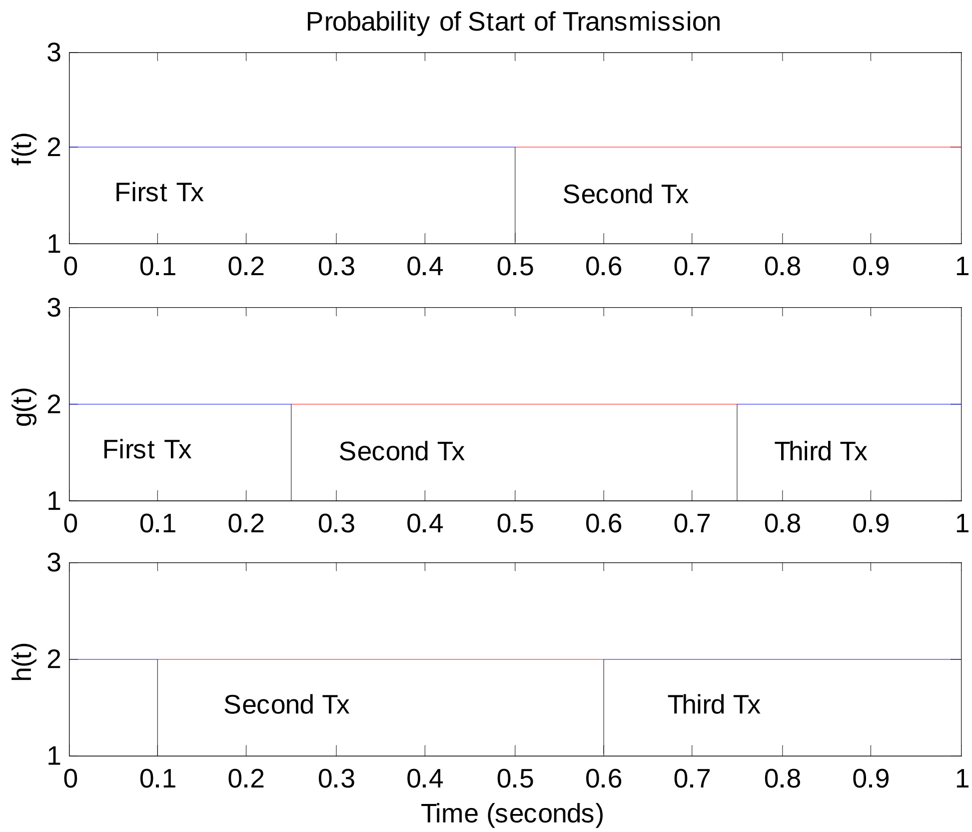


*Figure 5.1 Broadcast Timing Diagram*

This being the case, the probability of the second PIRB transmitting during the time interval given in Equation 5.2 is

$$P\{t_1 - \tau < t < t_1 + \tau\} = \int_{t_1-\tau}^{t_1+\tau} 2dt \quad (5.3)$$

Given that the message length τ = 120μs, then the probability that the second PIRB transmits during the time interval that would cause a collision with the first PIRB is

$$P\{t_1 - \tau < t < t_1 + \tau\} = 0.00048 = P_{collision} \tag{5.4}$$

or 0.048% probability of collision.

In the same manner, a third PIRB can be added to the scenario with the probability distribution function h(t). Using the same logic and mathematics, the probability that the third PIRB message will collide with that of the first PIRB is also equal to 0.048%. Now the probability of a collision for the message of the first PIRB is equal to the probability of collision with the second PIRB message plus the probability of collision with the third PIRB message or 0.096%. Generalizing this idea for any number of aircraft, the total probability of collision for the transmission of the first PIRB is

$$P_{total} = NumberofPIRB \times P_{collision} \tag{5.5}$$

Now that the probability of the a collision occurring to any one transmission is defined, the probability that two consecutive replies from one PIRB are not received due to collisions must be found. Since the probability of the first transmission colliding is $P_{total}$, the probability of the second transmission colliding is also $P_{total}$. This means that the probability of two consecutive responses having collisions is

$$P_{Consecutive} = P_{total}{}^{2} \tag{5.6}$$

The probability of single collisions and consecutive collisions verses the number of aircraft in an airspace is shown in Figure 5.2. For this system, the desired performance requirement is to achieve a reliability of 99.999%. If a system is defined as reliable if at least one response every two seconds, or one out of four responses arriving with no collisions at the ground station then

$$1 - [NumberofPIRB \times P_{collision}]^4 = .99999 \tag{5.7}$$

$$Numberof\,PIRB \times P_{collision} = \sqrt[4]{.00001} \tag{5.8}$$

$$NumberofPIRB = 117 \tag{5.9}$$

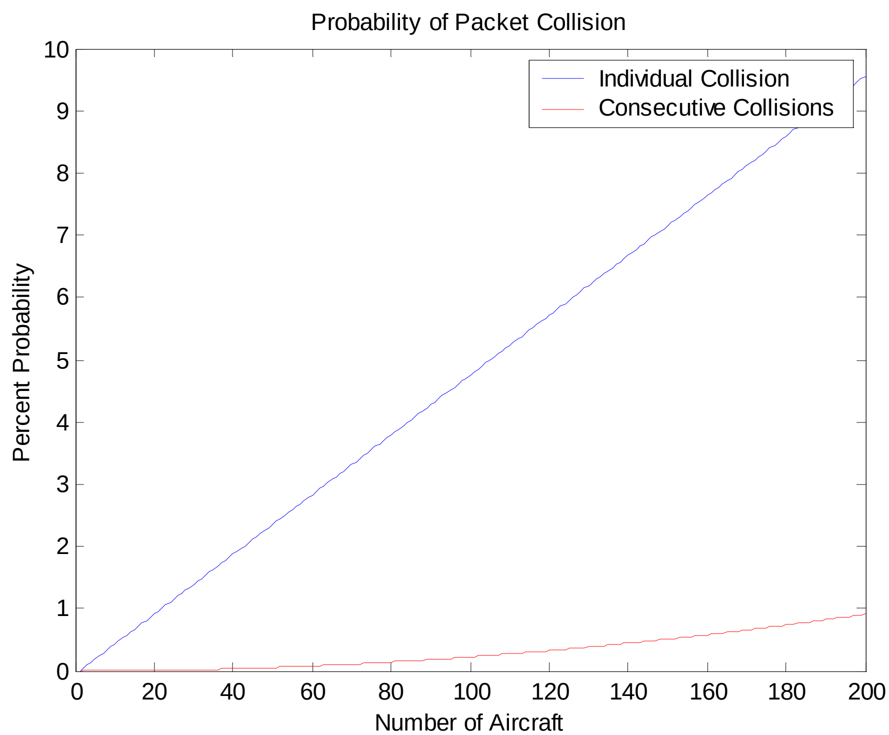


*Figure 5.2 Probability of Packet Collision*

This means that 117 different aircraft equipped with PIRBs can be in the same airspace at the same time and be tracked by an omni-directional receiving ground station with at least one message being received every two seconds from each aircraft with 99.999% reliability.

This level of reliability ensures that the aircraft can travel only a limited distance without a position report being received at the ground sensor. Even if an aircraft is flying at a speed of 650 km/hr, the aircraft will only move a maximum of 360 meters before a successful PIRB broadcast is received. Considering that the current Secondary Surveillance Radar uses a rotating antenna that only sweeps the entire sky once every 6-12 seconds, the PIRB system that receives at least one reply every two seconds allows for better tracking.

The evaluation used for ground station reception above can be applied to any airborne receiving station that makes use of the PIRB. The ADS-B system an airborne system in use today that contains a receiver capable of using the PIRB transmissions.

## 5.3 Position and Identification Reporting Beacon Design

The design of the PIRB depends greatly on the way in which the beacon will be used. Different RF frequencies are needed if the beacon is used solely for surveillance around Smart Landing Facilities and if the beacon is used throughout United States airspace. Despite the fact that the system may or may not be used for airspace surveillance, the PIRB can be designed to be placed in the anti-collision light found on aircraft and the system can be made tamper-proof. By making the PIRB very compact and by placing it in an anti-collision light, which is required on all aircraft, the PIRM is easier to install on existing aircraft and on ground vehicles for use around SLFs.

### *5.3.1 Beacon Frequency*

There are two possible frequencies for the PIRB: 1090 MHz and 5.1 GHz. Both of these frequencies are currently allocated for Aviation use and have advantages. The 1090 MHz frequency band has better propagation properties and can be used to make the PIRB compatible with current Air Traffic Control Systems. The 5.1 GHz band eliminates interference caused by and to existing systems, since this band is currently allocated to microwave landing systems and is little used.

By placing the PIRB at 1090 MHz, Secondary Surveillance Radar could make use of the PIRB transmissions. A software upgrade that can decode the PIRB broadcast allows a current SSR to decode and make use of the information that is being sent by the PIRB. A drawback of the PIRB using the 1090 MHz band is the interference caused by the PIRB broadcast with the replies needed for SSR. PIRB transmissions can overlap with SSR transponder responses and cause those responses to be discarded. In the same fashion, the effectiveness of the PIRB system is also reduced by collisions between SSR responses and PIRB transmissions.

Typical SSR operates with the following parameters:

| | |
|---|---|
| Azimuth Beamwidth | 2.75° |
| PRF | 120 Hz |
| RPM | 6-12 |
| Reply length | 20.75 μs |
| Range | 250 nm |
| Average Replies per Aircraft | 4 per second |

*Table 5.1 Secondary Surveillance Radar Parameters*

Using this information, it is easy to visualize an area like New York, Washington, or Los Angeles where a single aircraft would be in range of anywhere from one to 12 different SSRs. Assuming that there are 300 aircraft in the area and just five SSRs interrogating each aircraft, on average 12.5% of the 1090 MHz channel is used by transponders responding to SSRs.

By placing the PIRB at 1090 MHz, TCAS will still be able to make use of the transmissions of the PIRB. Since TCAS already uses 1090 MHz, a software change can be made that allows TCAS to see airplanes that are equipped with only the PIRB. Eventually, when all aircraft are equipped with PIRBs, TCAS will no longer be needed. A much lower cost system that listens passively to the frequency being used by the PIRB can perform all the functions of TCAS but without the need for interrogations.

TCAS and PIRB effectiveness will be reduced by placing both systems in the same frequency band, as described in the previous discussion of Secondary Radar. Collisions will occur between the transmissions of both systems. A typical TCAS interrogator operates with the following parameters:

| | |
|---|---|
| Interrogation Rate | 1 second |
| Reply Length | 20.75 μs |
| Maximum Range | 20 miles |

*Table 5.2 TCAS Parameters*

Using this information, and assuming that all aircraft are equipped with TCAS, as is the case around major airports that cater only to passenger aircraft, we can calculate the percentage of the 1090 MHz channel occupied by TCAS transmissions. Since the maximum range for TCAS is 20 nautical miles, only a few, possibly around twenty, aircraft will respond to any one aircraft's interrogation. Again using 300 aircraft in the area, each interrogating once per second with twenty different responses to each, the system uses 12.7% of the 1090 MHz channel.

Using the 1090 MHz frequency band for the PIRB allows for easier integration of the PIRB into the current ATC system. Secondary Radars and TCAS could be modified to recognize the PIRB transmissions and make use of the information. The problem of overuse of the 1090 MHz frequency band still exists though. Following the above examples, just with Secondary Radar and TCAS using the 1090 MHz band, over 24% of the channel is already occupied. Adding another system to the same frequency band that makes use of random access may not work since so much of the channel is already in use.

The advantages of using the 1090 MHz channel over higher frequency bands leads to the search for any other frequencies close to 1090 MHz can be used for this new system. Figures 5.3 and 5.4 show an example of the spread of transponder frequencies aboard aircraft. This data was collected by testing a random sample of transponders in both GA and commercial aircraft [4]. In studying Figures 5.3 and 5.4, it becomes obvious that the current transponders do not have highly accurate frequency control and vary somewhat in RF frequency. The system could use a frequency like 1087 MHz where less than 5% of both commercial and GA aircraft transponders typically operate and, by making the receiver narrowband, approximately 2.5 MHz, it would incur much less channel loss due to the current systems than previously calculated. The fact remains, though, that Secondary Radar and TCAS system receivers have an 8 MHz bandwidth. This means placing our system anywhere from 1086 to 1094 MHz will cause interference in those systems, which will likely not be allowed by the FAA since those systems must remain operational for years to come. If the FCC could reallocate two megahertz around 1085 or 1095 MHz, this system could be placed there and would still make use of the better propagation properties of this lower frequency.

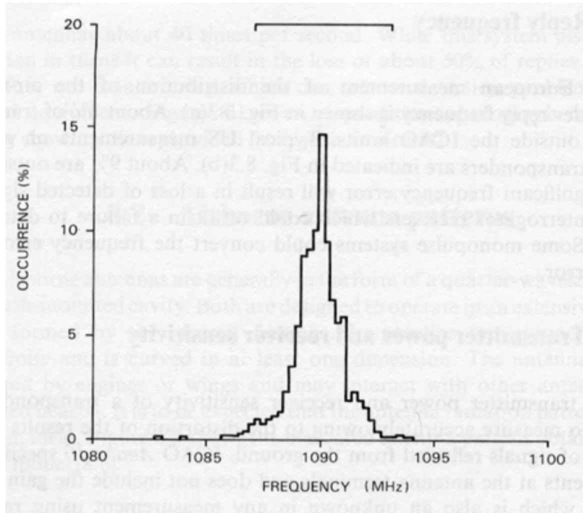


*Figure 5.3 Commercial Aircraft Transponder Frequency Distribution [4]*

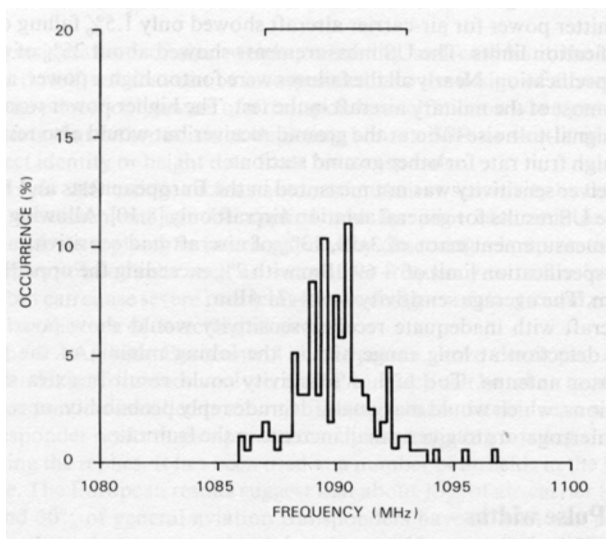


*Figure 5.4 General Aviation Aircraft Transponder Frequency Distribution [4]*

### 5.3.2 Message Format

Each message from the PIRB contains four pieces of information: aircraft or vehicle identification number, longitude, latitude, and altitude. These four pieces of information allow the precise location of the aircraft in space and provide a unique identifier for that aircraft. With this information being sent every half-second, the receiving station can extrapolate from multiple messages the aircraft's heading, and speed.

The proposed message format for the PIRB is identical to the Mode S transponder reply (Figure 5.5). This format is used so that the PIRB message is compatible with the ADS-B message. This is necessary if the system is designed to be used at 1090 MHz. If the system is designed for use at a different frequency, such as 5.1 GHz, then using the same message format as the Mode S transponder in ADS-B allows for the use of the ADS-B system at this new frequency as well.

First the Mode S reply message contains four ASK bits that are spaced in a unique way such that no two overlapping Mode A/C responses could generate them. These four bits are known as the Mode S preamble. Following these preamble bits is a block of either 56 or 112 data pulses, depending on the reply that is requested. The data pulses are sent in ASK format with Manchester encoding so that each data pulse lasts 1.0 μs but each pulse is constructed of two 0.5 μs pulses, one high and one low. This helps make the signal very resistant to noise interference and reduces the number of replies needed for Mode S to operate safely [4].

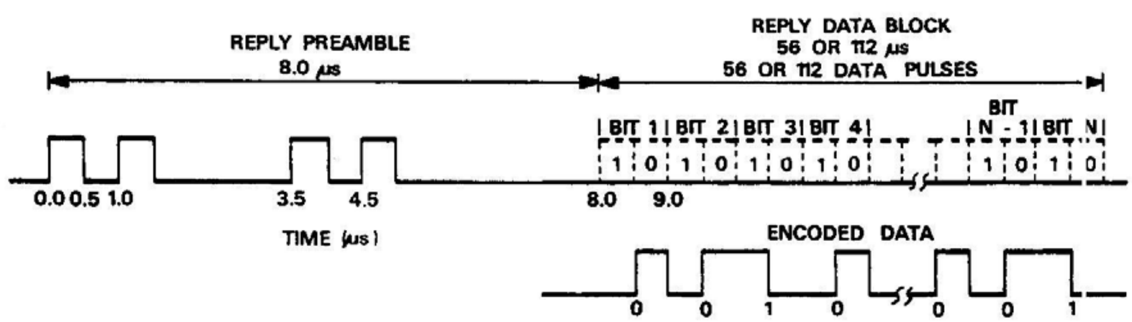


*Figure 5.5 Mode S Format Reply [4]*

For the PIRB message format, the long Mode S reply, containing 112 data pulses, is used. The 112 data pulses contain the latitude, longitude, altitude, and an identification number of the beacon. The latitude information contains 30 bits, which allows latitude position to be reported with a resolution of one meter. The longitude information contains 31 bits, which allows longitude position to be reported with a resolution of one meter. The altitude information contains 15 bits, which allows for altitude to be reported with a resolution of one meter. Lastly, 24 bits are reserved for an identification number that allows for over 16 million different identification numbers. The remaining 12 bits in the response could be used for error checking in the message. Including the Mode S preamble, the total message lasts for 120 μs.

### *5.3.3 Global Positioning System Receiver*

GPS is a Department of Defense system that uses satellites to trilaterate position. The DoD has shared with the public the use of part of the GPS system and it is now used in commercial navigation devices. Since the proliferation of hand-held GPS receivers began, the cost of GPS receivers has dropped dramatically. A low-cost GPS receiver that makes use of the Wide Area Augmentation System (WAAS) is needed to ensure the accuracy levels of 1-5 meters required by the PIRB. This level of accuracy is especially needed if the PIRB is placed on ground vehicles because of the smaller dimensions of the runway and airport area as compared to the airspace surrounding the SLF.

The basis of the GPS system is a constellation of at least 24 satellites. These satellites broadcast timing information that allows a GPS receiver to calculate its range from a GPS satellite by measuring the time delay from the time the signal is sent until the time it is received. Four satellite signals are needed by the receiver to calculate latitude, longitude, altitude, and precise timing.

GPS satellites broadcast two signals, the C/A code, and the P code. The C/A code is the course acquisition code and is transmitted on the L1 frequency, at 1574.2 MHz. The P code is the precise code and is modulated on both the L1 frequency and the L2 frequency, which is 1227.60 MHz [12]. Only the C/A code has been released by the Department of Defense for use by civilians. Only the military uses the P code, which allows for much more accurate positing. Only being able to use the C/A code limits the accuracy of the position measurement.

To further enhance GPS accuracy, WAAS was developed. This system, developed by the FAA, is based on a network of approximately 25 ground reference stations, two master control stations, and two geosynchronous satellites. The two master stations, located on either coast, collect data from the 25 reference stations and create a series of GPS correction messages. These GPS correction messages also contain geographic location information so that the correction information is location specific. This correction accounts for GPS satellite orbit and clock drift plus signal delays caused by the atmosphere and ionosphere. The corrected differential messages are then broadcast through one of two geostationary satellites, or satellites with a fixed position over the equator. The information is compatible with the basic GPS signal structure, which means any WAAS-enabled GPS receiver can read the signal. The WAAS improves the accuracy, integrity, and availability of the basic GPS signals to approximately two meters in the US, Northern Mexico, and Southern Canada [12].

Typical GPS receivers that can be used in the PIRB are the Motorola GT Plus Oncore and the Garmin GPS GPS25-LVC. Both of these receivers use the C/A code, which is the L1, 1575.42 MHz signal, that is broadcast by GPS satellites for commercial use and also are WAAS-enabled receivers. Both receivers also operate from a 5V supply and draw 100-120 mA. These receivers also come with a built-in microprocessor that can be programmed to output the desired bit stream needed for the PIRB.

### *5.3.4 System Block Diagram*

The block diagram in Figure 5.6 shows the overall design of the PIRB with a transmit carrier frequency of 1090 MHz. The following discussion describes the block diagram starting at the upper left-hand corner and follows the layout of the design.

First, the system is designed to receive the C/A codes from the GPS satellites on the L1 frequency via the receive antenna. The C/A codes are then fed into the GPS receiver. The GPS receiver uses that information to calculate the position of the aircraft. The position information is then sent into a microprocessor. An embedded identification number for the aircraft is also fed into the microprocessor. The microprocessor then assembles that information into the message format that is described in section 5.3.2.

Once the data is in the message format, it is then modulated into the ASK signal at an intermediate carrier frequency. Once at the IF, the signal is then passed through a filter that limits the bandwidth of the signal to 2.5 MHz. Since the message format is in Manchester encoded ASK with a data rate of 1Mbps, a signal bandwidth of 2MHz is required. The filter is a Raised Root Cosine filter with a roll-off factor of 0.25, which gives an output signal occupied bandwidth of 2.5MHz.

The signal is then amplified at the IF to increase signal strength and then passed through a bandpass filter to limit the noise. The signal is up-converted to 1090 MHz, which is the transmit frequency in this design. The signal is passed through another bandpass filter to eliminate the unwanted sideband generated in the up-converter. Next, the signal is amplified again by a variable gain amplifier to set the transmit power to 1 W. The signal is then passed through another filter and then the signal is transmitted via the transmit antenna.

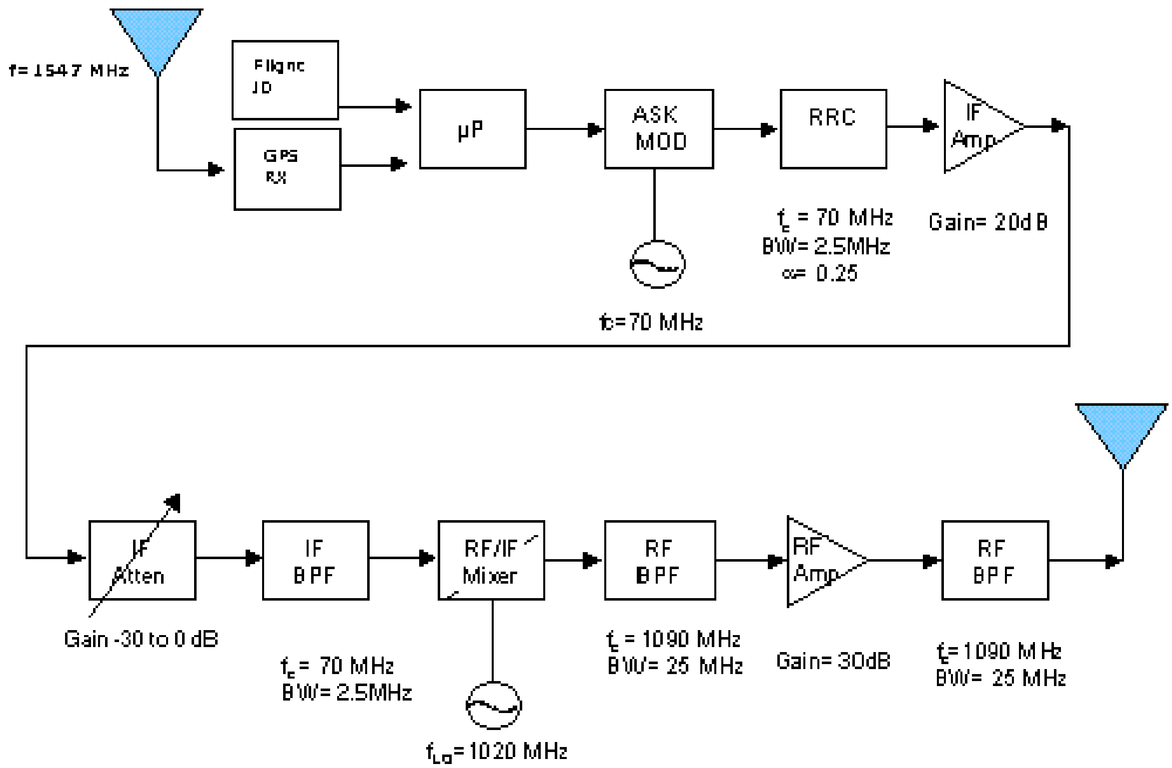


*Figure 5.6 Block Diagram for the PIRB at 1090 MHz*

### 5.3.5 Housing and Antenna Design

Since the PIRB is designed to be inside the anti-collision light found on GA aircraft, some special design considerations have to be made. The GPS receiver, microprocessor, the beacon transmitter, and the batteries are all in the base of the anti-collision light. The receiving antenna for the GPS receiver is placed on the top of the anti-collision light so that it will have an unobstructed view upwards. A microstrip patch antenna is used for GPS reception, as this antenna can provide the needed gain for the GPS receiver, and occupies approximately 5.25 $cm^2$.

The transmit antenna for the PIRB can be placed around the base of the anti-collision light. The requirements for the transmit antenna are that it has complete 360° coverage in azimuth and has a wide beamwidth in the vertical direction. These restrictions are made so that the transmit pattern is not dependent on the orientation of the aircraft. The transmit antenna is not required to have any gain in the case of operation in the 1090 MHz frequency band. Four monopoles placed every 90° around the base of the structure can provide the complete azimuth coverage needed and will also provide the large vertical beamwidth. The antenna can also be implemented as a series of deposited metal lines on the glass of the light dome. Figure 5.7 shows the placement of all the parts of the PIRB in the anti-collision light.

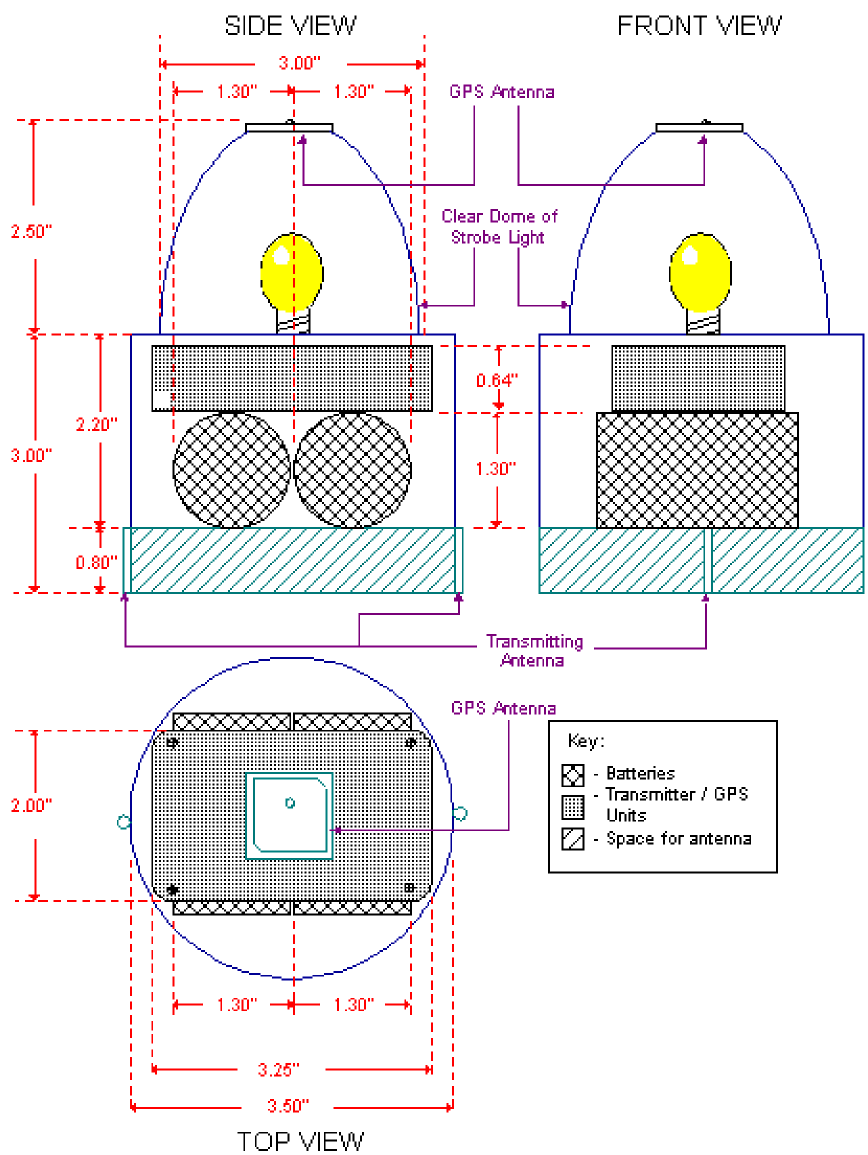


*Figure 5.7 PIRB Housing Diagram*

### *5.3.6 Power Supply*

Two power supply sources are utilized in the beacons. One source is self-sufficient, which does not rely on the aircraft for power, and should be able to last for approximately 10-15 hrs. The second uses the power from the aircraft electrical system, and in the event of a power failure, needs to revert to the self-sufficient power supply.

The power supply on the PRIB unit located on each aircraft will need to supply power to the GPS unit and the beacon transmitter. It is assumed that these units will need to be operated for 15 hrs and have a conversion efficiency ($\eta$) of 25%. The following are the calculations of the required power supply capacity © for each unit, and the total capacity needed. From the specifications given, the GPS receiver, which includes the microprocessor, draws a constant 120 mA at 5 V (i.e. 100% duty cycle) and is the major concern in terms of power consumption.

$$C_{GPS\,Unit} = \frac{i \times t}{\eta} = \frac{120mA \times 15hrs}{0.25} = 7200\ mAh \tag{5.10}$$

The transmitter is required to transmit 1 W for a total of 240 $\mu s$ each second (corresponding to a duty-cycle of less than 0.5%), and will also use the 5 V power supply. The average power required by this unit will be 5 mW, and the required current is therefore 1 mA.

$$C_{txUnit} = \frac{1mA \times 15hrs}{0.25} = 60mAh \tag{5.11}$$

This means that for this system to be self-sufficient for power for 15 hours without changing batteries or recharging the system, the batteries must have the following capacity:

$$C_{total} = C_{GPSUnit} + C_{txUnit} \tag{5.12}$$

$$C_{total} = 7200 + 60 \tag{5.13}$$

$$C_{total} = 7260mAh \tag{5.14}$$

Looking for a commercial, off the shelf solution to this battery problem, many possible solutions are available. One such battery is a NiCad D cell battery, which can store 5000 mAH and has a voltage of 1.2 volts. Four of the D cell batteries are needed for this application. This means that in the PIRB the NiCad cells will last for 10 hrs. This cell also has the added feature of being able to run under direct trickle charge conditions, which allows for the battery to be constantly charging when not in use.

However due to size restrictions, it was determined that a maximum of two size D cells could be placed in the beacon. In order to attain the desired voltage at least 4 D-cells will be required. This means that either the voltage requirement or the size constraint will have to be relaxed. Another option would be to use a specially designed cell made for the

PIRB. If the PIRB is mass-produced and placed on all aircraft, having a battery designed solely for this system will not add dramatically to the cost.

### *5.3.7 Link Budget and Propagation*

To solve for the link budget of the PIRB, certain system parameters are first chosen. The maximum transmit power of 1 W is used because of the power limitations of the battery power supply. The transmit antenna needs to have omni-directional coverage and needs to be low-cost. For these reasons a zero dB gain antenna is used. The receive antenna at the ground station also needs to be omni-direction, so again a zero dB gain antenna is used. The system must also work at a range of at least 40 km to ensure coverage in the airspace around the Smart Landing Facilities. The signal bandwidth of 2.5 MHz is also specified in the message format and block diagram of the system. With these parameters as starting points, the link budget for the system is solved for the system using 1090 MHz as the carrier frequency.

First the path loss is solved for using the equation

$$L_p = \left(\frac{4\pi R}{\lambda}\right)^2 \qquad (5.15)$$

where R is the range of 40 km and $\lambda$ is 0.275m, which is the wavelength of the carrier. This gives a path loss of 125.2dB. Next the received signal power is calculated using

$$P_r = P_t + G_t + G_r - L_p - L_{atmos} - L_{misc} \qquad (5.16)$$

with all values in dB form. $P_t$ is the transmit power of 1 W or 0 dBW . $G_t$ is the transmit antenna gain of 0 dB. $G_r$ is the receive antenna gain of 0 dB. $L_{atmos}$ is the atmospheric loss and a very conservative value, for this frequency, of 0.5 dB is used. $L_{misc}$ is the miscellaneous losses present in the system and the value of 0.5 dB is used. Solving this equation gives a received power of –126.2dBW.

The next step in the link budget is to calculate the noise level present in the receiver so that the carrier to noise ratio can be found. The equation

$$N = kTB \qquad (5.17)$$

is used.  N is the noise power in watts.  Boltzman's constant of –228.6 dBW/K/Hz is k.  T is the receiver noise temperature in degrees Kelvin.  300K or 24.8 dBK is used in the calculation.  B is the receiver bandwidth in Hz, which is 2.5MHz or 64.0 dBHz.  Solving this equation for N gives a noise power of –139.8 dBW.  Subtracting the noise power from the received signal power gives a carrier to noise ratio of 13.6 dB.

| | |
|---|---|
| Transmit Power | 0dBW |
| Transmit Antenna Gain | 0dB |
| Receive Antenna Gain | 0dB |
| Path Loss | 125.2dB |
| Atmospheric Loss | 0.5dB |
| Misc Loss | 0.5dB |
| Signal Power | -126.2dBW |
| Noise Calculations | |
| Boltzman's Constant | -228.6dBW/K/Hz |
| Bandwidth | 64.0dBHz |
| Noise Temperature | 24.8dBK |
| Noise Power | -139.8dBW |
| C/N Ratio | 13.6dB |

*Table 5.3 1090 MHz PIRB Link Budget*

As the link budget shows, the C/N is 13.6 dB.  For an ASK signal, a C/N of 13.5 dB is needed to ensure a bit error rate of $10^{-6}$ [13].  Since the signal is Manchester encoded though, a C/N of only 10.5 dB is needed for the same bit error rate since each bit is essentially sent twice.  This leaves a link margin of 3.1 dB.

One major difference between using 1090 MHz and 5.1 GHz in the design is the additional path losses incurred at the high frequencies.  If 5.1GHz were used, an additional 13.3 dB of path loss would occur and the C/N ratio would be too low for detection.  Taking into account the link margin already available, an extra 10.2 dB of gain is needed to ensure detection of the PIRB at 40 Km.  Some extra gain, possibly as much as 3 dB, can be provided by a more advanced receive antenna.  By having the antenna gain directed only towards the horizon, the antenna would have greater gain towards the locations where aircraft are the farthest from the receiver.  Less gain would need to be directed directly above the receiver since the aircraft are much closer to the receiver at that point.  A possible solution to find 7.2 dB more gain would be to increase the output power of the transmitter.  Increasing the transmit power of the PIRB to 5.5W would give an extra 7.5 dB of gain but would require more power from the power supply.  Another solution is to increase the gain of the receiving antenna even more than described above. This could be done by using a sectored antenna instead of the omni-directional antenna. A combination of the two solutions could also be used if the system is to be used at 5.1 GHz.

Another difficulty in using 5.1 GHz instead of 1090 MHz is the increased attenuation due to rain.  Its attenuation is primarily due to wave scattering by the raindrops, which have a large relative permittivity ($\varepsilon_r$ = 81). Figure 5.8 shows the predicted attenuation per km for an exponential drop-size distribution [14].

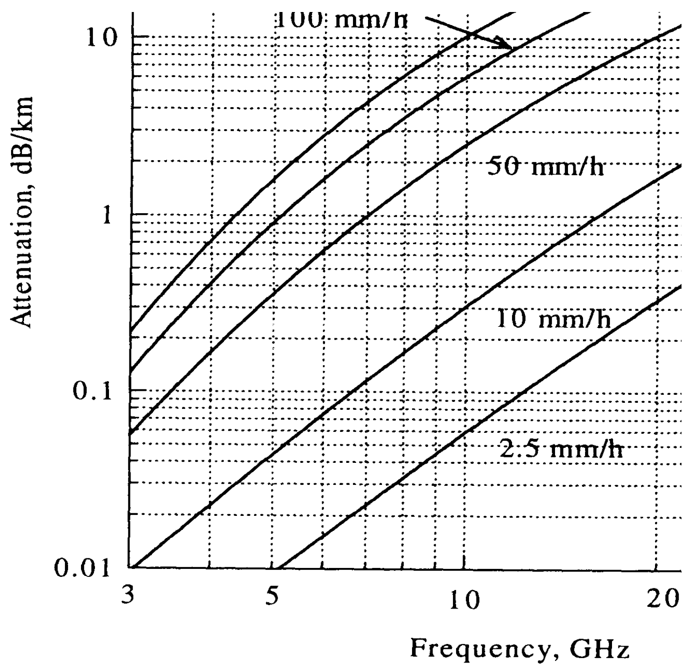


*Figure 5.8 Rain Attenuation at Different Frequencies [14]*

According to Figure 5.8, rain attenuation at 5 GHz will vary between 0.01 dB/km for a rainfall rate of 2.5 mm/h up to 2 dB/km for a rainfall of 150 mm/h.  Fortunately, high rainfalls of 150 mm/h are not very common in the US as they usually occur for short periods of the year (0.001% of time), and over short distances, as depicted in Figures 5.9

and 5.10 [14]. Moreover, usually heavy rain affects only a limited portion of the microwave link.

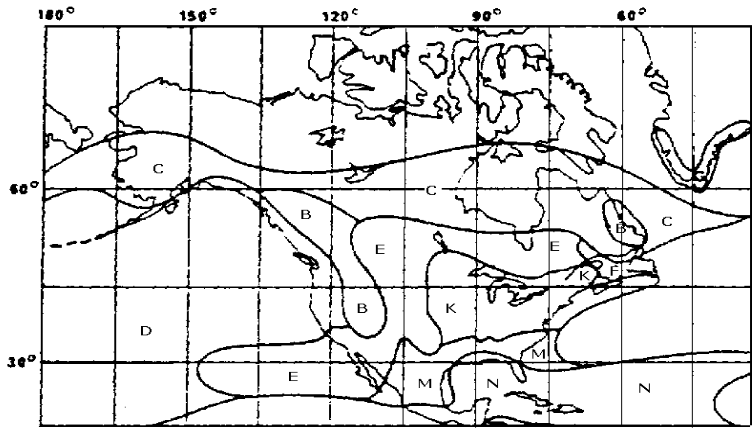


*Figure 5.9 Climate Zones of the United States [14]*

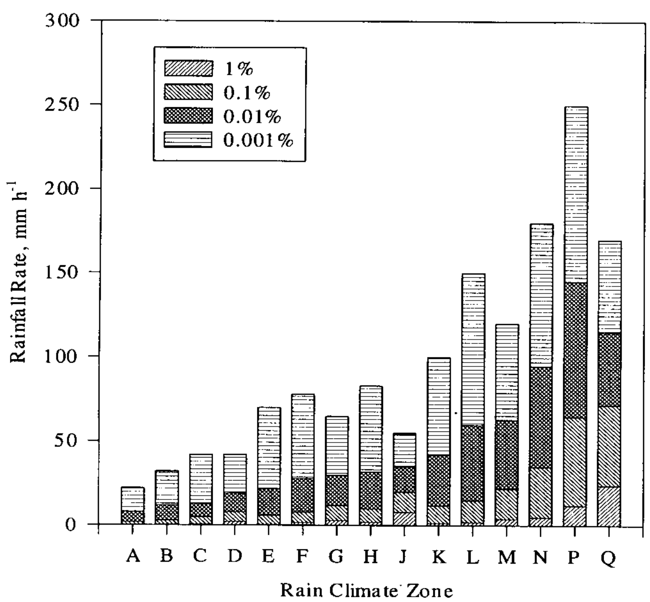


*Figure 5.10 Rainfall Rates for each Climate Zone [14]*

According to Figures 5.9 and 5.10, the maximum rainfall rate is recorded in the south and southeast regions (zones K and M), with a maximum rainfall rate of 130 mm/h occurring 0.001% of the time (around 5 minutes/year) and causing an attenuation of

1dB/km at 5 GHz. On average, a rate rainfall of 50 mm/h occurs 0.01% of the time (52 minutes/year) and causes 0.1 dB/km.

Taking into account the effects of rain attenuation 5.1 GHz, if this frequency is used for the PIRB, extra power or gain will need to be added to ensure that the beacons can still operate under most rain conditions. The very heavy rain, greater than 50 mm/h, does not need to be taken into account because of its rarity and the fact that aircraft avoid such severe weather.

## 5.4 Summary

A Position and Identification Reporting Beacon is a low cost alternative to the ADS-B system. The PIRB can be placed in the anti-collision light on aircraft and by making use of GPS, can broadcast the aircraft's location. By broadcasting randomly at a rate of 2 Hz, up to 117 PIRBs can be in an airspace with a 40 km radius with each aircraft's broadcast being received at least once every two seconds with 99.999% reliability.

There are many different uses for the PIRB in SLF surveillance and in air surveillance in general. The PIRB system can be used on older GA aircraft to make them visible to ADS-B equipped aircraft. The PIRB system can also be used on ground vehicles to allow ADS-B equipped aircraft to avoid runway obstacles. Another possible use of the PIRB system is as a back-up system to Secondary Surveillance Radar in the current Air Traffic Control system.

# Chapter 6 - Air Traffic Control at Smart Landing Facilities

In the Small Aircraft Transportation System (SATS), it is envisioned that pilots of these advanced aircraft will be able to receive traffic information for all the aircraft that are around it. This data will be displayed in the cockpit and allow the pilot to self-separate from all the other traffic. For this to become a reality, the SATS aircraft must not only be able to track other SATS aircraft, but any aircraft that it might share airspace with. SATS aircraft and non-SATS aircraft will share airspace with each other at the Smart Landing Facilities (SLFs).

The Air Traffic Control (ATC) issues that arise for the Smart Landing Facilities are directly linked to the type of ground sensor that is chosen for surveillance at SLFs. To ensure that surveillance can be maintained around SLFs certain ATC rules must be implemented, depending on the surveillance system used. The type of surveillance chosen also has an effect on the ATC needed for SATS aircraft while transiting between SLFs. The Traffic Alert and Collision Avoidance System (TCAS) as a ground sensor and the Automated Dependant Surveillance-Broadcast (ADS-B) system in conjunction with the Position and Identification Report Beacon (PIRB) system, and the PIRB system alone are explored in this chapter with respect to those systems effects on ATC.

This chapter is not intended to present any ATC rules or regulations that should be implemented. Instead this chapter is used to present the ATC issues that must be addressed when a surveillance system for the SLFs is chosen. The TCAS ground sensor, the ADS-B/PIRB system, the PIRB ground sensor system, and a combination of the two systems are explored with respect to ATC issues when used for surveillance in the SLFs and when used for enroute surveillance. Each option is also examined for additional ATC concerns that arise from allowing mixed equipage aircraft to use the SLFs.

## 6.1 TCAS Ground Sensor

Using the Traffic Alert and Collision Avoidance System as a ground sensor at SLFs has the advantage that practically all aircraft have a Mode A/C transponder and thus are compatible with the system. The TCAS ground sensor is also known as "TCAS on a Stick." The system works by having the TCAS ground sensor interrogate the transponders of aircraft in the airspace around it. The system then times the delay in responses to determine range and uses the phase difference between different fixed antenna elements to determine bearing. For further discussion on the operation of TCAS, the TCAS ground sensor, or the analysis of the system refer to Chapters 2 - 4.

The evaluation in Chapter 4 showed that this system is not capable of tracking the needed number of aircraft when the aircraft do not maintain proper separation. To use TCAS as a ground sensor at SLFs, certain ATC rules are needed to ensure safe use of SLFs. Using TCAS as a ground sensor also has implications for surveillance during enroute flying.

### *6.1.1 SLF Surveillance*

The evaluation of the TCAS ground sensor in Chapter 4 identified the need for specific ATC rules to allow continuous surveillance of all aircraft at SLFs. The Matlab simulation that was run for the Chapter 4 evaluation operated under the assumption that the aircraft were not maintaining any specific separation. The simulation showed that the TCAS ground sensor could not adequately track the aircraft under those conditions. For the TCAS ground sensor to be able to track all aircraft in the airspace, a separation standard of at least 3.1 km, or approximately two miles, must be maintained. To ensure that a two-mile separation between aircraft is always maintained, a larger separation should be used. For this discussion, a four-mile separation standard between aircraft is assumed.

One possible solution to the surveillance problems with the TCAS ground sensor is to have positive ATC control over the aircraft before they are allowed to enter the SLF airspace. For this argument, assume that there is only one allowed path into the SLF airspace. All aircraft that wished to land at the SLF would be directed to a holding point outside the SLF airspace. The ATC controller then could separate the aircraft and allow only one aircraft to enter the airspace at a time, ensuring a four-mile separation, just as an air traffic controller in the current ATC system.

If the aircraft are properly separated when entering the airspace, the TCAS ground sensor can continuously track those aircraft. The proposed data link from the ground sensor to an aircraft allows the pilot of the aircraft to track the aircraft in front of him or her and maintain the required 4-mile separation the entire way to the runway.

Separation of departing aircraft must also be maintained for the TCAS ground sensor to have continuous surveillance. Assuming the TCAS ground sensor antenna can separate arriving and departing aircraft by using sectored antennas, there would be no need for coordination between arriving and departing aircraft beyond sharing the runway. Again assume that there is only one allowed departure path out of the SLF. The departing aircraft could use a timing scheme to ensure the 4-mile separation that is needed. If each pilot waits approximately five minutes after the previous aircraft has departed before taking off, the separation standard can be maintained. Once airborne, the pilot receives the traffic information from the data link and maintains separation from the leading aircraft until out of the SLF airspace.

The above descriptions of how a TCAS ground sensor could be used at a SLF and maintain continuous surveillance are very simplified examples. Using an antenna with more discrete sectors would allow for more than one entry and exit path from the SLF airspace, but the more complex the entry and exit patterns, the larger the workload on the ATC controllers to ensure proper separation as the aircraft enter the airspace.

The TCAS ground sensor has three major drawbacks when used as described in this section. First the system will increase the workload placed on ATC controllers. This may not be acceptable to the Federal Aviation Administration. Secondly, surveillance at the SLF may be disrupted by over-flying commercial aircraft. Since all commercial aircraft are equipped with TCAS, an over-flying aircraft, which is above the controlled airspace of the SLF, could still elicit responses from the aircraft in the SLF airspace and cause collisions in replies. Before the TCAS ground sensor can be used, the effects of over-flying commercial aircraft will have to be researched further.

The third major drawback of the TCAS ground sensor is that it relies on cooperative targets. A lost student pilot could wander into the SLF airspace unknowingly and disrupt the separation pattern causing collisions in the replies. A pilot could also intentional defeat the surveillance at the SLF by purposefully flying too close to other aircraft. VFR traffic flying legally below an overcast are not required to carry transponders. SATS traffic using an instrument approach would not necessarily be aware of the VFR traffic, although this is no different from the current situation with conventional approach procedures into untowered airports. However, with the increased IFR traffic capacity, the problem is compounded and safety further compromised

### 6.1.2 Enroute Surveillance

Using the TCAS ground sensor at SLFs does not address the problem of the separation of SATS aircraft while away from the SLF. Since the TCAS ground sensor uses a data link to relay traffic information to the aircraft when in the SLF, when the aircraft are out of the SLF airspace, no traffic information is available to the aircraft. Separation of the aircraft must also be maintained while away from the SLF though, to ensure the safety of the aircraft.

Since all the aircraft are equipped with Mode A/C transponders, one way to ensure separation is to follow existing ATC procedures and operate under Instrument Flight Rules (IFR). Under these conditions, the SATS aircraft would have to follow existing flight paths, the same as commercial aircraft, so that positive ATC control could be maintained. Along these flight paths, there are Secondary Surveillance Radars (SSRs) that track IFR traffic. ATC controllers use the SSRs to track the aircraft and give verbal directions to the pilots. The SATS aircraft could operate at a flight level not currently used, such as 10,000-12,000 feet, and thus be vertically separated from the commercial aircraft as well as the General Aviation (GA) aircraft while in the flight paths. The drawback of such a plan is that there will be an increased workload on ATC controllers as the number of SATS aircraft increase. These altitudes are also an issue with unpressurized aircraft. Long periods about 10,000 ft make the use of oxygen advisable, although it is not required below 12,500 ft.

Another way to maintain enroute separation between SATS aircraft is to install data links that can transmit traffic information to the SATS aircraft at the current enroute (SSR) sites. The SATS aircraft must follow existing flight routes, but now the traffic information acquired by the SSR about the SATS aircraft can be transmitted via the data link back to the aircraft. The aircraft can then maintain proper separation while in the flight paths and cause no increased workload for the ATC controllers.

One possible problem exists with the two enroute separation ideas discussed above. Both systems rely on the existing enroute SSRs operating correctly with the SATS traffic. Before either of these ideas could be implemented, a study of the impact of SATS aircraft on enroute SSRs must be done.

### *6.1.3 Mixed Equipage Aircraft*

Another ATC issue that arises for SLFs, is the use of the SLFs by non-SATS aircraft. Since the TCAS ground sensor relies on regular Mode A/C transponders to track aircraft, even non-SATS aircraft will be visible to the TCAS ground Sensor. This means that the SATS aircraft will still be able to track the non-SATS aircraft via the traffic data link. Under Visual Flight Conditions (VMC), the non-SATS aircraft are able to maintain visual separation from the SATS aircraft in the airspace.

Under Instrument Meteorological Conditions (IMC), the ATC controller that separates the inbound traffic could leave a large separation between the leading SATS aircraft and the non-SATS aircraft. This gap would have to be large enough to ensure that the non-SATS aircraft could not close within the 4-mile separation of the leading SATS aircraft before both land. The SATS aircraft following the non-SATS aircraft could maintain the normal 4-mile separation upon entering the SLF airspace since the non-SATS aircraft is visible to the TCAS ground sensor and thus visible to the SATS traffic via the data uplink.

## 6.2 ADS-B/PIRB System

The use of the ADS-B and PIRB systems allows much greater freedom of motion for the SATS aircraft than the TCAS ground sensor allowed while maintaining continuous surveillance. ADS-B is a GPS based position system. The ADS-B GPS receiver calculates its own position using GPS and broadcasts that information. The system is also equipped with a receiver for receiving the transmission of other similarly equipped aircraft and displaying that information to the pilot. For further discussion of ADS-B, refer to Chapter 2-3. The PIRB is a low-cost alternative to ADS-B. The PIRB also uses GPS to determine its location and broadcasts that information. The PIRB does not have any receiving capabilities. For further discussion of the PIRB refer to Chapters 3 & 5.

For the discussion in this section, it is assumed SATS aircraft are equipped with the ADS-B system and non-SATS aircraft are equipped with the PIRB. As the statistical analysis in Chapter 5 showed, the PIRB system can track up to 117 aircraft in the same 40 km radius airspace, with at least one position update every two seconds, with 99.999% reliability. The ADS-B broadcasts are assumed to operate with the same reliability as the PIRB.

### *6.2.1 SLF Surveillance*

Unlike the TCAS ground sensor, the ADS-B system needs no ground sensor nor requires any restrictions on the movement of aircraft in the airspace to provide continuous surveillance. As the analysis in Chapter 5 showed, the rate of collisions of transmitted packets has nothing to do with the positioning of the aircraft. This being the case, no separation minimum is required. The aircraft in the airspace can detect the aircraft around them by listening to the position information being broadcast by each aircrafts' ADS-B or PIRB and can self-separate. Obviously, certain ATC rules would have to govern the separation of the aircraft for safety reasons, but surveillance would not be the limiting factor.

A major advantage of this system over the TCAS ground sensor is that if the aircraft are properly equipped with either a working PIRB or ADS-B transmitter, the aircraft are always visible to the system. Non-cooperative targets that accidentally wander into the airspace are still visible to the system as are targets that try to defeat the system by flying close to other aircraft.

### *6.2.2 Enroute Surveillance*

The ADS-B system has major advantages over the TCAS system when used for enroute surveillance. Since the system does not rely on a ground sensor to track the aircraft and does not rely on a data link from that ground sensor, the ADS-B system can operate the same while enroute as while in the SLF airspace. If the airspace between 10,000 and 12,000 feet were used for SATS traffic only, then no outside ATC would be needed for safe operation of the SATS aircraft. The SATS aircraft can use the ADS-B broadcasts to track all the surround aircraft and could maintain separation.

### *6.2.3 Mixed Equipage Aircraft*

The use of the PIRB greatly reduces the problems that are caused by mixed equipage aircraft with the ADS-B system. If all aircraft are required to have a PIRB installed, then all aircraft will be visible to the ADS-B system. When non-SATS aircraft make use of the SLFs, those aircraft will still be seen by the ADS-B system. This allows the SATS aircraft to track the non-SATS aircraft and keep a safe separation from them. This is a signification improvement. Safety in the approaching aircraft while in or about the overcast can “see” VRF traffic in the pattern below the overcast. By assigning known identification numbers to the PIRBs, the SATS aircraft are able to distinguish between SATS and non-SATS aircraft. If the non-SATS aircraft are operating under VFR, then those aircraft are required to keep visual separation from all other aircraft and would have no effect on the SATS aircraft.  If the non-SATS aircraft are operating under IFR, then those aircraft will be flying under positive ATC.  The SATS aircraft will still be able to see the non-SATS aircraft and maintain separation.

## 6.3 PIRB with Ground Sensor

This section investigates the ATC issues when all aircraft are equipped with PIRBs..  Unlike the previous discussion, the SATS aircraft in this section are not assumed to have ADS-B.  Instead the SATS aircraft are equipped with a data link, similar to the one used in the TCAS ground sensor, that enables the reception of traffic information from ground sensors at the SLFs.

### *6.3.1 SLF Surveillance*

Unlike the TCAS ground sensor, the PIRB ground sensor does not require any specific flight patterns or separation.  The system operates very similar to the ADS-B system, but instead of each individual aircraft collecting traffic information, the information is collected by a ground sensor and then sent to the individual aircraft via a data link.  As long as an aircraft is equipped with the PIRB, it is always be visible to the ground sensor while in the SLF airspace.

### *6.3.2 Enroute Surveillance*

As in the other enroute surveillance scenarios, again it is assumed that the 10,000-12,000 foot airspace is used solely by SATS aircraft.  Since this system relies on ground sensors to provide traffic information to the aircraft, as did the TCAS ground Sensor system, the aircraft can only fly where ground surveillance coverage is provided. Unlike the TCAS ground sensor system though, the PIRB system, depending on the carrier frequency used, would need new ground stations installed to cover the airways that SATS aircraft travel. One advantage of the PIRB ground station, because it is a random access system, is that it needs only an omni-directional antenna, which is cheaper and easier to maintain.

### *6.3.3 Mixed Equipage Aircraft*

Like the TCAS ground sensor system, the only difference between SATS and non-SATS aircraft is the presence of a data link for traffic information. Since all aircraft in the proposed scenario are equipped with the PIRB, the SATS aircraft will always be able to track the non-SATS aircraft via the traffic data link. Since no special separation is needed to be maintained between aircraft for surveillance reasons, the mixing of traffic becomes much easier. If non-SATS aircraft are given identification numbers from a known set, then SATS aircraft will be able to distinguish between SATS and non-SATS aircraft. This allows SATS aircraft to avoid non-SATS aircraft while using the SLF. Non-SATS aircraft under VMC are be responsible to keep visual separation from the SATS aircraft. Under IMC, the non-SATS aircraft must be under positive ATC control and the SATS aircraft could avoid its path.

## 6.4 Mixed Sensors

The ADS-B system has major advantages over the TCAS ground sensor. The ADS-B system, though, relies on the placement of the PIRB on all aircraft to allow for mixed equipage aircraft to use the SLF. The TCAS ground sensor does not rely on any new airborne hardware to make the SLF usable to any aircraft. The possibility of making use of both systems is an alternate solution to putting PIRBs on all aircraft. In this section, SATS aircraft are assumed to be equipped with ADS-B transmitters and non-SATS aircraft are equipped with Mode A/C transponders.

### 6.4.1 SLF Surveillance

SLF surveillance, with SATS aircraft equipped with ADS-B transmitters and non-SATS aircraft equipped with a Mode A/C transponder, is accomplished in two different ways. SATS aircraft make use of the ADS-B transmission to track all other SATS aircraft in the airspace. The SLF is equipped with a TCAS ground sensor that can track low numbers of non-SATS aircraft.

The non-SATS aircraft must keep proper separation for the TCAS ground sensor to work and there must be prescribed flight paths into and out of the SLF airspace for non-SATS aircraft. The TCAS ground sensor can not only track all the non-SATS aircraft but also use ADS-B type transmissions to broadcast the identification and position of those non-SATS aircraft. This allows the SATS aircraft to track the non-SATS aircraft with no additional equipment since the ADS-B receives the transmissions from the TCAS ground sensor and treats them as any other ADS-B transmission. This also eliminates the need for a separate traffic data link.

### 6.4.2 Enroute Surveillance

It is assumed that SATS aircraft will have a separate altitude level, between 10,000 and 12,000 feet, in which only SATS aircraft will operate. By equipping SATS aircraft with the ADS-B system, no ground sensors are needed for the enroute surveillance. As discussed in section 6.2.2, the aircraft will be able to detect the ADS-B transmissions of all the other SATS aircraft around it and self-separate accordingly.

## 6.5 Conclusions

As described throughout this chapter, the ADS-B system has many advantages over the TCAS ground sensor, especially when used for enroute surveillance. By using ADS-B, SATS aircraft would require neither separate traffic data links nor special ground equipment for enroute surveillance.  The lone drawback of the ADS-B system is that it is not compatible with the current transponder system that the large majority of all aircraft possess.  To make SATS aircraft that are equipped with ADS-B able to operate in mixed traffic environments, either all aircraft need to be equipped with PIRBs, or the SLFs need to be equipped with a TCAS ground sensor that retransmits position and identification information in ADS-B so that SATS aircraft can track non-SATS aircraft.

# Chapter 7 - Conclusion

The aircraft detection requirements for Smart Landing Facilities (SLFs) in the Small Aircraft Transportation System (SATS) presents many unique surveillance issues. Air traffic equipped with current technology, Mode A/C transponders, and any proposed technology, must be tracked while in the SLF airspace. That traffic information must also be available to the individual pilots of the SATS aircraft. An overview of the studies of the Traffic Alert and Collision Avoidance System (TCAS) ground sensor and of the Position and Identification Reporting Beacon (PIRB) are presented in Sections 7.1 and 7.2. Section 7.3 gives an overview of the proposed surveillance system that should be employed at the SLFs according the research done in this thesis.

## 7.1 TCAS Ground Sensor Summary

The Traffic Alert and Collision Avoidance System (TCAS) used as a ground sensor has problems tracking multiple aircraft unless strict Air Traffic Control (ATC) rules are used. The simulation described in Chapter 4 showed that the TCAS ground sensor, providing air surveillance for an airspace where no specific flight paths are followed, is not reliable. The system, even when using an antenna that allows for four distinct interrogation sectors, could not reliably track even five targets arriving and departing per hour when no set separation standard or flight paths were followed.

One way to make the TCAS ground sensor more reliable is to mandate certain separation standards and flight paths. Positive Air Traffic Control (ATC) could be used to ensure a four-mile separation between aircraft before they are allowed to enter the SLF airspace. By using this separation and by allowing only one flight path per antenna sector, collisions between responses would be avoided. This separation scheme between aircraft would then allow the TCAS ground sensor to track the aircraft continuously.

Even when positive ATC control is used to separate aircraft and to ensure that they are on the proper flight paths before entering the SLF, there are still numerous ways that collisions could occur between responses at the TCAS ground sensor. If aircraft disobeys the flight rules and enter the airspace randomly, as a lost pilot is apt to do, that aircraft's responses could collide with the responses of aircraft that are following the proper ATC rules. Collisions between response can also be caused by over-flying commercial aircraft that are not in the SLF airspace but are within the interrogation range of the TCAS ground sensor. If the over-flying aircraft is equipped with a TCAS, then the aircraft will elicit responses from the aircraft in the SLF airspace, which also causes collisions in the responses at the TCAS ground sensor. These collisions still cause certain tracks to be lost for large lengths of time.

The TCAS ground sensor is not a reliable system. Since the system relies on the spacing between aircraft to be maintained for surveillance to be maintained, the system will always fail when needed the most, when two aircraft are about to collide. The airborne TCAS system successfully makes use of the whisper-shout method to track nearby targets. With the TCAS ground sensor, though, two aircraft could be close together and still far from the sensor in which case the whisper-shout method cannot help. The one advantage of the TCAS ground sensor is that it makes use of the Mode A/C transponders that are already on most General Aviation (GA) aircraft. Since the system does not require any extra airborne hardware, the can be implemented more quickly than if the new hardware is required on all aircraft.

## 7.2 PIRB System Summary

The Position and Identification Reporting Beacon (PIRB) is a low-cost alternative to the Automated Dependent Surveillance-Broadcast (ADS-B) system that makes use of GPS positioning equipment designed for use on all aircraft. This beacon broadcasts the aircraft's identity and position in the same format as ADS-B. This broadcast message can be used in two ways to provide surveillance at SLFs for SATS aircraft. The first way is for SATS aircraft to be equipped with ADS-B, which allows the aircraft to individually receive the broadcasts made by all other aircraft in the airspace and thus have a complete traffic picture for the airspace. The second way the PIRB can provide the needed surveillance at SLFs is for the SATS aircraft to be equipped with the PIRB and a traffic data link. A ground station receives the PIRB broadcasts made by all aircraft in the airspace and transmit the traffic information to the SATS aircraft via the traffic data link.

The advantage of the PIRB broadcast over the use of Mode A/C transponder replies as a method to track aircraft is that the PIRB system does not rely on interrogations by the ground station. Since a PIRB randomly transmits its position and identification message every half-second, the overall system becomes a random access system. The random access properties of the system allow for the reliability of the system to depend solely on the number of aircraft in the airspace and not the positioning of the aircraft, as the TCAS ground sensor does. The PIRB system, as designed in Chapter 5, can track up to 117 aircraft in a 40 km radius airspace with 99.999% reliability that at least one complete PIRB broadcast will be received every two seconds.

## 7.3 Proposed System Summary

Both the TCAS ground sensor and the PIRB system have their advantages. The TCAS ground sensor allows for the surveillance of GA aircraft with no additional airborne systems, which makes the system easily deployable. The PIRB system is a much more reliable system that has greater potential for growth. For the SLFs to become operational as soon as possible and to be a viable system as air traffic increases, both systems should be employed. By using both systems, both aircraft equipped with a PIRB and aircraft equipped with just a Mode A/C transponder can be tracked.

Using both systems in conjunction, there are two ways to provide the SATS aircraft with traffic information. The first way is to have a data link from the ground sensors to the aircraft. The traffic information collected by the TCAS ground sensor and the PIRB ground sensor could be merged and sent out over the traffic data link to the SATS aircraft. The second way for the information to be disseminated to the individual aircraft is to have the SATS aircraft equipped with the ADS-B system. The ADS-B system receives the transmissions of other aircraft with ADS-B and aircraft equipped with the PIRB. The TCAS ground sensor can be modified to collect the position and identification data from aircraft with Mode A/C transponders and to place that data in the PIRB/ADS-B message format and to rebroadcast that information. This allows the ADS-B aircraft to receive traffic information for the Mode A/C transponder equipped aircraft with no additional equipment.

## 7.4 Future Research

The research into what surveillance system should be employed at the Smart Landing Facilities has just begun. Although this paper researches the use of the TCAS ground sensor and investigates the use of a PIRB system, both systems need to be studied further before any system is chosen.

1. The simulation of the TCAS ground sensor was done using no specific flight paths into the airspace. Further simulation should be done to test specific flight paths and ATC rules once they are developed for the SLF to test whether or not the TCAS ground sensor can track all the aircraft in the airspace.
2. The TCAS whisper-shout interrogation technique was not implemented in this simulation. This interrogation technique helps reduce collisions in transponder replies at short ranges. This interrogation technique should be investigated to see whether it provides any improvements to the TCAS ground sensor at the greater ranges needed for SLF surveillance.
3. A cost and feasibility study should be done concerning the PIRB as to whether or not the entire U.S. fleet of aircraft could be equipped with such a system.
4. If the PIRB is to be used in the 1090 MHz frequency band, research must be conducted as to the degradation to the Secondary Surveillance Radar system that would be caused by the PIRB transmissions.

5. Research needs to be conducted to find whether two or more overlapping Mode A/C transponder replies can be separated. Since the Mode A/C transponders vary in center frequency, it might be possible to extract overlapping replies and make the TCAS ground sensor more reliable.

# Appendix A – Simulation Results

| Omni-Directional Antenna | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **#of Aircraft** | **1** | **2** | **3** | **4** | **5** | **10** | **15** | **20** |
| **Trial #1** | | | | | | | | |
| **Total Replies** | 1806 | 2737 | 4125 | 5212 | 6216 | 12531 | 19648 | 26337 |
| **Total Collisions** | 114 | 334 | 910 | 706 | 802 | 5232 | 10557 | 17233 |
| **Max Consec. Collisions** | 57 | 66 | 355 | 208 | 69 | 577 | 740 | 688 |
| **Percent Collisions** | 6.31 | 12.2 | 22.06 | 13.55 | 12.9 | 41.74 | 53.73 | 65.43 |
| **Trial #2** | | | | | | | | |
| **Total Replies** | 658 | 2460 | 3335 | 5570 | 5727 | 12522 | 21163 | 26617 |
| **Total Collisions** | 0 | 430 | 348 | 3347 | 540 | 4817 | 10600 | 16829 |
| **Max Consec. Collisions** | 0 | 101 | 174 | 793 | 79 | 303 | 623 | 900 |
| **Percent Collisions** | 0 | 17.48 | 10.43 | 60.09 | 9.43 | 38.47 | 50.09 | 63.23 |
| **Trial #3** | | | | | | | | |
| **Total Replies** | 853 | 3197 | 3977 | 5518 | 6330 | 12609 | 20537 | 24638 |
| **Total Collisions** | 0 | 759 | 202 | 1743 | 936 | 4321 | 12331 | 16228 |
| **Max Consec. Collisions** | 0 | 247 | 51 | 397 | 135 | 376 | 841 | 914 |
| **Percent Collisions** | 0 | 23.74 | 5.08 | 31.42 | 14.79 | 34.27 | 60.04 | 65.87 |
| **Trial #4** | | | | | | | | |
| **Total Replies** | 997 | 2371 | 4009 | 6098 | 7283 | 13491 | 19677 | 26845 |
| **Total Collisions** | 0 | 154 | 654 | 1799 | 1838 | 6321 | 11651 | 18351 |
| **Max Consec. Collisions** | 0 | 77 | 232 | 482 | 466 | 683 | 651 | 712 |
| **Percent Collisions** | 0 | 6.5 | 16.31 | 29.5 | 25.24 | 46.85 | 59.21 | 68.36 |
| **Trial #5** | | | | | | | | |
| **Total Replies** | 1223 | 2713 | 3291 | 4476 | 6847 | 11638 | 18872 | 24405 |
| **Total Collisions** | 108 | 78 | 90 | 420 | 1490 | 6380 | 9854 | 17675 |
| **Max Consec. Collisions** | 54 | 39 | 45 | 111 | 168 | 768 | 754 | 813 |
| **Percent Collisions** | 8.83 | 2.88 | 2.73 | 9.38 | 21.76 | 54.82 | 52.21 | 72.42 |
| **Trial #6** | | | | | | | | |
| **Total Replies** | 1805 | 2069 | 3934 | 4602 | 6189 | 13320 | 17143 | 25655 |
| **Total Collisions** | 0 | 0 | 476 | 822 | 1393 | 5423 | 9085 | 16785 |
| **Max Consec. Collisions** | 0 | 0 | 66 | 204 | 158 | 744 | 805 | 801 |
| **Percent Collisions** | 0 | 0 | 12.1 | 17.86 | 22.51 | 40.71 | 53 | 65.43 |
| **Trial #7** | | | | | | | | |
| **Total Replies** | 1669 | 2255 | 3684 | 5714 | 7264 | 13822 | 19021 | 26797 |
| **Total Collisions** | 0 | 154 | 438 | 1203 | 3763 | 6024 | 9723 | 18646 |
| **Max Consec. Collisions** | 0 | 41 | 163 | 322 | 686 | 474 | 826 | 944 |
| **Percent Collisions** | 0 | 6.83 | 11.89 | 21.05 | 51.8 | 43.58 | 51.12 | 69.58 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Trial #8** | | | | | | | | |
| **Total Replies** | 1640 | 2575 | 3600 | 6198 | 6703 | 12704 | 21141 | 29018 |
| **Total Collisions** | 146 | 190 | 552 | 804 | 966 | 5440 | 12492 | 19649 |
| **Max Consec. Collisions** | 73 | 48 | 70 | 83 | 75 | 416 | 612 | 653 |
| **Percent Collisions** | 8.9 | 7.38 | 15.33 | 12.97 | 14.41 | 42.82 | 59.09 | 67.71 |
| **Trial #9** | | | | | | | | |
| **Total Replies** | 1533 | 2747 | 3205 | 6162 | 6692 | 11983 | 18588 | 25072 |
| **Total Collisions** | 112 | 228 | 346 | 2085 | 1785 | 4908 | 11777 | 16237 |
| **Max Consec. Collisions** | 56 | 58 | 173 | 483 | 455 | 568 | 746 | 854 |
| **Percent Collisions** | 7.31 | 8.3 | 10.8 | 33.84 | 26.67 | 40.96 | 63.36 | 64.76 |
| **Trial #10** | | | | | | | | |
| **Total Replies** | 1152 | 2989 | 4200 | 4579 | 5790 | 13358 | 16619 | 26601 |
| **Total Collisions** | 0 | 170 | 230 | 596 | 1364 | 4220 | 8297 | 17472 |
| **Max Consec. Collisions** | 0 | 85 | 62 | 84 | 165 | 347 | 602 | 801 |
| **Percent Collisions** | 0 | 5.69 | 5.48 | 13.02 | 23.56 | 31.59 | 49.92 | 65.68 |
| | | | | | | | | |
| **Mean Replies** | **1333.6** | **2611.3** | **3736** | **5412.9** | **6504.1** | **12798** | **19241** | **26199** |
| Standard Deviation | 413.31 | 338.83 | 365.21 | 670.35 | 548.03 | 692.56 | 1535.8 | 1345.7 |
| 90% Confidence Interval | 1152.8 | 2463.1 | 3576.3 | 5119.7 | 6264.4 | 12495 | 18569 | 25610 |
| | 1514.4 | 2759.5 | 3895.7 | 5706.1 | 6743.8 | 13101 | 19913 | 26787 |
| **Mean Collisions** | **48** | **249.7** | **424.6** | **1352.5** | **1487.7** | **5308.6** | **10637** | **17511** |
| Standard Deviation | 62.787 | 215.91 | 240.07 | 902.52 | 904.14 | 766.19 | 1413.4 | 1102.1 |
| 90% Confidence Interval | 20.54 | 155.28 | 319.61 | 957.79 | 1092.3 | 4973.5 | 10019 | 17028 |
| | 75.46 | 344.12 | 529.59 | 1747.2 | 1883.1 | 5643.7 | 11255 | 17993 |
| **Mean Max Cont. Collision** | **24** | **76.2** | **139.1** | **316.7** | **245.6** | **525.6** | **720** | **808** |
| Standard Deviation | 31.394 | 66.27 | 100.48 | 227.04 | 212.62 | 168.05 | 91.343 | 98.925 |
| 90% Confidence Interval | 10.27 | 47.217 | 95.157 | 217.41 | 152.61 | 452.1 | 680.05 | 764.74 |
| | 37.73 | 105.18 | 183.04 | 415.99 | 338.59 | 599.1 | 759.95 | 851.26 |
| **Mean % Collisions** | **3.135** | **9.1** | **11.221** | **24.268** | **22.307** | **41.581** | **55.177** | **66.847** |
| Standard Deviation | 4.1116 | 7.0143 | 5.822 | 15.259 | 11.891 | 6.435 | 4.805 | 2.6943 |
| 90% Confidence Interval | 1.3368 | 6.0324 | 8.6748 | 17.595 | 17.107 | 38.767 | 53.076 | 65.669 |
| | 4.9332 | 12.168 | 13.767 | 30.941 | 27.507 | 44.395 | 57.278 | 68.025 |

## 2 180 degree Sectored Antennas

| #of Aircraft | 1 | 2 | 3 | 4 | 5 | 10 | 15 | 20 |
|---|---|---|---|---|---|---|---|---|
| **Trial #1** | | | | | | | | |
| **Total Replies** | 1442 | 2138 | 4780 | 6116 | 7304 | 12683 | 18590 | 25072 |
| **Total Collisions** | 0 | 376 | 84 | 640 | 1036 | 3202 | 5872 | 12279 |
| **Max Consec. Collisions** | 0 | 188 | 42 | 256 | 461 | 605 | 1063 | 830 |
| **Percent Collisions** | 0 | 17.59 | 1.76 | 10.46 | 14.18 | 25.25 | 31.59 | 48.98 |
| **Trial #2** | | | | | | | | |
| **Total Replies** | 1313 | 1898 | 4747 | 5771 | 6285 | 13496 | 21486 | 27061 |
| **Total Collisions** | 0 | 0 | 450 | 308 | 258 | 5044 | 9603 | 11793 |
| **Max Consec. Collisions** | 0 | 0 | 225 | 154 | 129 | 674 | 794 | 870 |
| **Percent Collisions** | 0 | 0 | 9.78 | 5.34 | 4.11 | 37.37 | 44.69 | 43.58 |
| **Trial #3** | | | | | | | | |
| **Total Replies** | 2015 | 2580 | 3552 | 5349 | 5783 | 13545 | 18475 | 27861 |
| **Total Collisions** | 0 | 0 | 0 | 0 | 1360 | 1598 | 8279 | 17590 |
| **Max Consec. Collisions** | 0 | 0 | 0 | 0 | 513 | 554 | 681 | 1029 |
| **Percent Collisions** | 0 | 0 | 0 | 0 | 23.52 | 11.8 | 44.81 | 63.13 |
| **Trial #4** | | | | | | | | |
| **Total Replies** | 1834 | 2929 | 3515 | 5354 | 5235 | 15156 | 21618 | 25694 |
| **Total Collisions** | 0 | 0 | 0 | 504 | 364 | 3321 | 11259 | 9923 |
| **Max Consec. Collisions** | 0 | 0 | 0 | 252 | 182 | 429 | 1073 | 749 |
| **Percent Collisions** | 0 | 0 | 0 | 9.41 | 6.95 | 21.91 | 52.08 | 38.62 |
| **Trial #5** | | | | | | | | |
| **Total Replies** | 1282 | 1533 | 3930 | 5856 | 7742 | 12604 | 20833 | 26923 |
| **Total Collisions** | 0 | 0 | 0 | 0 | 326 | 3745 | 5595 | 12328 |
| **Max Consec. Collisions** | 0 | 0 | 0 | 0 | 152 | 734 | 678 | 910 |
| **Percent Collisions** | 0 | 0 | 0 | 0 | 4.21 | 29.71 | 26.86 | 45.79 |
| **Trial #6** | | | | | | | | |
| **Total Replies** | 1080 | 2806 | 3782 | 4386 | 7488 | 12260 | 19594 | 27339 |
| **Total Collisions** | 0 | 0 | 566 | 0 | 844 | 1114 | 4257 | 13555 |
| **Max Consec. Collisions** | 0 | 0 | 283 | 0 | 188 | 412 | 464 | 741 |
| **Percent Collisions** | 0 | 0 | 14.97 | 0 | 11.27 | 9.09 | 21.73 | 49.58 |
| **Trial #7** | | | | | | | | |
| **Total Replies** | 1373 | 1915 | 3796 | 5642 | 7306 | 11975 | 20230 | 24725 |
| **Total Collisions** | 0 | 0 | 0 | 0 | 380 | 4252 | 7452 | 8295 |
| **Max Consec. Collisions** | 0 | 0 | 0 | 0 | 146 | 672 | 740 | 607 |
| **Percent Collisions** | 0 | 0 | 0 | 0 | 5.2 | 35.51 | 36.84 | 33.55 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Trial #8** | | | | | | | | |
| **Total Replies** | 1986 | 2103 | 4537 | 5599 | 6724 | 13377 | 19500 | 24582 |
| **Total Collisions** | 0 | 0 | 0 | 1432 | 1266 | 1946 | 8421 | 14291 |
| **Max Consec. Collisions** | 0 | 0 | 0 | 716 | 487 | 359 | 905 | 910 |
| **Percent Collisions** | 0 | 0 | 0 | 25.58 | 18.83 | 14.55 | 43.18 | 58.14 |
| **Trial #9** | | | | | | | | |
| **Total Replies** | 1247 | 3026 | 3904 | 4760 | 5749 | 14393 | 19942 | 25871 |
| **Total Collisions** | 0 | 0 | 0 | 0 | 222 | 4387 | 8414 | 9310 |
| **Max Consec. Collisions** | 0 | 0 | 0 | 0 | 111 | 562 | 772 | 826 |
| **Percent Collisions** | 0 | 0 | 0 | 0 | 3.86 | 30.48 | 42.19 | 35.99 |
| **Trial #10** | | | | | | | | |
| **Total Replies** | 1744 | 3516 | 4065 | 4965 | 5324 | 13994 | 20463 | 25165 |
| **Total Collisions** | 0 | 972 | 182 | 588 | 802 | 2384 | 8597 | 12870 |
| **Max Consec. Collisions** | 0 | 486 | 91 | 164 | 401 | 554 | 642 | 759 |
| **Percent Collisions** | 0 | 27.65 | 4.48 | 11.84 | 15.06 | 17.04 | 42 | 51.14 |
| | | | | | | | | |
| **Mean Replies** | **1531.6** | **2444.4** | **4060.8** | **5379.8** | **6494** | **13348** | **20073** | **26029** |
| Standard Deviation | 334.15 | 622.76 | 466.81 | 535.83 | 941.16 | 994.67 | 1078.4 | 1179.9 |
| 90% Confidence Interval | 1385.5 | 2172 | 3856.6 | 5145.5 | 6082.4 | 12913 | 19601 | 25513 |
| | 1677.7 | 2716.8 | 4265 | 5614.1 | 6905.6 | 13783 | 20545 | 26545 |
| **Mean Collisions** | **0** | **134.8** | **128.2** | **347.2** | **685.8** | **3099.3** | **7774.9** | **12223** |
| Standard Deviation | 0 | 317.01 | 210.47 | 465.4 | 431.66 | 1303.1 | 2057.2 | 2680.8 |
| 90% Confidence Interval | 0 | -3.8415 | 36.152 | 143.66 | 497.02 | 2529.4 | 6875.2 | 11051 |
| | 0 | 273.44 | 220.25 | 550.74 | 874.58 | 3669.2 | 8674.6 | 13396 |
| **Mean Max Cont. Collision** | **0** | **67.4** | **64.1** | **154.2** | **277** | **555.5** | **781.2** | **823.1** |
| Standard Deviation | 0 | 158.5 | 105.24 | 224.73 | 166.07 | 123.46 | 189.3 | 116.81 |
| 90% Confidence Interval | 0 | -1.9207 | 18.076 | 55.916 | 204.37 | 501.51 | 698.41 | 772.02 |
| | 0 | 136.72 | 110.12 | 252.48 | 349.63 | 609.49 | 863.99 | 874.18 |
| **Mean % Collisions** | **0** | **4.524** | **3.099** | **6.263** | **10.719** | **23.271** | **38.597** | **46.85** |
| Standard Deviation | 0 | 9.8278 | 5.2375 | 8.3583 | 6.9804 | 9.9741 | 9.2943 | 9.412 |
| 90% Confidence Interval | 0 | 0.2259 | 0.8084 | 2.6076 | 7.6662 | 18.909 | 34.532 | 42.734 |
| | 0 | 8.8221 | 5.3896 | 9.9184 | 13.772 | 27.633 | 42.662 | 50.966 |

## 4 90 degree Sectored Antennas

| #of Aircraft | 1 | 2 | 3 | 4 | 5 | 10 | 15 | 20 |
|---|---|---|---|---|---|---|---|---|
| **Trial #1** | | | | | | | | |
| **Total Replies** | 1447 | 2931 | 3887 | 5589 | 5407 | 13216 | 19460 | 25570 |
| **Total Collisions** | 0 | 0 | 0 | 0 | 1530 | 2608 | 2980 | 9212 |
| **Max Consec. Collisions** | 0 | 0 | 0 | 0 | 413 | 537 | 536 | 688 |
| **Percent Collisions** | 0 | 0 | 0 | 0 | 28.3 | 19.73 | 15.31 | 36.03 |
| **Trial #2** | | | | | | | | |
| **Total Replies** | 1485 | 2840 | 2789 | 5577 | 6169 | 12562 | 20160 | 24681 |
| **Total Collisions** | 0 | 0 | 0 | 0 | 330 | 1720 | 2952 | 7273 |
| **Max Consec. Collisions** | 0 | 0 | 0 | 0 | 165 | 363 | 566 | 695 |
| **Percent Collisions** | 0 | 0 | 0 | 0 | 5.35 | 13.69 | 14.64 | 29.47 |
| **Trial #3** | | | | | | | | |
| **Total Replies** | 1269 | 2442 | 3966 | 5171 | 6362 | 13203 | 19014 | 28330 |
| **Total Collisions** | 0 | 0 | 0 | 0 | 0 | 760 | 2494 | 6872 |
| **Max Consec. Collisions** | 0 | 0 | 0 | 0 | 0 | 221 | 381 | 632 |
| **Percent Collisions** | 0 | 0 | 0 | 0 | 0 | 5.76 | 13.12 | 25.26 |
| **Trial #4** | | | | | | | | |
| **Total Replies** | 1627 | 2865 | 3673 | 4460 | 7109 | 12082 | 17639 | 25884 |
| **Total Collisions** | 0 | 0 | 746 | 210 | 42 | 2012 | 5148 | 8655 |
| **Max Consec. Collisions** | 0 | 0 | 373 | 105 | 21 | 367 | 766 | 777 |
| **Percent Collisions** | 0 | 0 | 20.31 | 4.71 | 0.59 | 16.65 | 29.19 | 33.44 |
| **Trial #5** | | | | | | | | |
| **Total Replies** | 1831 | 1838 | 3167 | 4768 | 5706 | 14591 | 19043 | 25058 |
| **Total Collisions** | 0 | 0 | 0 | 732 | 432 | 4488 | 4900 | 8366 |
| **Max Consec. Collisions** | 0 | 0 | 0 | 349 | 201 | 793 | 764 | 669 |
| **Percent Collisions** | 0 | 0 | 0 | 15.35 | 7.57 | 30.76 | 25.73 | 33.39 |
| **Trial #6** | | | | | | | | |
| **Total Replies** | 1499 | 3002 | 4124 | 3702 | 4994 | 13998 | 19209 | 25265 |
| **Total Collisions** | 0 | 0 | 0 | 272 | 0 | 1830 | 5213 | 8003 |
| **Max Consec. Collisions** | 0 | 0 | 0 | 136 | 0 | 575 | 704 | 828 |
| **Percent Collisions** | 0 | 0 | 0 | 7.35 | 0 | 13.07 | 27.14 | 31.67 |
| **Trial #7** | | | | | | | | |
| **Total Replies** | 1281 | 2453 | 4617 | 6589 | 6997 | 15153 | 20328 | 26220 |
| **Total Collisions** | 0 | 0 | 0 | 260 | 0 | 2890 | 5470 | 11665 |
| **Max Consec. Collisions** | 0 | 0 | 0 | 130 | 0 | 655 | 753 | 930 |
| **Percent Collisions** | 0 | 0 | 0 | 3.95 | 0 | 19.07 | 26.91 | 44.49 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Trial #8** | | | | | | | | |
| **Total Replies** | 1479 | 2804 | 3096 | 5216 | 6008 | 13104 | 18093 | 24529 |
| **Total Collisions** | 0 | 0 | 0 | 0 | 0 | 3104 | 4377 | 7195 |
| **Max Consec. Collisions** | 0 | 0 | 0 | 0 | 0 | 479 | 472 | 624 |
| **Percent Collisions** | 0 | 0 | 0 | 0 | 0 | 23.69 | 24.19 | 29.33 |
| **Trial #9** | | | | | | | | |
| **Total Replies** | 1325 | 1591 | 3372 | 5311 | 6737 | 14041 | 17683 | 26061 |
| **Total Collisions** | 0 | 0 | 0 | 0 | 488 | 1618 | 6342 | 9325 |
| **Max Consec. Collisions** | 0 | 0 | 0 | 0 | 170 | 345 | 663 | 486 |
| **Percent Collisions** | 0 | 0 | 0 | 0 | 7.24 | 11.52 | 35.87 | 35.78 |
| **Trial #10** | | | | | | | | |
| **Total Replies** | 1280 | 2940 | 4050 | 5432 | 7623 | 14385 | 19026 | 25837 |
| **Total Collisions** | 0 | 0 | 516 | 0 | 916 | 632 | 1719 | 8101 |
| **Max Consec. Collisions** | 0 | 0 | 258 | 0 | 367 | 116 | 332 | 616 |
| **Percent Collisions** | 0 | 0 | 12.74 | 0 | 12.02 | 4.39 | 9.04 | 31.35 |
| | | | | | | | | |
| **Mean Replies** | **1452.3** | **2570.6** | **3674.1** | **5181.5** | **6311.2** | **13634** | **18966** | **25744** |
| Standard Deviation | 178.5 | 493.61 | 560.69 | 764.84 | 819.38 | 959.43 | 928.84 | 1073.9 |
| 90% Confidence Interval | 1374.2 | 2354.7 | 3428.9 | 4847 | 5952.8 | 13214 | 18559 | 25274 |
| | 1530.4 | 2786.5 | 3919.3 | 5516 | 6669.6 | 14053 | 19372 | 26213 |
| **Mean Collisions** | **0** | **0** | **126.2** | **147.4** | **373.8** | **2166.2** | **4159.5** | **8466.7** |
| Standard Deviation | 0 | 0 | 271.52 | 236.7 | 507.51 | 1152.6 | 1518.1 | 1394.5 |
| 90% Confidence Interval | 0 | 0 | 7.4527 | 43.881 | 151.84 | 1662.1 | 3495.6 | 7856.8 |
| | 0 | 0 | 244.95 | 250.92 | 595.76 | 2670.3 | 4823.4 | 9076.6 |
| **Mean Max Cont. Collision** | **0** | **0** | **63.1** | **72** | **133.7** | **445.1** | **593.7** | **694.5** |
| Standard Deviation | 0 | 0 | 135.76 | 113.72 | 157.57 | 203.57 | 161.13 | 124.41 |
| 90% Confidence Interval | 0 | 0 | 3.7263 | 22.267 | 64.786 | 356.07 | 523.23 | 640.09 |
| | 0 | 0 | 122.47 | 121.73 | 202.61 | 534.13 | 664.17 | 748.91 |
| **Mean % Collisions** | **0** | **0** | **3.305** | **3.136** | **6.107** | **15.833** | **22.114** | **33.021** |
| Standard Deviation | 0 | 0 | 7.1924 | 5.0452 | 8.8889 | 7.9869 | 8.5565 | 5.1597 |
| 90% Confidence Interval | 0 | 0 | 0.1595 | 0.9295 | 2.2195 | 12.34 | 18.372 | 30.764 |
| | 0 | 0 | 6.4505 | 5.3425 | 9.9945 | 19.326 | 25.856 | 35.278 |

| Omni-Directional Antenna with Separation on the Glide Slopes | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **#of Aircraft** | **1** | **2** | **3** | **4** | **5** | **10** | **15** | **20** |
| **Trial #1** | | | | | | | | |
| **Total Replies** | 1742 | 2666 | 4431 | 4513 | 6415 | 13132 | 19165 | 25485 |
| **Total Collisions** | 0 | 230 | 274 | 652 | 890 | 4639 | 10778 | 14422 |
| **Max Consec. Collisions** | 0 | 72 | 57 | 84 | 55 | 383 | 558 | 572 |
| **Percent Collisions** | 0 | 8.63 | 6.18 | 14.45 | 13.87 | 35.33 | 56.24 | 56.59 |
| **Trial #2** | | | | | | | | |
| **Total Replies** | 1057 | 2442 | 4222 | 4537 | 6633 | 12919 | 20009 | 27237 |
| **Total Collisions** | 0 | 100 | 1059 | 410 | 1602 | 3907 | 9525 | 16911 |
| **Max Consec. Collisions** | 0 | 49 | 273 | 63 | 359 | 274 | 533 | 775 |
| **Percent Collisions** | 0 | 4.1 | 25.08 | 9.04 | 24.15 | 30.24 | 47.6 | 62.09 |
| **Trial #3** | | | | | | | | |
| **Total Replies** | 1415 | 3037 | 4434 | 4638 | 6612 | 14941 | 20394 | 27279 |
| **Total Collisions** | 0 | 184 | 470 | 184 | 1420 | 6503 | 9060 | 15782 |
| **Max Consec. Collisions** | 0 | 54 | 61 | 49 | 242 | 631 | 488 | 667 |
| **Percent Collisions** | 0 | 6.06 | 10.6 | 3.97 | 21.48 | 43.52 | 44.42 | 57.85 |
| **Trial #4** | | | | | | | | |
| **Total Replies** | 1422 | 2845 | 4157 | 5162 | 6252 | 8675 | 17898 | 26806 |
| **Total Collisions** | 0 | 136 | 352 | 1411 | 1292 | 3317 | 6690 | 15308 |
| **Max Consec. Collisions** | 0 | 68 | 66 | 249 | 140 | 388 | 377 | 699 |
| **Percent Collisions** | 0 | 4.78 | 8.47 | 27.33 | 20.67 | 38.24 | 37.38 | 57.11 |
| **Trial #5** | | | | | | | | |
| **Total Replies** | 1210 | 3049 | 4029 | 5195 | 7204 | 13259 | 19372 | 27121 |
| **Total Collisions** | 94 | 406 | 562 | 1090 | 1435 | 4304 | 7737 | 15649 |
| **Max Consec. Collisions** | 47 | 93 | 89 | 136 | 236 | 295 | 413 | 675 |
| **Percent Collisions** | 7.77 | 13.32 | 13.95 | 20.98 | 19.92 | 32.46 | 39.94 | 57.7 |
| **Trial #6** | | | | | | | | |
| **Total Replies** | 1012 | 3062 | 3835 | 5218 | 6482 | 12974 | 19756 | 27127 |
| **Total Collisions** | 0 | 210 | 462 | 790 | 1311 | 5156 | 9116 | 15332 |
| **Max Consec. Collisions** | 0 | 56 | 77 | 134 | 141 | 257 | 296 | 562 |
| **Percent Collisions** | 0 | 6.86 | 12.05 | 15.14 | 20.23 | 39.74 | 46.14 | 56.52 |
| **Trial #7** | | | | | | | | |
| **Total Replies** | 1327 | 2948 | 2995 | 5553 | 5625 | 13790 | 19236 | 26588 |
| **Total Collisions** | 84 | 194 | 214 | 704 | 1084 | 4585 | 8317 | 14917 |
| **Max Consec. Collisions** | 42 | 49 | 56 | 92 | 245 | 420 | 478 | 626 |
| **Percent Collisions** | 6.33 | 6.58 | 7.15 | 12.68 | 19.27 | 33.25 | 43.24 | 56.1 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Trial #8** | | | | | | | | |
| **Total Replies** | 1578 | 2822 | 4200 | 4862 | 6817 | 12167 | 17087 | 24785 |
| **Total Collisions** | 102 | 0 | 1307 | 442 | 1475 | 4662 | 8131 | 12559 |
| **Max Consec. Collisions** | 51 | 0 | 547 | 64 | 343 | 441 | 363 | 723 |
| **Percent Collisions** | 6.46 | 0 | 31.12 | 9.09 | 21.64 | 38.32 | 47.59 | 50.67 |
| **Trial #9** | | | | | | | | |
| **Total Replies** | 1508 | 3389 | 4227 | 5629 | 5473 | 12447 | 20216 | 26807 |
| **Total Collisions** | 106 | 282 | 462 | 1019 | 730 | 4681 | 9249 | 14915 |
| **Max Consec. Collisions** | 53 | 72 | 74 | 150 | 73 | 404 | 579 | 661 |
| **Percent Collisions** | 7.03 | 8.32 | 10.93 | 18.1 | 13.34 | 37.61 | 45.75 | 55.64 |
| **Trial #10** | | | | | | | | |
| **Total Replies** | 1171 | 2618 | 4210 | 5259 | 7008 | 10901 | 19528 | 27305 |
| **Total Collisions** | 0 | 180 | 1136 | 1188 | 1111 | 4008 | 9724 | 14670 |
| **Max Consec. Collisions** | 0 | 62 | 363 | 90 | 131 | 387 | 626 | 431 |
| **Percent Collisions** | 0 | 6.88 | 26.98 | 22.59 | 15.85 | 36.77 | 49.8 | 53.73 |
| | | | | | | | | |
| **Mean Replies** | **1344.2** | **2887.8** | **4074** | **5056.6** | **6452.1** | **12521** | **19266** | **26654** |
| Standard Deviation | 233.8 | 270.86 | 417.27 | 401.37 | 552.86 | 1709.3 | 1037 | 850.28 |
| 90% Confidence Interval | 1242 | 2769.3 | 3891.5 | 4881.1 | 6210.3 | 11773 | 18813 | 26282 |
| | 1446.4 | 3006.3 | 4256.5 | 5232.1 | 6693.9 | 13268 | 19720 | 27026 |
| **Mean Collisions** | **38.6** | **192.2** | **629.8** | **789** | **1235** | **4576.2** | **8832.7** | **15047** |
| Standard Deviation | 50.147 | 107.67 | 389.04 | 386.67 | 276.44 | 849.93 | 1150.5 | 1119.7 |
| 90% Confidence Interval | 16.669 | 145.11 | 459.66 | 619.89 | 1114.1 | 4204.5 | 8329.5 | 14557 |
| | 60.531 | 239.29 | 799.94 | 958.11 | 1355.9 | 4947.9 | 9335.9 | 15536 |
| **Mean Max Cont. Collision** | **19.3** | **57.5** | **166.3** | **111.1** | **196.5** | **388** | **471.1** | **639.1** |
| Standard Deviation | 25.073 | 24.213 | 170.86 | 59.261 | 105.24 | 106.44 | 106.42 | 97.506 |
| 90% Confidence Interval | 8.3343 | 46.911 | 91.576 | 85.183 | 150.47 | 341.45 | 424.56 | 596.46 |
| | 30.266 | 68.089 | 241.02 | 137.02 | 242.53 | 434.55 | 517.64 | 681.74 |
| **Mean % Collisions** | **2.759** | **6.553** | **15.251** | **15.337** | **19.042** | **36.548** | **45.81** | **56.4** |
| Standard Deviation | 3.582 | 3.4282 | 9.0193 | 7.0843 | 3.5453 | 3.8707 | 5.2201 | 2.9317 |
| 90% Confidence Interval | 1.1925 | 5.0537 | 11.306 | 12.239 | 17.491 | 34.855 | 43.527 | 55.118 |
| | 4.3255 | 8.0523 | 19.196 | 18.435 | 20.593 | 38.241 | 48.093 | 57.682 |

| 2 180 Degree Sectored Antennas with Separation on the Glide Slopes | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **#of Aircraft** | **1** | **2** | **3** | **4** | **5** | **10** | **15** | **20** |
| **Trial #1** | | | | | | | | |
| **Total Replies** | 1745 | 2443 | 4080 | 5303 | 6080 | 11997 | 19884 | 27162 |
| **Total Collisions** | 0 | 0 | 0 | 1390 | 0 | 826 | 3785 | 7613 |
| **Max Consec. Collisions** | 0 | 0 | 0 | 429 | 0 | 265 | 603 | 656 |
| **Percent Collisions** | 0 | 0 | 0 | 26.61 | 0 | 6.89 | 19.04 | 28.03 |
| **Trial #2** | | | | | | | | |
| **Total Replies** | 1558 | 3268 | 3746 | 5399 | 6694 | 13710 | 18793 | 25313 |
| **Total Collisions** | 0 | 86 | 0 | 0 | 308 | 2948 | 3540 | 4139 |
| **Max Consec. Collisions** | 0 | 43 | 0 | 0 | 154 | 651 | 768 | 380 |
| **Percent Collisions** | 0 | 2.63 | 0 | 0 | 4.6 | 21.5 | 18.84 | 16.35 |
| **Trial #3** | | | | | | | | |
| **Total Replies** | 1923 | 3086 | 4860 | 5632 | 7825 | 13014 | 20466 | 28727 |
| **Total Collisions** | 0 | 380 | 0 | 1340 | 2278 | 2387 | 5087 | 8721 |
| **Max Consec. Collisions** | 0 | 190 | 0 | 450 | 582 | 498 | 458 | 545 |
| **Percent Collisions** | 0 | 12.31 | 0 | 23.79 | 29.11 | 18.34 | 24.86 | 30.36 |
| **Trial #4** | | | | | | | | |
| **Total Replies** | 1335 | 3061 | 3950 | 4960 | 6858 | 14613 | 18913 | 27884 |
| **Total Collisions** | 0 | 0 | 136 | 0 | 1296 | 3785 | 1760 | 5554 |
| **Max Consec. Collisions** | 0 | 0 | 68 | 0 | 548 | 617 | 198 | 580 |
| **Percent Collisions** | 0 | 0 | 3.44 | 0 | 18.9 | 25.9 | 9.31 | 19.92 |
| **Trial #5** | | | | | | | | |
| **Total Replies** | 1402 | 2680 | 4012 | 4577 | 7048 | 14293 | 19991 | 26674 |
| **Total Collisions** | 0 | 0 | 0 | 0 | 736 | 374 | 4923 | 8234 |
| **Max Consec. Collisions** | 0 | 0 | 0 | 0 | 368 | 130 | 521 | 459 |
| **Percent Collisions** | 0 | 0 | 0 | 0 | 10.44 | 2.62 | 24.63 | 30.87 |
| **Trial #6** | | | | | | | | |
| **Total Replies** | 1190 | 2782 | 3479 | 5546 | 6412 | 12494 | 20835 | 26955 |
| **Total Collisions** | 0 | 0 | 0 | 0 | 268 | 2682 | 5541 | 7919 |
| **Max Consec. Collisions** | 0 | 0 | 0 | 0 | 134 | 476 | 494 | 439 |
| **Percent Collisions** | 0 | 0 | 0 | 0 | 4.18 | 21.47 | 26.59 | 29.38 |
| **Trial #7** | | | | | | | | |
| **Total Replies** | 1538 | 2626 | 3941 | 4415 | 7719 | 12942 | 20899 | 25066 |
| **Total Collisions** | 0 | 0 | 0 | 0 | 2637 | 1766 | 4813 | 6931 |
| **Max Consec. Collisions** | 0 | 0 | 0 | 0 | 591 | 253 | 474 | 620 |
| **Percent Collisions** | 0 | 0 | 0 | 0 | 34.16 | 13.65 | 23.03 | 27.65 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Trial #8** | | | | | | | | |
| **Total Replies** | 1096 | 2616 | 3446 | 3980 | 5302 | 12362 | 19323 | 25759 |
| **Total Collisions** | 0 | 0 | 524 | 108 | 264 | 1534 | 3349 | 8441 |
| **Max Consec. Collisions** | 0 | 0 | 134 | 54 | 132 | 214 | 376 | 550 |
| **Percent Collisions** | 0 | 0 | 15.21 | 2.71 | 4.98 | 12.41 | 17.33 | 32.77 |
| **Trial #9** | | | | | | | | |
| **Total Replies** | 992 | 1926 | 4032 | 4474 | 6526 | 13049 | 18191 | 28300 |
| **Total Collisions** | 0 | 0 | 0 | 142 | 598 | 2945 | 1683 | 6606 |
| **Max Consec. Collisions** | 0 | 0 | 0 | 71 | 299 | 583 | 308 | 802 |
| **Percent Collisions** | 0 | 0 | 0 | 3.17 | 9.16 | 22.57 | 9 | 23.34 |
| **Trial #10** | | | | | | | | |
| **Total Replies** | 1882 | 2557 | 4598 | 5266 | 7030 | 11719 | 20843 | 28807 |
| **Total Collisions** | 0 | 0 | 178 | 806 | 0 | 1364 | 3492 | 6603 |
| **Max Consec. Collisions** | 0 | 0 | 85 | 256 | 0 | 336 | 417 | 364 |
| **Percent Collisions** | 0 | 0 | 3.87 | 15.31 | 0 | 11.64 | 16.75 | 22.92 |
| | | | | | | | | |
| **Mean Replies** | **1466.1** | **2704.5** | **4014.4** | **4955.2** | **6749.4** | **13019** | **19814** | **27065** |
| Standard Deviation | 321.87 | 381.08 | 441.15 | 561.65 | 744.36 | 948.1 | 970.07 | 1371.9 |
| 90% Confidence Interval | 1325.3 | 2537.8 | 3821.5 | 4709.6 | 6423.9 | 12605 | 19390 | 26465 |
| | 1606.9 | 2871.2 | 4207.3 | 5200.8 | 7074.9 | 13434 | 20238 | 27665 |
| **Mean Collisions** | **0** | **46.6** | **83.8** | **378.6** | **838.5** | **2061.1** | **3797.3** | **7076.1** |
| Standard Deviation | 0 | 120.22 | 168.17 | 575.02 | 938.53 | 1067.4 | 1332.7 | 1426.6 |
| 90% Confidence Interval | 0 | -5.9783 | 10.252 | 127.12 | 428.04 | 1594.3 | 3214.5 | 6452.2 |
| | 0 | 99.178 | 157.35 | 630.08 | 1249 | 2527.9 | 4380.1 | 7700 |
| **Mean Max Cont. Collision** | **0** | **23.3** | **28.7** | **126** | **280.8** | **402.3** | **461.7** | **539.5** |
| Standard Deviation | 0 | 60.111 | 48.954 | 182.96 | 231.84 | 185.69 | 156.71 | 134.81 |
| 90% Confidence Interval | 0 | -2.9892 | 7.2905 | 45.983 | 179.41 | 321.09 | 393.17 | 480.54 |
| | 0 | 49.589 | 50.11 | 206.02 | 382.19 | 483.51 | 530.23 | 598.46 |
| **Mean % Collisions** | **0** | **1.494** | **2.252** | **7.159** | **11.553** | **15.699** | **18.938** | **26.159** |
| Standard Deviation | 0 | 3.8892 | 4.8009 | 10.611 | 11.987 | 7.4933 | 6.161 | 5.3044 |
| 90% Confidence Interval | 0 | -0.2069 | 0.1524 | 2.5184 | 6.3107 | 12.422 | 16.244 | 23.839 |
| | 0 | 3.1949 | 4.3516 | 11.8 | 16.795 | 18.976 | 21.632 | 28.479 |

| 4 90 Degree Sectored Antennas with Separation on Glide Slopes | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **#of Aircraft** | **1** | **2** | **3** | **4** | **5** | **10** | **15** | **20** |
| **Trial #1** | | | | | | | | |
| **Total Replies** | 1097 | 2848 | 5059 | 5742 | 5860 | 13880 | 19101 | 22955 |
| **Total Collisions** | 0 | 0 | 76 | 0 | 0 | 364 | 750 | 2486 |
| **Max Consec. Collisions** | 0 | 0 | 38 | 0 | 0 | 180 | 194 | 623 |
| **Percent Collisions** | 0 | 0 | 1.5 | 0 | 0 | 2.62 | 3.93 | 10.83 |
| **Trial #2** | | | | | | | | |
| **Total Replies** | 1569 | 2482 | 3509 | 5298 | 5469 | 12210 | 18331 | 26376 |
| **Total Collisions** | 0 | 0 | 614 | 1378 | 0 | 992 | 1191 | 3365 |
| **Max Consec. Collisions** | 0 | 0 | 250 | 465 | 0 | 431 | 393 | 690 |
| **Percent Collisions** | 0 | 0 | 17.5 | 26.01 | 0 | 8.12 | 6.5 | 12.76 |
| **Trial #3** | | | | | | | | |
| **Total Replies** | 1249 | 2701 | 4327 | 4543 | 5426 | 12091 | 21717 | 24946 |
| **Total Collisions** | 0 | 0 | 0 | 0 | 0 | 1816 | 3338 | 2805 |
| **Max Consec. Collisions** | 0 | 0 | 0 | 0 | 0 | 459 | 657 | 476 |
| **Percent Collisions** | 0 | 0 | 0 | 0 | 0 | 15.12 | 15.37 | 11.24 |
| **Trial #4** | | | | | | | | |
| **Total Replies** | 1813 | 2105 | 3502 | 5566 | 7131 | 13690 | 16899 | 23459 |
| **Total Collisions** | 0 | 68 | 0 | 0 | 376 | 368 | 1360 | 2663 |
| **Max Consec. Collisions** | 0 | 34 | 0 | 0 | 188 | 184 | 262 | 301 |
| **Percent Collisions** | 0 | 3.23 | 0 | 0 | 5.27 | 2.69 | 8.05 | 11.35 |
| **Trial #5** | | | | | | | | |
| **Total Replies** | 1593 | 2094 | 4223 | 4375 | 5696 | 12281 | 18333 | 25776 |
| **Total Collisions** | 0 | 0 | 0 | 0 | 2 | 176 | 2552 | 5659 |
| **Max Consec. Collisions** | 0 | 0 | 0 | 0 | 1 | 87 | 510 | 593 |
| **Percent Collisions** | 0 | 0 | 0 | 0 | 0.04 | 1.43 | 13.92 | 21.95 |
| **Trial #6** | | | | | | | | |
| **Total Replies** | 1060 | 2062 | 4340 | 4894 | 6082 | 12573 | 19514 | 21150 |
| **Total Collisions** | 0 | 0 | 0 | 0 | 2 | 504 | 942 | 2739 |
| **Max Consec. Collisions** | 0 | 0 | 0 | 0 | 1 | 250 | 208 | 254 |
| **Percent Collisions** | 0 | 0 | 0 | 0 | 0.03 | 4.01 | 4.83 | 12.95 |
| **Trial #7** | | | | | | | | |
| **Total Replies** | 1066 | 2479 | 3599 | 4753 | 7473 | 13723 | 21199 | 26034 |
| **Total Collisions** | 0 | 0 | 0 | 0 | 488 | 288 | 3798 | 3056 |
| **Max Consec. Collisions** | 0 | 0 | 0 | 0 | 244 | 75 | 536 | 260 |
| **Percent Collisions** | 0 | 0 | 0 | 0 | 6.53 | 2.1 | 17.92 | 11.74 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Trial #8** | | | | | | | | |
| **Total Replies** | 1710 | 3211 | 2721 | 4029 | 6942 | 13804 | 18714 | 28522 |
| **Total Collisions** | 0 | 0 | 0 | 270 | 0 | 406 | 2039 | 2000 |
| **Max Consec. Collisions** | 0 | 0 | 0 | 135 | 0 | 193 | 431 | 347 |
| **Percent Collisions** | 0 | 0 | 0 | 6.7 | 0 | 2.94 | 10.9 | 7.01 |
| **Trial #9** | | | | | | | | |
| **Total Replies** | 1059 | 2612 | 4085 | 3789 | 7476 | 13424 | 20589 | 27130 |
| **Total Collisions** | 0 | 0 | 2 | 354 | 344 | 162 | 1293 | 6523 |
| **Max Consec. Collisions** | 0 | 0 | 1 | 177 | 171 | 81 | 192 | 497 |
| **Percent Collisions** | 0 | 0 | 0.05 | 9.34 | 4.6 | 1.21 | 6.28 | 24.04 |
| **Trial #10** | | | | | | | | |
| **Total Replies** | 1364 | 2145 | 4456 | 6207 | 5071 | 14692 | 18980 | 26451 |
| **Total Collisions** | 0 | 0 | 156 | 148 | 4 | 280 | 2927 | 4500 |
| **Max Consec. Collisions** | 0 | 0 | 78 | 74 | 2 | 93 | 637 | 435 |
| **Percent Collisions** | 0 | 0 | 3.5 | 2.38 | 0.08 | 1.91 | 15.42 | 17.01 |
| | | | | | | | | |
| **Mean Replies** | **1358** | **2473.9** | **3982.1** | **4919.6** | **6262.6** | **13237** | **19338** | **25280** |
| Standard Deviation | 293.29 | 381.85 | 657.56 | 776.96 | 907.9 | 885.14 | 1463.1 | 2191.1 |
| 90% Confidence Interval | 1229.7 | 2306.9 | 3694.5 | 4579.8 | 5865.5 | 12850 | 18698 | 24322 |
| | 1486.3 | 2640.9 | 4269.7 | 5259.4 | 6659.7 | 13624 | 19978 | 26238 |
| **Mean Collisions** | **0** | **6.8** | **84.8** | **215** | **121.6** | **535.6** | **2019** | **3579.6** |
| Standard Deviation | 0 | 21.503 | 192.99 | 429.05 | 197.21 | 507.56 | 1076.6 | 1490.4 |
| 90% Confidence Interval | 0 | -2.6044 | 0.3978 | 27.358 | 35.353 | 313.62 | 1548.2 | 2927.8 |
| | 0 | 16.204 | 169.2 | 402.64 | 207.85 | 757.58 | 2489.8 | 4231.4 |
| **Mean Max Cont. Collision** | **0** | **3.4** | **36.7** | **85.1** | **60.7** | **203.3** | **402** | **447.6** |
| Standard Deviation | 0 | 10.752 | 79.275 | 148.64 | 98.478 | 140.45 | 181.17 | 155.76 |
| 90% Confidence Interval | 0 | -1.3022 | 2.0298 | 20.095 | 17.631 | 141.87 | 322.77 | 379.48 |
| | 0 | 8.1022 | 71.37 | 150.11 | 103.77 | 264.73 | 481.23 | 515.72 |
| **Mean % Collisions** | **0** | **0.323** | **2.255** | **4.443** | **1.655** | **4.215** | **10.312** | **14.088** |
| Standard Deviation | 0 | 1.0214 | 5.4762 | 8.2792 | 2.6707 | 4.3112 | 5.0509 | 5.3154 |
| 90% Confidence Interval | 0 | -0.1237 | -0.14 | 0.8221 | 0.487 | 2.3295 | 8.103 | 11.763 |
| | 0 | 0.7697 | 4.65 | 8.0639 | 2.823 | 6.1005 | 12.521 | 16.413 |

# Appendix B – Matlab Code for Simulation

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Tcas.m
%
% Created by Eric Shea
% Last Updated 10 March, 2002
%
% This Program is designed to find the number of collisions that occur
% between responses to "TCAS on a Stick" interrogations with varying
% traffic levels and varying Beamwidths of interrogation.  The program
% enters into the airspace the given number of aircraft at the maximum
% range of the simulation at any point north of the initial approach
% fix. The aircraft then proceed to the arrival point.  Once
% there the aircraft follows the glide slope down to the airport
% surface.  Departing aircraft start at the airport surface and follow
% a slope to what is called the departure point.  Once there, the aircraft
% go in random directions that are all south of the departure fix.
% The aircraft will only be interrogated if the aircraft is
% within the airspace and not on the airport surface.  Collisions
% between responses occur whenever the slant path between two aircraft
% is below the minimum slant path required and both aircraft are
% within the same beam of the antenna.
%

clear

% Time is in seconds, there are 3600 seconds/hour and one
% interrogation/sec

Tmax=3600;      % Max time in seconds, Simulation run time
Vmin=41;        % Minimum Aircraft Velocity, in meter/sec, approx. 80 kts
Vmax=101;       % Maximum Aircraft Velocity, approx. 200kts
Zmin=1350;      % In meters, approx. 4430 ft
Zap=610;        % Z coordinate of Airport, in meters, (Blacksburg)
Xif=0;          % X coordinate of Arrival Point
Yif=15000;      % Y coordinate of Arrival Point
Xdf=0;          % X coordinate of Departure Point
Ydf=-10000;     % Y coordinate of Departure Point
Zdf=Zmin;       % Z coordinate of Departure Point
Xap=0;          % X coordinate of Airport
Yap=0;          % Y coordinate of Airport
Rmax=40000;     % Max range of TCAS unit

Approachangle=atan((Zmin-Zap)/Yif);      % Glide Slope angle
departangle=atan((Zmin-Zap)/Ydf);        % Departure Slope angle
Slantmin=3111;                           % Corresponds to distance a 20.75us pulse covers /2

% Aircraft Arrival and Departure rates are assumed to be equal

acnum=input('Please enter the number of Aircraft arrivals per hour:  ');

% The following loop will assign arrival and departure times for the
```

```
% aircraft and will assign the initial position of all aircraft to
% (0,0,-1).  Aircraft with negative altitude have not yet entered the
% system and will not respond to interrogations.  The times given will
% be the time that the aircraft will become visible to the system.
% Aircraft velocity will also be assigned in the range of Vmin to Vmax.

for x =1:acnum;
   acarrive(x)=ceil(rand*Tmax);               % Time Arriving Aircraft are Visible
   if acarrive(x)==1  acarrive(x)=2; end;       % Ensures t=2 is lowest time
   acdepart(x)=ceil(rand*Tmax);               % Time Departing Aircraft are Visible
   if acdepart(x)==1  acdepart(x)=2; end;       % Ensures t=2 is lowest time
   aircraftax(x,1)=0;                         % Sets initial position of arriving aircraft
   aircraftay(x,1)=0;
   aircraftaz(x,1)=-1;
   aircraftdx(x,1)=0;                         % Sets initial position of depart aircraft
   aircraftdy(x,1)=0;
   aircraftdz(x,1)=-1;
   aircraftav(x)=floor(rand*(Vmax-Vmin))+Vmin;      % Sets velocities
   aircraftdv(x)=floor(rand*(Vmax-Vmin))+Vmin;

% acif is a logic statement needed for the plane movements and is a 0 if
% the aircraft is not yet on finial approach and is a 1 if it is.
% Similarly, acdf is a 1 if the aircraft is still on the departure slope
% and a zero otherwise.

   acif(x)=0;
   acdf(x)=1;
end;


% The following loop will simulate the interrogations of the aircraft
% over the course of an hour and will keep count of the number of
% collisions between responses.

for t=2:Tmax;
   for x=1:acnum;
      if acarrive(x)==t

% If the aircraft arrives at this time, it is given a random position at the maximum
% range and a random velocity in the specified range

         az=-1.1864+rand*(1.1864*2);
         aircraftax(x,t)=Rmax*sin(az);
         aircraftay(x,t)=Rmax*cos(az);
         aircraftaz(x,t)=Zmin;
         aircraftangle(x)=pi/2-abs(atan((aircraftay(x,t)-Yif)/aircraftax(x,t)));
      end;

      if acarrive(x)<t
         if acif(x)==1

% If the aircraft is in the airspace and already pas the arrival point, the following code
% moves the aircraft and finds its distance to the ground sensor.  If the aircraft arrives
% at the airport , the aircraft is assigned an altitude of –1 and a velocity of 0 which stops
%  the responses from the aircraft
```

```
            distance=sqrt((aircraftax(x,t-1)-Xap)^2+(aircraftay(x,t-1)-Yap)^2+(aircraftaz(x,t-1)-Zap)^2);
            if distance<aircraftav(x)
                acarrive(x)=Tmax+1;
                aircraftax(x,t)=Xap;
                aircraftay(x,t)=Yap;
                aircraftaz(x,t)=-1;
                aircraftav(x)=0;
            else
                distance=distance-aircraftav(x);
                aircraftax(x,t)=Xap;
                aircraftay(x,t)=distance*cos(Approachangle)+Yap;
                aircraftaz(x,t)=distance*sin(Approachangle)+Zap;
            end;
        end;

% The following code moves the aircraft and finds the distance to the ground sensor if the
% aircraft is in the airspace but has not yet reached the arrival point.  If the aircraft reaches
% the arrival point , it is turned onto the glide slope and its velocity is reduced.

        if acif(x)==0
            distance=sqrt((aircraftax(x,t-1)-Xif)^2+(aircraftay(x,t-1)-Yif)^2);
            if distance<aircraftav(x)
                acif(x)=1;
                aircraftax(x,t)=Xif;
                aircraftay(x,t)=Yif;
                aircraftaz(x,t)=Zmin;
                aircraftav(x)=Vmin;
            else
                distance=distance-aircraftav(x);
                aircraftax(x,t)=distance*sin(aircraftangle(x))+Xif;
                if aircraftax(x,t-1)<0 aircraftax(x,t)=aircraftax(x,t)*-1; end;
                aircraftay(x,t)=distance*cos(aircraftangle(x))+Yif;
                aircraftaz(x,t)=aircraftaz(x,t-1);
            end;
        end;
    end;

% If the aircraft has not yet entered the airspace, the following code is used
    if acarrive(x)>t
        if acarrive(x)<Tmax
            aircraftax(x,t)=aircraftax(x,t-1);
            aircraftay(x,t)=aircraftay(x,t-1);
            aircraftaz(x,t)=aircraftaz(x,t-1);
        end;
    end;

% If the aircraft has already landed, then the following code is used

    if acarrive(x)>Tmax
        aircraftax(x,t)=0;
        aircraftay(x,t)=0;
        aircraftaz(x,t)=-1;
    end;

% The following code is almost identical to the code above but is used to move
% and to track departing aircraft instead of arriving aircraft.
```

```
    if acdepart(x)==t
        aircraftdz(x,t)=Zap;
        aircraftdx(x,t)=Xap;
        aircraftdy(x,t)=Yap;
        outbearing=.58*pi+rand*0.84*pi;
        xout(x)=Rmax*sin(outbearing);
        yout(x)=Rmax*cos(outbearing);
        outangle(x)=atan(xout(x)/(yout(x)-Ydf));
    end;

    if acdepart(x)<t
        if acdf(x)==0
            distance=sqrt((aircraftdx(x,t-1)-xout(x))^2+(aircraftdy(x,t-1)-yout(x))^2);
            if distance<aircraftdv(x)
                acdepart(x)=Tmax+1;
                aircraftdz(x,t)=-1;
                aircraftdx(x,t)=0;
                aircraftdy(x,t)=0;
            else
                aircraftdx(x,t)=aircraftdx(x,t-1)-aircraftdv(x)*sin(outangle(x));
                aircraftdy(x,t)=aircraftdy(x,t-1)-aircraftdv(x)*cos(outangle(x));
                aircraftdz(x,t)=aircraftdz(x,t-1);
            end;
        end;
        if acdf(x)==1
           distance=sqrt((aircraftdx(x,t-1)-Xdf)^2+(aircraftdy(x,t-1)-Ydf)^2+(aircraftdz(x,t-1)-Zdf)^2);
            if distance<aircraftdv(x)
                acdf(x)=0;
                aircraftdx(x,t)=Xdf;
                aircraftdy(x,t)=Ydf;
                aircraftdz(x,t)=Zmin;
            else
                distance=distance-aircraftdv(x);
                aircraftdx(x,t)=Xdf;
                aircraftdy(x,t)=distance*cos(departangle)+Ydf;
                aircraftdz(x,t)=distance*sin(departangle)+Zdf;
            end;
        end;
    end;
    if acdepart(x)>t
        if acdepart(x)<Tmax
            aircraftdx(x,t)=aircraftdx(x,t-1);
            aircraftdy(x,t)=aircraftdy(x,t-1);
            aircraftdz(x,t)=aircraftdz(x,t-1);
        end;
    end;
    if acdepart(x)>Tmax
        aircraftdx(x,t)=0;
        aircraftdy(x,t)=0;
        aircraftdz(x,t)=-1;
    end;
    rangea(x,t)=sqrt((aircraftax(x,t)-Xap)^2+(aircraftay(x,t)-Xap)^2+(aircraftaz(x,t)-Zap)^2);
    if aircraftaz(x,t)==-1  rangea(x,t)=0; end;
    ranged(x,t)=sqrt((aircraftdx(x,t)-Xap)^2+(aircraftdy(x,t)-Xap)^2+(aircraftdz(x,t)-Zap)^2);
    if aircraftdz(x,t)==-1  ranged(x,t)=0; end;
end;
```

```
end;

%  The following code calculates whether a collision occurred between responses
% throughout the simulation by comparing ranges and locations of the aircraft.

w=1:Tmax;
b=1:acnum;
collisiona(b,w)=0;
collisiond(b,w)=0;
for t=1:Tmax
    for x=1:acnum
        for b=1:acnum
            if b==x
                collisiona(x,t)=collisiona(x,t);
            else

% The following two if statements are only needed when separation on the glide
% slope is guaranteed.

                if rangea(x,t)>Yif
                    if rangea(b,t)>Yif

% The following two if statements are only needed when using a 4 sector antenna

                        if aircraftax(x,t)>=0
                            if aircraftax(b,t)>=0
                                if abs(rangea(x,t)-rangea(b,t))<Slantmin
                                    collisiona(x,t)=1;
                                    collisiona(b,t)=1;
                                end;
                            end;
                        end;
                    end;
                end;

% The following two if statements are only needed when separation on the glide
% slope is guaranteed.


                if rangea(x,t)>Yif
                    if rangea(b,t)>Yif

% The following two if statements are only needed when using a 4 sector antenna

                        if aircraftax(x,t)<0
                            if aircraftax(b,t)<0
                                if abs(rangea(x,t)-rangea(b,t))<Slantmin
                                    collisiona(x,t)=1;
                                    collisiona(b,t)=1;
                                end;
                            end;
                        end;
                    end;
                end;
            end;
```

```
% The following code is the same as above but for departing aircraft

            if b==x
                collisiond(x,t)=collisiond(x,t);
            else
                if ranged(x,t)>abs(Ydf)
                    if ranged(b,t)>abs(Ydf)
                        if aircraftdx(x,t)>=0
                            if aircraftdx(b,t)>=0
                                if abs(ranged(x,t)-ranged(b,t))<Slantmin
                                    collisiond(x,t)=1;
                                    collisiond(b,t)=1;
                                end;
                            end;
                        end;
                    end;
                end;
                if ranged(x,t)>abs(Ydf)
                    if ranged(b,t)>abs(Ydf)
                        if aircraftdx(x,t)<0
                            if aircraftdx(b,t)<0
                                if abs(ranged(x,t)-ranged(b,t))<Slantmin
                                    collisiond(x,t)=1;
                                    collisiond(b,t)=1;
                                end;
                            end;
                        end;
                    end;
                end;
            end;
        end;
    end;
end;

% The following code calculates the totals of the data and also finds the maximum
% length string of collisions for each aircraft.

q=1:acnum;
totalcollisionsa(q)=0;
totalcollisionsd(q)=0;
totalrepliesa(q)=0;
totalrepliesd(q)=0;
maxcollisionsa(q)=0;
maxcollisionsd(q)=0;
for h=1:acnum
    counta=0;
    countd=0;
    for t=1:Tmax
        totalcollisionsa(h)=totalcollisionsa(h)+collisiona(h,t);
        totalcollisionsd(h)=totalcollisionsd(h)+collisiond(h,t);
        if aircraftaz(h,t)>0
            totalrepliesa(h)=totalrepliesa(h)+1;
        end;
        if aircraftdz(h,t)>0
            totalrepliesd(h)=totalrepliesd(h)+1;
        end;
```

```
        if collisiona(h,t)==1
            counta=counta+1;
        else
            counta=0;
        end;
        if collisiond(h,t)==1
            countd=countd+1;
        else
            countd=0;
        end;
        if counta>maxcollisionsa(h)
            maxcollisionsa(h)=counta;
        end;
        if countd>maxcollisionsd(h)
            maxcollisionsd(h)=countd;
        end;
    end;
end;

totalrepliesa;
totalcollisionsa;
maxcollisionsa;
totalrepliesd;
totalcollisionsd;
maxcollisionsd;
Totalreplies=0;
Totalcollisions=0;
for p=1:acnum
    Totalreplies=Totalreplies+totalrepliesa(p)+totalrepliesd(p);
    Totalcollisions=Totalcollisions+totalcollisionsa(p)+totalcollisionsd(p);
end;
maxca=sort(maxcollisionsa);
maxcd=sort(maxcollisionsd);
if maxca(acnum)>maxcd(acnum)
    Maxcollisions=maxca(acnum);
else
    Maxcollisions=maxcd(acnum);
end;
Totalreplies
Totalcollisions
Maxcollisions
Percentcollisions=Totalcollisions/Totalreplies*100
```

# References


1. Merrill I. Skolnik. Introduction to Radar Systems. Boston: McGraw-Hill, 1980.

2. Robert M. Page. The Origins of Radar. Westport, CT: Greenwood Press, Publishers, 1962.

3. S. S. Swords. Technical History of the Beginnings of Radar. London: Peter Peregrinus Ltd., 1986.

4. Michael C. Stevens. Secondary Surveillance Radar. Boston: Artech House, 1988.

5. Peter Honold. Secondary Radar. London: Siemens, Aktiengesellschaft, Heyden & Son Ltd., 1976.

6. Jonathan Baldwin, Alexander Smith, and Rick Cassell. "General Aviation Collision Avoidance." In IEEE, 1994: 504-509.

7. Bassam Abdul-Baki, Jonathan Baldwin, and Marc-Philippe Rudel. "Independent Validation and Verification of the TCAS II Collision Avoidance Subsystem." In AIAA 18th Annual Digital Avionics Systems Conference, 1999.

8. U.S. Congress, Office of Technology Assessment. Safer Skies with TCAS. OTA-SET-431. Washington: U.S. Government Printing Office, 1989.

9. Thomas Williamson and Ned A. Spencer. "Development and Operation of the Traffic Alert and Collision Avoidance System (TCAS)." In Proceedings of the IEEE, Vol. 77, No. 11, Nov 1989: 1735-1744.

10. Robert E. Boisvert and Vincent A. Orlando. "ADS-Mode S System Overview." In IEEE, 1993: 104-109.

11. Raj Jain. The Art of Computer System Performance Analysis: Techniques for Experimental Design, Measurement, and Modeling. New York: Wiley, 1991.

12. B. Hofmann-Wellenhof, H. Lichtenegger, and J. Collins. Global Positionling System: Theory and Practice. New York: Springer-Verlag, 1997.

13. Bernard Sklar. Digital Communications Fundamentals and Application. Upper Saddle River, New Jersey: PTR Prentice Hall, 1988.

14. Leslie W. Barclay, Martin P. Hall, and M. T. Hewitt. Propagation of Radiowaves. London: Institute of Electrical Engineers, 1996.

# Vita

Eric Shea was born in Fredericksburg, Virginia on February 24, 1978 to George and Eileen Shea. He was raised in King George, Virginia until the age of 18. Upon graduation from King George High School, Eric accepted a nomination from Congressman Herbert Bateman to attend the United States Naval Academy.

At USNA, Eric studied electrical engineering, specializing in communications engineering. Following his senior year, he was named the 2000 Captain Boyd R. Alexander, USN Honor Award Recipient for excellence in electrical engineering. Eric graduated with distinction from the Naval Academy on May 24, 2000 with a Bachelors of Science degree. Upon graduation he received his commission in the United States Navy as an Ensign and chose submarine warfare as his service selection.

Eric was awarded with one of 25 immediate graduate education slots from the Naval Academy in 2000 as part of the Immediate Graduate Education Program (IGEP). He was awarded a tuition scholarship from and attended Virginia Polytechnic Institute and State University. He specialized in communication engineering, specifically radars, satellite communications, and digital communications.

Upon receiving his Masters of Science degree, Eric will report to Charleston, SC where he will continue with his Naval career in the submarine force.