Project Report
ATC-370

MIT Lincoln Laboratory TCAS Performance

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16. Abstract

The Traffic Alert and Collision Avoidance System (TCAS) Version 7 surveillance requirements were developed in the mid-1990s with the use of limited radar data. Recently, a more comprehensive radar data source has become available, enabling a thorough analysis of TCAS surveillance performance throughout the National Airspace System (NAS).

This paper characterizes six high traffic terminal environments over three months. A busy one hour period was selected from each location for density and equipage measurements. This paper then describes the use of a high fidelity simulation to characterize TCAS surveillance performance in the six locations. Transponder utilization due to TCAS and TCAS surveillance range are compared with the design requirements, including interference limiting specifications. The effect of TCAS surveillance activity on Air Traffic Control (ATC) ground radar performance is also investigated. Results indicate that the surveillance algorithms perform as intended and that TCAS has a minimal impact on ground radar. Areas of concern are noted for future investigation.

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EXECUTIVE SUMMARY

The primary purposes of the surveillance performance analysis are to:

- Determine if a surveillance implementation of the Version 7/7.1 TCAS MOPS [1] operates as the requirements intend in the current aircraft environment seen in busy terminal areas throughout the National Airspace System (NAS),
- Identify areas of concern for potential changes to the surveillance requirements in the TCAS MOPS, and
- Serve as a baseline against which to measure future changes, both in terms of environment (e.g., aircraft density) and surveillance algorithm performance.

A secondary goal of the analysis is to characterize the aircraft density experienced in terminal environments. Measurements of aircraft density were performed in the mid-1980s as a part of the original TCAS surveillance development. Comparisons between these previous measurements and current measurements are useful for understanding the growth of air traffic over recent decades and in predicting air traffic growth in the future.

TCAS Surveillance Background

Air Traffic Control (ATC) ground radars and TCAS units operate on the same 1030/1090 MHz secondary surveillance channels; as a result, both must share access to a given transponder. A major consideration in the development of the TCAS surveillance requirements has been to balance the needs of both TCAS and ground radars. Current TCAS MOPS and International Civil Aviation Organization (ICAO) Airborne Collision Avoidance System (ACAS) Standards and Recommended Practices (SARPs) [2] have requirements to limit each TCAS unit's interrogations such that the aggregate of all TCAS interrogations occupy no more than 2% of any transponder's time.

TCAS performs this limiting function, called interference limiting, by counting special TCAS broadcast messages transmitted by TCAS units. When the count exceeds a defined threshold, TCAS reduces its maximum possible interrogation power, thus no longer eliciting replies from more distant transponders. In this way, the aggregate rate of TCAS interrogations received by any single transponder is limited to an acceptable upper bound. (Note, however, that regardless of the interrogation power limit, a TCAS unit is prohibited from reducing its interrogation power below a specified level in order for it to maintain a minimum capability for collision avoidance protection.) The maximum power reduction was expected to be necessary only below 10,000 feet and near busy terminal areas, where aircraft would be subject to 250 knot speed restrictions. The low closing speeds require less surveillance range for collision avoidance protection.

The current interference limiting algorithms were developed in part with the use of previously recorded radar data (circa 1990). This paper investigates how well the interference limiting algorithms are working in today's surveillance environment.

Three main metrics are used in this report to assess TCAS surveillance performance:

- Transponder utilization on TCAS equipped aircraft due to TCAS activity.
- The frequency/location of "interference limiting hotspots," defined as areas in which TCAS has reduced its interrogation power by the maximum amount allowed, but the interference limiting algorithms desire to further reduce power in order to keep transponder utilization below 2%. This metric is expected to correlate highly with the first metric.
- The frequency/location of "surveillance hotspots," defined as areas in which surveillance range has been reduced to an extent that it can no longer provide timely TCAS alerts. This could potentially occur at altitudes just above 10,000 feet, where a TCAS aircraft has reduced its interrogation power due to interference limiting but still can experience very high closure rate encounters.

Scope of Report

The Version 7 TCAS surveillance requirements were developed in the mid-1990s using a brief (15-minute) radar dataset from Dallas Fort Worth. Occasional TCAS surveillance performance analyses have been undertaken in the intervening years, but not until the current TCAS Operational Performance Assessment (TOPA) program [3] has there been sufficient detailed radar data available to perform a comprehensive TCAS surveillance analysis.

The extent (both duration and location) of detailed ground radar data available via the TOPA program exceeds by many orders of magnitude the amount of data previously available for TCAS surveillance performance analysis. It is not practical to perform in-depth analysis on all of these data. Therefore, an attempt has been made in this report to provide certain statistics for all locations and all available time (generally 24/7) to detect anomalies and/or areas of concern and then to focus on smaller time periods for in-depth analysis. This process of choosing the time periods of interest is described further in Section 3.

This paper characterizes six high traffic terminal environments over three months. The average number of aircraft being tracked by beacon radar at LAX (Los Angeles International Airport), JFK (John F. Kennedy International Airport), PHL (Philadelphia International Airport), DFW (Dallas Fort Worth Airport), LGB (Long Beach Airport), and ONT (LA/Ontario International Airport) was calculated for each one hour period in August, September, and October of 2009. The busiest one hour period was selected from each location for density and equipage measurements. The measurements conformed to the maximum acceptable density requirements in the TCAS MOPS and agreed with density measurements recorded in 1976. Equipage data revealed a higher than expected percentage of ATCRBS aircraft.

A high fidelity simulation was then used to characterize TCAS surveillance performance on the busy one hour period in each of the six high traffic terminal environments. Transponder utilization due to TCAS and TCAS surveillance range were compared with the interference limiting design requirements. It was found that a MOPS implementation of the TCAS surveillance logic performed as the requirements intended in the crowded areas. Interference limiting kept transponder utilization figures around 2%, and little or no activity measured above 3.5%. Surveillance range analyses revealed the potential for interference limiting and surveillance hotspots to exist. Interference limiting hotspots were expected and will contribute to the previously mentioned transponder utilization due to TCAS. Surveillance hotspots represent a potential safety concern, the scope and nature of which will be investigated in future reports, along with mitigations if necessary.

The effect of TCAS surveillance activity on Air Traffic Control (ATC) ground radar performance was also investigated. Analyses performed to assess the potential for ground ATC radar interference from TCAS indicated that transponder utilizations up to 5% have a negligible impact on U.S. ground radar performance.

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The authors would like to thank Neal Suchy, FAA TCAS Program Manager, who is responsible for overseeing the Lincoln Laboratory TCAS work. It is because of his vision that research into the performance of TCAS surveillance logic is being completed.

We would also like to thank the other members of the Lincoln TCAS surveillance team, Barbara Chludzinski, Ann Drumm, Tomas Elder, Bill Harman, Garrett Harris, and Wes Olson, who contributed regularly to this work by discussion of analyses and results and review of documentation.

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INTRODUCTION

1.1 PURPOSE

The primary purposes of the surveillance performance analysis are to:

- Determine if a surveillance implementation of the Version 7/7.1[1] TCAS MOPS [1] operates as the requirements intend in the current aircraft environment seen in busy terminal areas throughout the National Airspace System (NAS),
- Identify areas of concern for potential changes to the surveillance requirements in the TCAS MOPS, and
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1.2 TCAS SURVEILLANCE BACKGROUND

Air Traffic Control (ATC) ground radars and TCAS units operate on the same 1030/1090 MHz secondary surveillance channels; as a result, both must share access to a given transponder. A major consideration in the development of the TCAS surveillance requirements has been to balance the needs of both TCAS and ground radars. Current TCAS MOPS and International Civil Aviation Organization (ICAO) Airborne Collision Avoidance System (ACAS) Standards and Recommended Practices (SARPs) [2] have requirements to limit each TCAS unit's interrogations such that the aggregate of all TCAS interrogations occupy no more than 2% of any transponder's time.

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[1] TCAS surveillance requirements did not change from Version 7 to Version 7.1. The surveillance requirements in both documents are identical.

TCAS unit is prohibited from reducing its interrogation power below a specified level in order for it to maintain a minimum capability for collision avoidance protection.) The maximum power reduction was expected to be necessary only below 10,000 feet and near busy terminal areas, where aircraft would be subject to 250 knot speed restrictions. The low closing speeds require less surveillance range for collision avoidance protection.

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1.3 SCOPE OF REPORT

The Version 7 TCAS surveillance requirements were developed in the mid-1990s using a brief (15-minute) radar dataset from Dallas Fort Worth. Occasional TCAS surveillance performance analyses have been undertaken in the intervening years, but not until the current TCAS Operational Performance Assessment (TOPA) program [3] has there been sufficient detailed radar data available to perform a comprehensive TCAS surveillance analysis.

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Following Section 1, the report is divided into four additional main sections. Section 2 gives an overview of the MIT Lincoln Laboratory TCAS surveillance simulation and the inputs to the simulation. Section 3 gives a three month summary of aircraft tracks observed at each radar site, discusses the aircraft density results, and provides a comparison between current and mid 1970s measurements. Section 4 gives simulation results, with one subsection for each of the three main metrics. Section 5 contains a summary and our plans for future work.

2. SIMULATION AND DATA OVERVIEW

The following two sections describe the TCAS surveillance simulation and the aircraft track data source used throughout this report.

2.1 MIT SURVEILLANCE SIMULATION OVERVIEW

The MIT TCAS Surveillance Simulation has been utilized over the past 15 years for surveillance analysis and played a crucial role in the development of Version 7 surveillance algorithms. Over the past year significant effort has been applied to updating the simulation to accurately reflect TCAS Version 7/7.1 surveillance requirements. Additional revisions have been made to allow for the input of new data sources. Updates to the simulation and associated processing tools have been made to take advantage of substantial increases in processing speed from parallel computing.

In this report, the simulation makes use of actual aircraft flight paths as measured by a Mode S radar. In the simulation it is necessary to designate the values of transmitter power and receiver sensitivity for the transponder and the TCAS unit of each aircraft. These values are not available from the radar data and are assigned by the simulation randomly based on the allowed variations in the transponder MOPS [4] and the TCAS MOPS. Aircraft antenna gains are also assigned by the simulation, using a horizontal gain pattern measured from a Bendix antenna.

Figure 1 provides an overview surveillance simulation program flow. The simulation reads inputs of one second aircraft track updates including the following information: update time, position, velocity, altitude, track number, Mode A code, Mode S address, and TCAS and transponder equipages. The data is processed to either update existing aircraft tracks or create new tracks and assign transponder characteristics. Once a full one second update has been input, the operation of each TCAS unit is simulated. For each TCAS unit, the Number of TCAS Aircraft (NTA) within communication range is determined, the interference limiting inequalities are calculated, and the Mode C and Mode S surveillance sequences are performed. Important outputs include: monitoring and tracking lists, transponder utilization due to mutual suppression from own aircraft's TCAS interrogations, transponder utilization due to interrogations received from other TCAS aircraft, and TCAS surveillance range. After the entire TCAS environment run has completed, the simulation processes the next second of input data and repeats the procedure until the input file is completed.

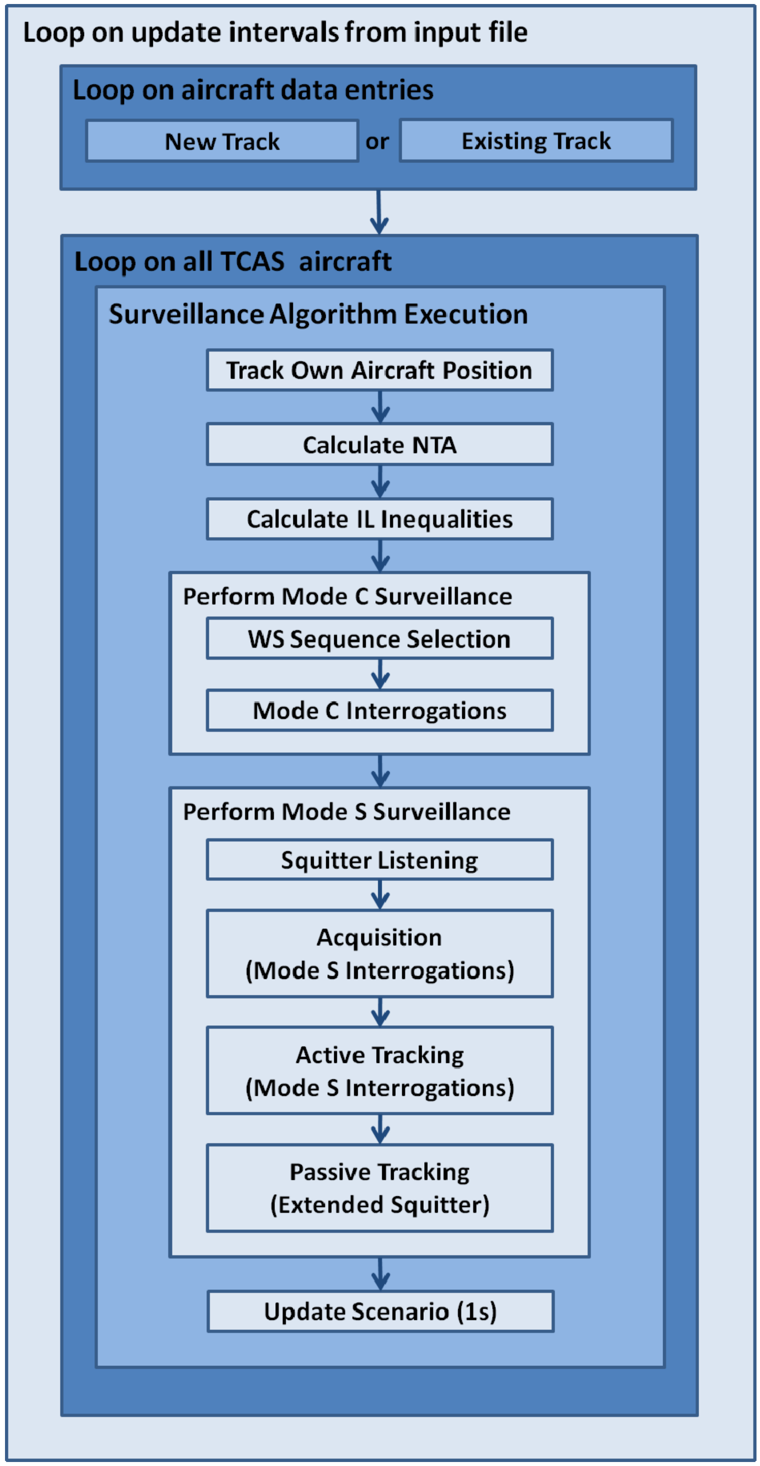

Figure 1. MIT Surveillance Simulation Flow Diagram

The Surveillance Simulation is aided by a collection of pre- and post-processing tools. Pre-processing tools condition the input data for the simulation by extracting all relevant information from the data source, removing duplicate tracks and tracks with insufficient data, smoothing and interpolating the data to one second updates, and generating appropriately formatted track updates for the surveillance simulation. Data sources currently include TRAMS, described in Section 2.2, and simulated inputs. The post-processing tools analyze and interpret the detailed and extensive outputs from the simulation, and display the information in an effective visual form.

2.2 TRAMS DATA OVERVIEW

The TCAS Resolution Advisory Monitoring System (TRAMS) is the source for the Mode S radar tracks used for the studies contained in this report. TRAMS is developed and maintained by the Engineering Services Development Group, Airborne Team at the FAA Technical Center (AJP-651). This system uses the data extraction capability available at existing FAA Mode S radars to gather Resolution Advisory (RA) downlinks, Data Link Capability (DLC) reports, and associated surveillance information to form aircraft track datasets with 24 hour surveillance. A key point is that the data extraction procedure provides more information than is possible with standard radar outputs: the 24-bit ICAO aircraft address is recorded for all Mode S-equipped aircraft and the equipage of each aircraft from DLC reports is extracted. This detailed information makes it possible for the surveillance simulation to use actual assignments for the ATCRBS, Mode S, and TCAS avionics on each aircraft. Twenty-one TRAMS locations are planned for installation at various radar locations within the NAS by mid 2011. Future TCAS Surveillance Performance Reports will broaden the area of research to include data from all TRAMS sites available. The locations noted in Table 1 are studied in this report. The months of August through October 2009 were chosen for examination as data was available from all six sites and included busy air traffic periods in the summer and fall.

TABLE 1

TRAMS Sensors, Locations, and Operational Dates

Sensor Identification	*Location*	*Date Operational*
PHL	Philadelphia, PA	May 2008
JFK	New York, NY	May 2008
LAX	Los Angeles, CA	November 2008
DFW	Dallas, TX	April 2009
LGB	Long Beach, CA	July 2009
ONT	Ontario, CA	July 2009

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3. CHARACTERIZING THE TCAS ENVIRONMENT

An important component of TCAS surveillance performance analysis is characterizing the environment in which TCAS operates. This report looks at several environmental factors that impact TCAS surveillance performance. First, a general characterization of aircraft concentration is made based on the average number of aircraft each radar is tracking. Aircraft equipage information for each site is presented. Density measurements are then explored.

3.1 RADAR TRACK COUNTS

3.1.1 Three Month Track Counts

In order to determine an appropriate time interval for comprehensive study, each TRAMS site was studied using three months of data (August through October 2009). Individual sites are described over the three month period by counting the number of aircraft tracked by the radar. The aircraft track counts were calculated by finding the number of unique aircraft tracks for each scan and then averaging those numbers over a one hour period.

Results are shown in Figure 2, Figure 3, and Figure 4[2]. Each column represents one day, each row represents an hour. The number within each cell represents the average number of aircraft tracks per scan observed for that hour divided by 10; greater track counts are highlighted in two shades of red. Light red shading represents between 60 and 119 tracks per scan inclusive, and dark red shading represents 120 or greater tracks per scan. Black indicates insufficient data, less than 50 minutes provided during that hour. As expected radars near larger, more heavily traveled airports such as JFK and LAX track significantly more aircraft than the radar near ONT, which tracks aircraft landing at several small airports. JFK has the highest track counts, with values reaching over 220 tracks per scan. These high track counts can be attributed to the JFK radar tracking aircraft traveling to and from three high traffic airports: JFK, EWR (Newark, NJ), and LGA (La Guardia, NY), as well as other smaller airports in the area. DFW displays a non-trivial number of hours with insufficient data throughout the three month period. The DFW data loss results from an issue with the TRAMS recording process and plans have been made for a correction.

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[2] Figure 2, Figure 3, and Figure 4 show the total number of aircraft tracks seen by the radar, including both airborne and on ground aircraft. A limitation in the TRAMS data causes aircraft reporting altitude below 0 feet to be left out of the aircraft track data. Therefore the aircraft track counts are also a function of the barometric pressure for sites close to sea level (JFK, PHL, and LAX). However, on-ground aircraft account for only a small portion, approximately 5%, of the total aircraft tracks during peak hours of the day, so this limitation is not considered to be significant.

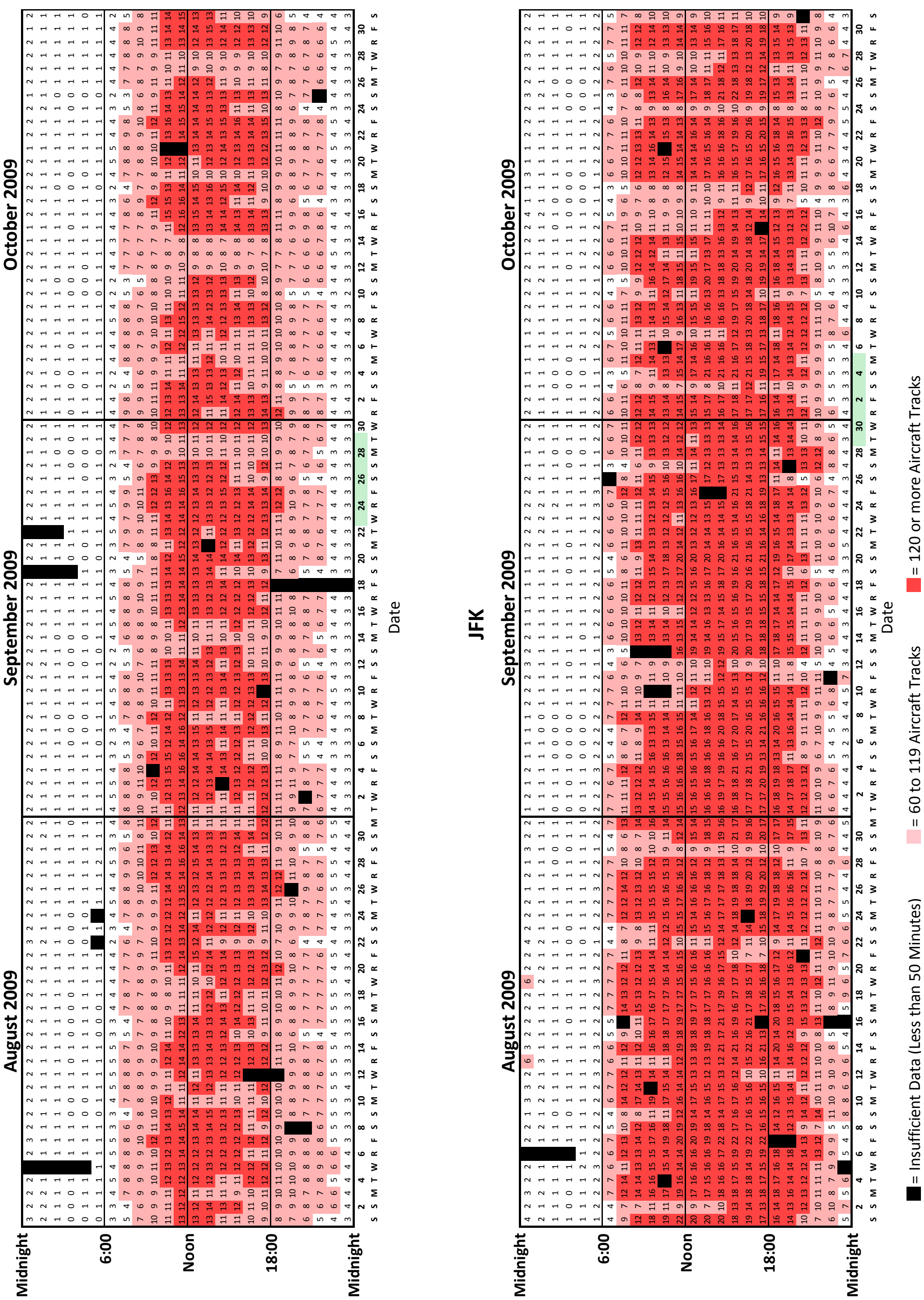


Figure 2. Aircraft Track Counts LAX and JFK

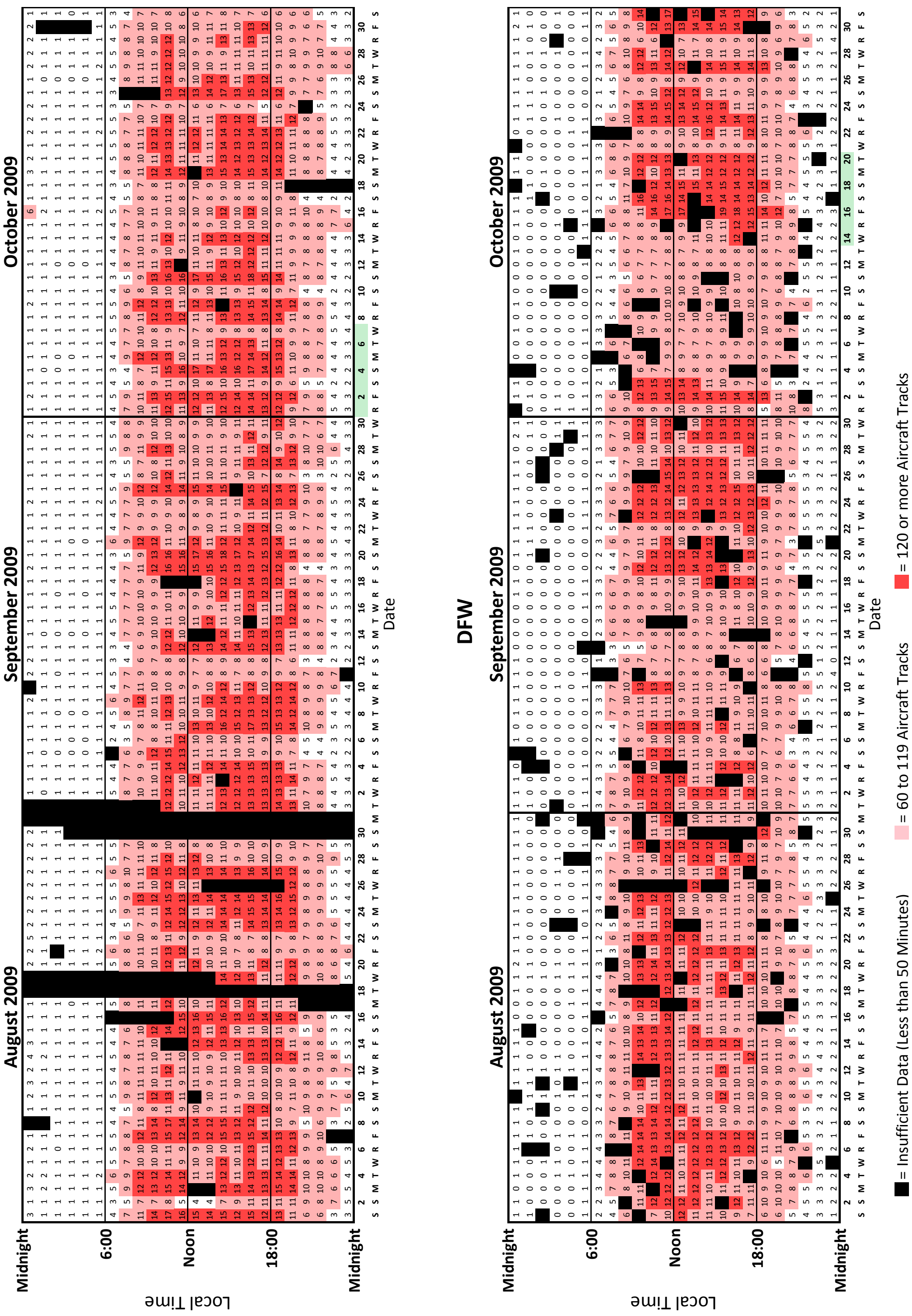


Figure 3. Aircraft Track Counts PHL and DFW

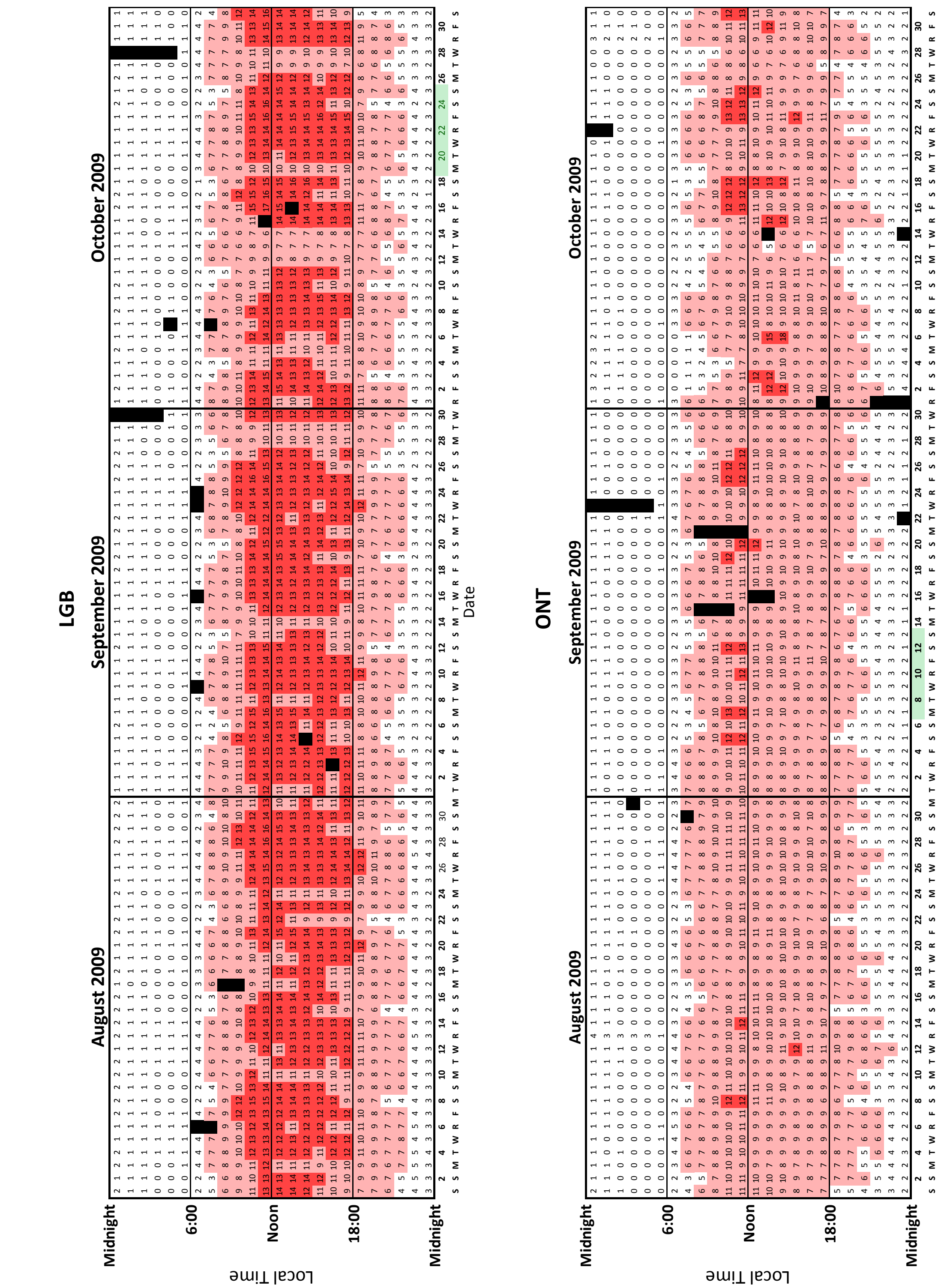


Figure 4. Aircraft Track Counts LGB and ONT

3.1.2 One Week Detailed Track Counts

For each of the six three month track count charts in Section 3.1.1, a one week period of high aircraft activity is highlighted in green for further investigation. The criteria for choosing the one week period was a sufficiently busy time with at least one day of very high activity with low barometric pressure. As noted earlier, a limitation of the TRAMS data causes aircraft track updates reporting altitudes of less than zero to be omitted; therefore, a time with low barometric pressure is necessary for aircraft on the ground to be included. The selected one week periods were examined in greater detail by creating a separate graph of the number of aircraft tracks for each day. Each graph plots the average number of aircraft tracks per hour within six different airspace volumes based on aircraft range from the radar, R = 10, 20, 30, 40, 50, and 60 nm. A very busy hour with low pressure within the week, highlighted in green, was chosen for all further analysis conducted in this report. This procedure was completed for all six sites. Detailed aircraft track counts for two sites of high interest, LAX and JFK, are shown in Figure 5 and Figure 6.

The one hour periods of interest chosen for further study are shown below in Table 2.

TABLE 2

Selected One Hour Period

Airport	Date	Local Time
LAX	09/25/2009	11-12
JFK	10/04/2009	15-16
PHL	10/04/2009	16-17
DFW	10/16/2009	15-16
LBG	10/23/2009	15-16
ONT	09/12/2009	11-12

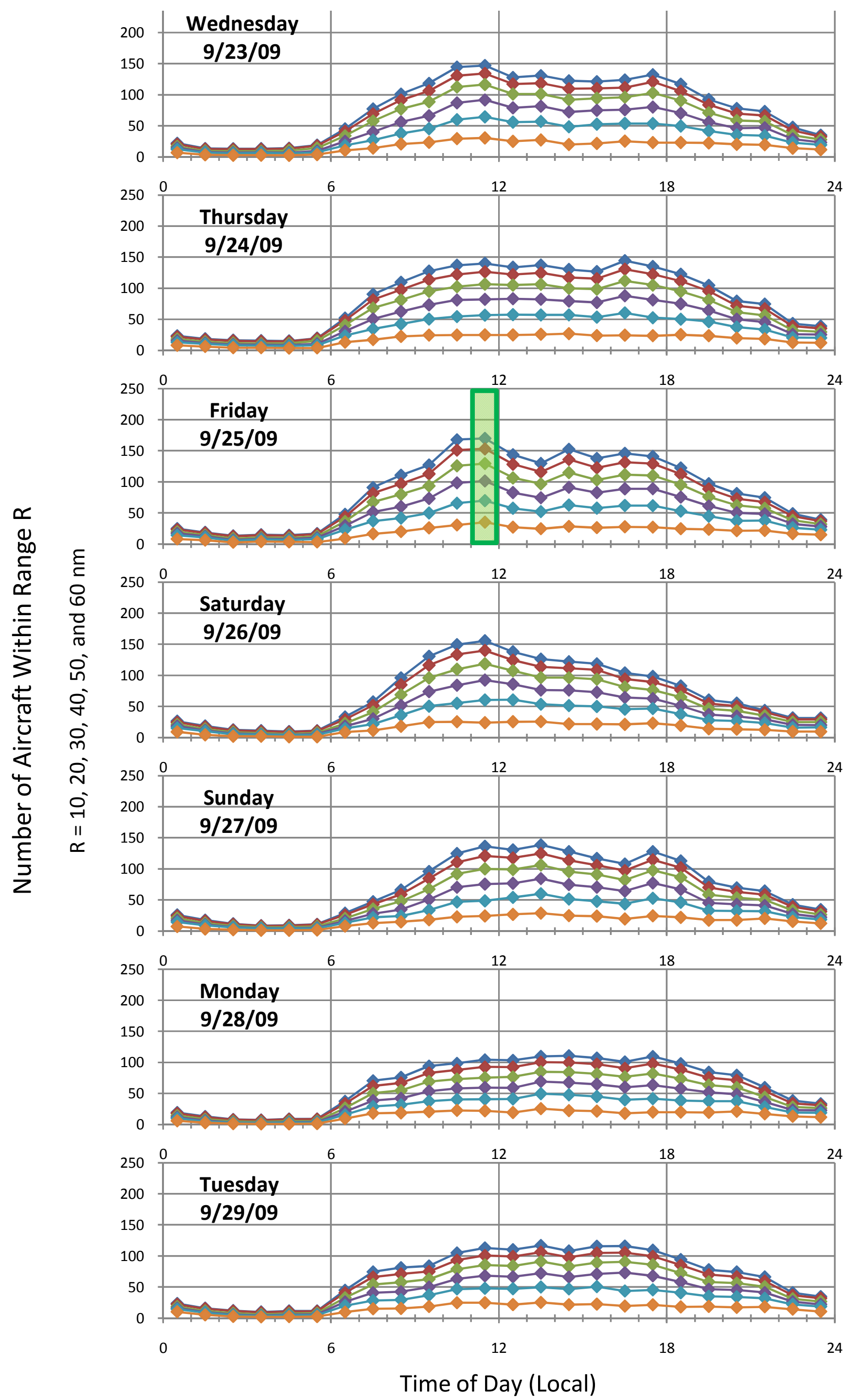


Figure 5. One Week Detailed Radar Track Counts LAX

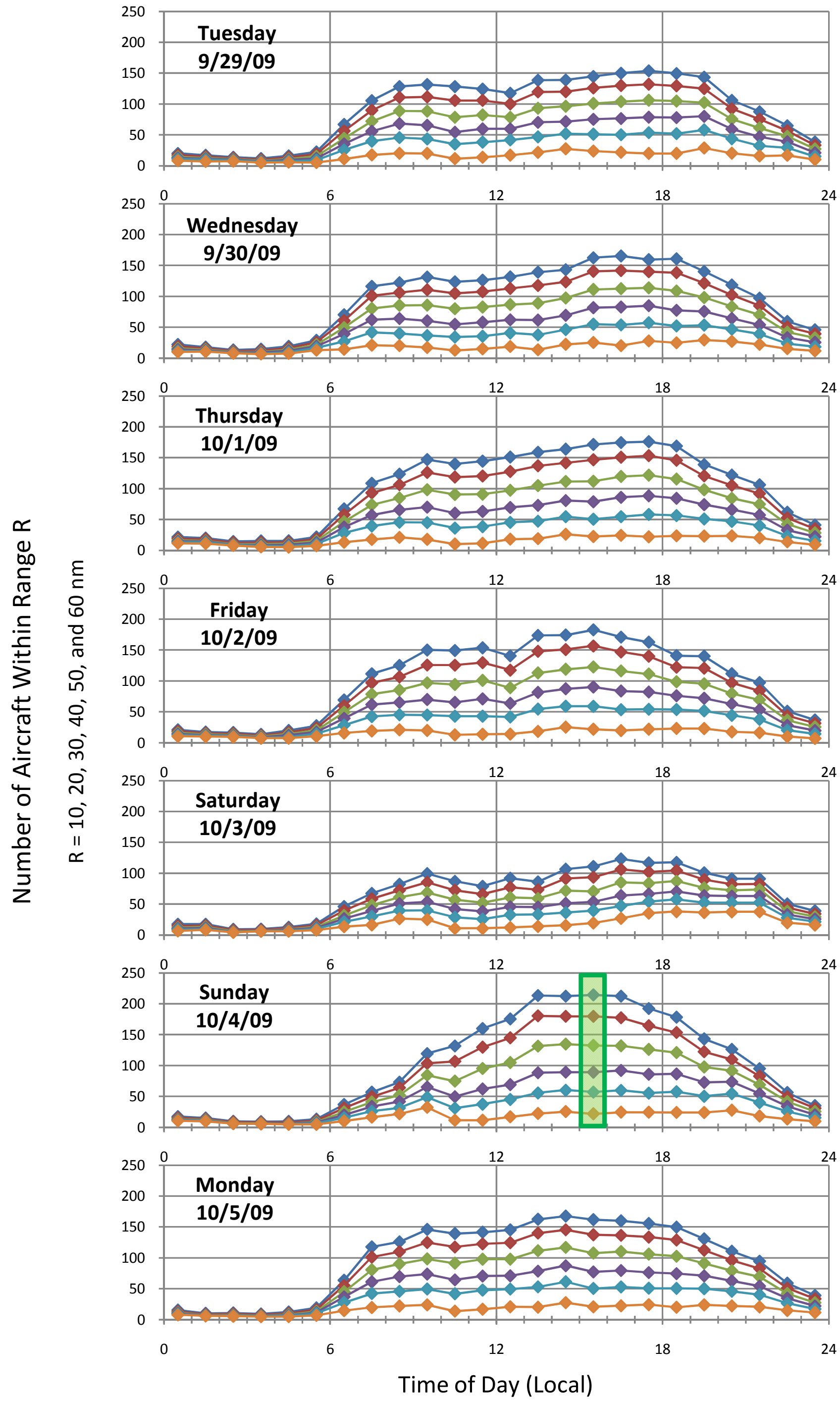


Figure 6. One Week Detailed Radar Track Counts JFK

3.1.3 Aircraft Equipage Information

Figure 7 displays the equipage information for each unique track as seen by the radar. As expected LAX, LGB, and ONT areas are dominated by ATCRBS tracks on busy days, while JFK and PHL show a higher percentage of TCAS traffic. Even so, TCAS and Mode S equipage percentages appear to be lower than expected at all airports. This is a result of the criteria for choosing the one hour period. The one hour period was selected by searching for a time when the radar was tracking the greatest number of aircraft. A short investigation revealed that, predictably, around the same number of TCAS equipped aircraft fly in and out of major airports per day. These aircraft are mostly passenger airliners that conform to planned schedules. The fluctuation in the number of tracked aircraft, other than from adverse weather or day of the week, is mostly due to general aviation (GA) ATCRBS equipped aircraft. Therefore, choosing a time with very high numbers of tracked aircraft correlates to the time when ACTRBS traffic is high. Future reports will investigate equipages in greater detail over a range of days and weather conditions.

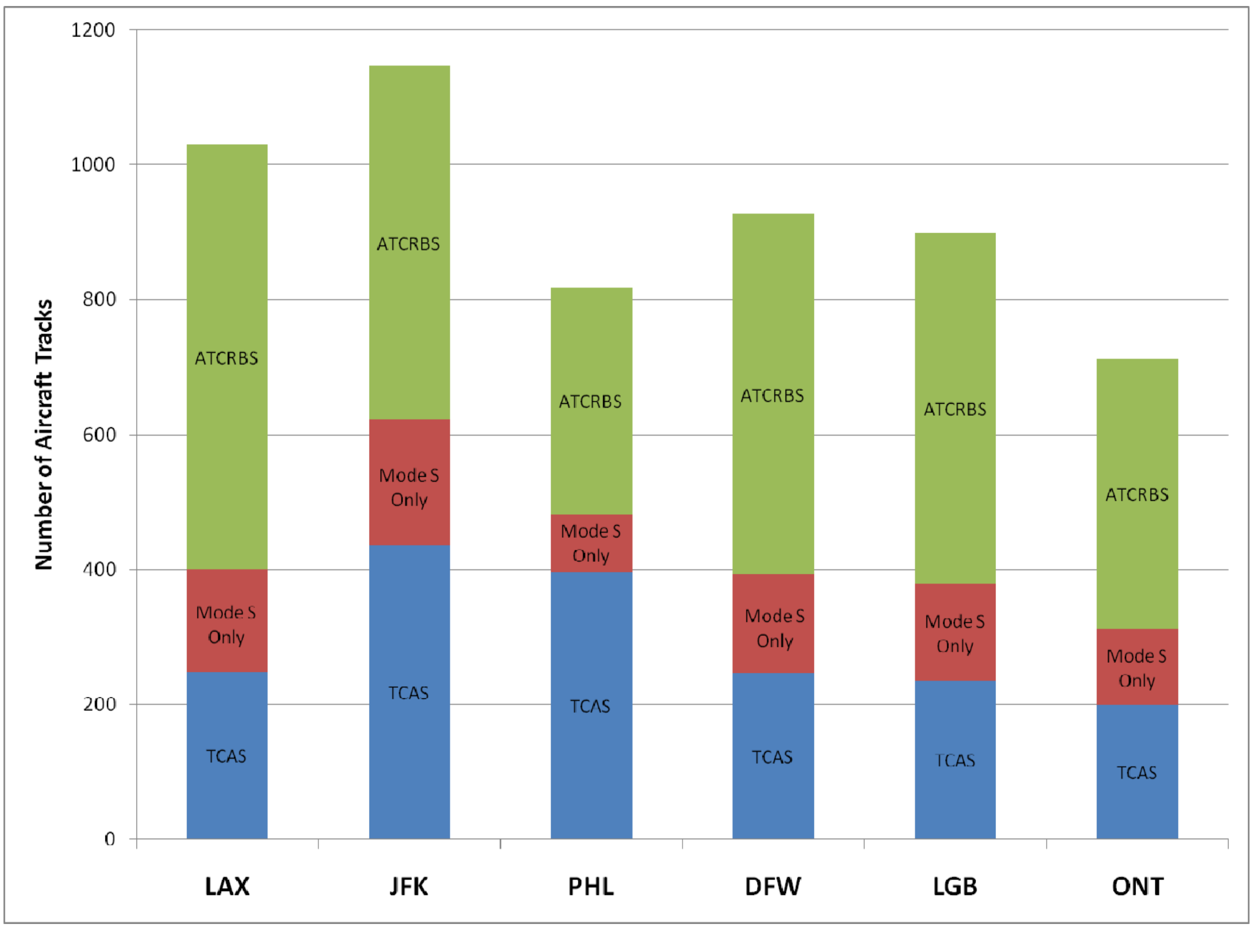


Figure 7. Aircraft Track Equipages

3.2 AIRCRAFT DENSITY

Aircraft density information is important to the study of the TCAS surveillance algorithms as several factors integrated in the algorithms are based on maximum aircraft density assumptions. Two specific density functions that relate to the surveillance algorithms are local maximum density and cumulative aircraft distribution. Each function is evaluated for the one hour period of high activity selected from each site.

3.2.1 Local Maximum Density

Local maximum density describes the largest number of aircraft a TCAS unit is likely to see at any given time. Local maximum density is calculated by counting the number of aircraft within range of a given point, then dividing the aircraft number by the area over which the count was summed. The two assumptions in the MOPS DO-185B Table 2-1 for aircraft density are contained in Table 2.

TABLE 3

TCAS II Assumed Maximum Aircraft Density

Airspace	Max. Closing Speed Knots	Max. Traffic Density A/C per sq nm	Ro nm
Lower Altitude	500	0.3	5
Higher Altitude	1200	0.06	10

The lower altitude assumption of 0.3 aircraft per sq nm uses a range, Ro, of 5 nm which corresponds with the minimum reliable surveillance range of TCAS; see Figure 15. The higher altitude assumption of 0.06 aircraft per sq nm uses a range of 10 nm. The values in Table 3 display the greatest local maximum density calculated within 30 nm of each airport. All density values are well below the maximum values included in the MOPS.

TABLE 4

TCAS II Measured Maximum Aircraft Density

Airspace	LAX	JFK	PHL	DFW	LGB	ONT
Lower Altitude <= 10,000 feet	0.0868	0.0981	0.0655	0.0660	0.1010	0.1040
Higher Altitude > 10,000 feet	0.0070	0.0098	0.0090	0.0081	0.0083	0.0069

Aircraft density measurements from the 1970s and 1980s were used for the initial development of TCAS surveillance algorithms. The FAA ATC report titled “Air Traffic Density and Distribution Measurements” [5] computes local maximum densities in the Los Angeles Basin. The measurements in 1976 were taken from a radar located in Brea, California, just east of LAX and LGB. Local maximum densities were calculated over 20 minute periods on four separate days around Thanksgiving. Each local density figure used a radius of 10 nm. The same techniques were used to calculate local densities in the same area with radar data from LAX and LGB recorded in 2008 and 2009. A comparison of the 1976, 2008, and 2009 maximum local densities are shown in Figure 8. A 1% exponential growth figure is shown from the mean 1976 value for comparison. It is evident that current local maximum densities in the LA area are not significantly different from those measured in 1976.

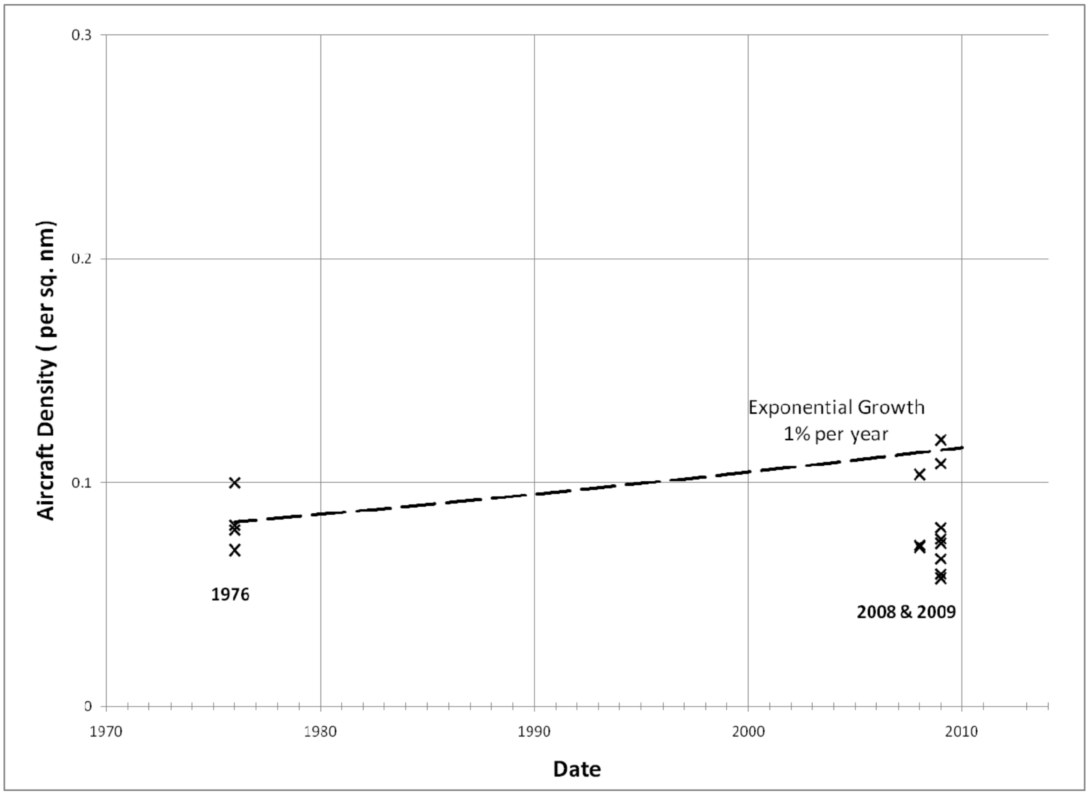


Figure 8. Local Maximum Density Comparison

3.2.2 Cumulative Aircraft Density

Figure 9 shows the average range distribution of airborne traffic over the one hour period under study. Two simple mathematical models are included in the plot for comparison: uniform-in-area and uniform-in-range. Comparisons indicate that within 20 nm all radars display a uniform-in-area distribution centered on .05 aircraft per sq nm. The densities at LAX are slightly greater, around 0.07 aircraft per sq nm, while JFK, PHL, and DFW data is better described by 0.04 aircraft per sq nm. Ranges 20 to 60 nm at all airports are best described by a uniform-in-range distribution with a density varying slightly between 2.4 and 2.8 aircraft per nm.

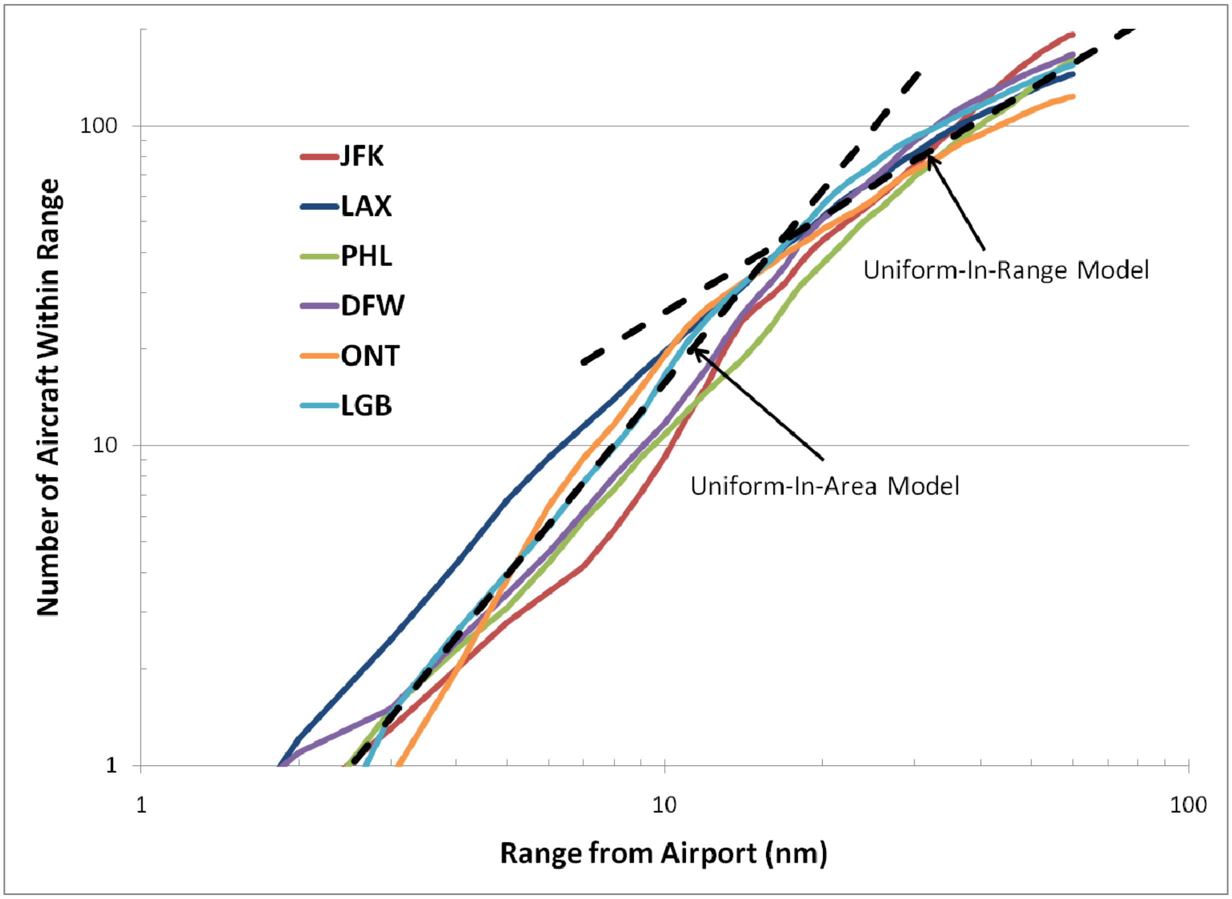


Figure 9. Range Distribution of Traffic

4. SURVEILLANCE SIMULATION RESULTS

The following results from the TCAS surveillance simulation provide an initial look into the performance of the TCAS surveillance algorithms. Previously the surveillance simulation used only one 15 minute dataset from DFW due to the limited availability of radar data, the high degree of preprocessing required before running the simulation, and the limitations of computer resources at the time. In contrast, this report gives an indication of TCAS surveillance performance over a much broader area, using one hour periods from several interesting high traffic airspace environments. The simulation results can uncover situations in the TCAS surveillance environment that require further study and potential algorithm modifications. Subsequent TCAS Surveillance Performance Reports will focus on possible mitigations for concerns noted in this paper.

The following paragraphs discuss simulation fidelity and highlight some of the areas where the simulation results may differ from the real-world.

Ground radar vs. airborne radar. The use of ground radar data[3] to estimate the surveillance environment visible to an airborne aircraft requires several important considerations. Because all of the current TRAMS sites use terminal radars, data is limited in range to 60 nm. Also, the minimum measurable target altitude from a ground radar increases proportional to range, from near ground level when close to the radar to approximately 3,000 feet at a range of 60 nm. In contrast, the range and altitude visible to an airborne TCAS aircraft are limited generally only by the TCAS transmit power and receiver sensitivity. Thus, aircraft near the edge of the radar coverage will see many aircraft not seen by the ground radar. This could cause the simulation to undercount a long-range TCAS aircraft's NTA value or to undercount 1030 MHz interrogations received by its transponder.

In addition, using the TRAMS data as a source for aircraft tracks means that when an aircraft enters or re-enters the view of the radar, it appears as a new track. In the simulation this is equivalent to an aircraft appearing and activating its onboard TCAS in mid-air. This can occur when a track is dropped and restarted or when a track emerges from behind an obstruction such as a mountain. This can produce a momentary burst of transmissions from the simulated TCAS aircraft that would not occur in the actual aircraft, potentially causing a slight over-count of 1030 MHz interrogations and subsequent 1090 MHz replies related to that aircraft.

A mitigation for the use of ground data to simulate airborne results is to focus attention on areas near the radar where the ground and airborne views are nearly identical. Therefore, this paper will focus the analysis of transponder utilization and "interference limiting hotpots" to only show results from data

[3] The simulation is most often run using ground radar data as the input source. Indeed, simulation results included in this paper use TRAMS radar data as input. However, the simulation can also be run using airborne-recorded data as input. In this case, the simulation results would exactly capture the environment seen by the aircraft.

within 10 NM of the radar. “Surveillance hotspots” are an exception, as that analysis only uses aircraft at high altitude which are not as affected by the limitations of ground radar. Therefore, the range of study for “surveillance hotspots” is extended to 30 nm.

Future analysis will compare simulation outputs generated using ground data with recorded data from airborne TCAS test flights. This will provide insight into the effects of ground vs. airborne data and allow for improvements to be introduced into the simulation to better represent the environment as seen by an airborne aircraft.

TRAMS input data limitations. Current TRAMS data does not provide flight status information. Therefore, the simulation must set the “on-ground” or “airborne” bit status based on an altitude cutoff just above ground level. As a consequence, an aircraft must switch TCAS operation between “on-ground” and “airborne” in mid-air rather than based on the actual bit status as would normally occur. The flight status information will be included in later TRAMS software versions, allowing a more accurate simulation of aircraft take off performance.

Furthermore, TRAMS does not provide continually updated TCAS functionality information, so the simulation assumes that a TCAS unit is powered on just as an aircraft is set to take off from an airport and its speed exceeds taxi speed. This could lead to the simulation underestimating the contributions of TCAS units on the ground if they have been powered on for long periods of time.

MOPS implementation vs. manufacturer implementation. The surveillance simulation used to create the figures in this report currently implements surveillance requirements as given in the TCAS MOPS. Due to manufacturer specific implementations and deviations, it is likely that the simulation may not exactly represent all aspects of a specific manufacturer’s TCAS implementation.

Assumption of NTA 30. The simulation assumes a TCAS unit would receive TCAS broadcasts (used to determine NTA) from aircraft within a range of approximately 30 NM, which is the MOPS anticipated range for the TCAS data link. Several test flights conducted by the FAA Technical Center have shown that this assumption may be inaccurate. It has been shown that the number of TCAS aircraft nominally within range is greater than expected. NTA counts of over 150 have been recorded in the JFK area, while the surveillance simulation sees a maximum NTA of approximately 100 during the busiest times near JFK.

The surveillance simulation produces large volumes of data for all tracks within coverage. Intensity maps are used to display a meaningful picture of the surveillance environment. An intensity map shows the magnitude of a given output across all aircraft included in the simulation. The values of interest are pooled together and displayed in an image based on aircraft position before being overlaid into Google Earth. Each point in the intensity map represents an area in latitude and longitude, and the values of interest of all aircraft that pass within a set distance from the center of the area are collected.

4.1 TRANSPONDER UTILIZATION DUE TO TCAS

The simulation calculates the time that an aircraft transponder is unavailable due to its own TCAS interrogations (mutual suppressions) and the time during which the transponder is unavailable due to interrogations from other TCAS aircraft. These values are summed to provide total transponder utilization due to TCAS on a TCAS equipped aircraft. In other words, the total transponder utilization is the time the Mode S transponder on a TCAS equipped aircraft is not available to ATC because of TCAS. Transponders on non-TCAS aircraft are also affected by TCAS. However, non-TCAS aircraft are not included in the results below because they do not have transponder utilization due to mutual suppressions and therefore would have lower transponder utilization than a TCAS aircraft in the same situation.

4.1.1 Average Utilization

The intensity maps in Figure 10 show average transponder utilization due to TCAS on TCAS equipped aircraft in the terminal areas at LAX, JFK, PHL, and DFW. Intensity maps for LGB and ONT are not shown because both exhibited low transponder utilization due to TCAS in the terminal areas. Any one point in the intensity map is the average utilization of all transponders that passed within 0.5 NM within the one hour period of study. Only points on highly traveled routes were chosen to display.

The highest transponder utilizations are centered on the runways and the approach/departure flight paths around the airports. Transponder utilization at or slightly above the desired 2% figure is seen in these highly traveled routes at each of the four airports. Five contributors to transponder utilization above 2% are discussed below. A sixth contributor is discussed later in Section 4.2.1 Interference Limiting Hotspots

The first two contributors to transponder utilization above 2% are the result of time and magnitude restrictions placed on a TCAS unit's ability to adjust its surveillance range. Interference limiting algorithms allow TCAS to adjust its maximum transmit power and reception sensitivity 1 dB every eight seconds. The "eight second freeze" between 1 dB changes provides necessary hysteresis in power adjustments to ensure deliberate surveillance range alterations that will not result in rapidly varying surveillance range due to momentary changes in aircraft density. These restrictions effectively prohibit interference limiting from adjusting to the current environment in exchange for stable surveillance. High transponder utilizations due to this effect are seen when an aircraft encounters a crowded environment and is prevented from reducing power levels quickly enough.

A third contributor to transponder utilization above 2% results from the method used by TCAS to drop an out of range track. When a tracked aircraft flies out of TCAS surveillance range, the TCAS unit will drop the track when it does not receive replies to multiple interrogation attempts. TCAS will increase the number of interrogations sent to the out of range aircraft to ensure the missed replies were not due to a brief loss in the communication link. Normally this method is sufficient for regulating tracks; however, when interference limiting reduces surveillance range, several aircraft that were previously being tracked may now be outside surveillance range. This results in extra interrogations and higher transponder utilization as TCAS attempts to reestablish communication with the out of range aircraft.

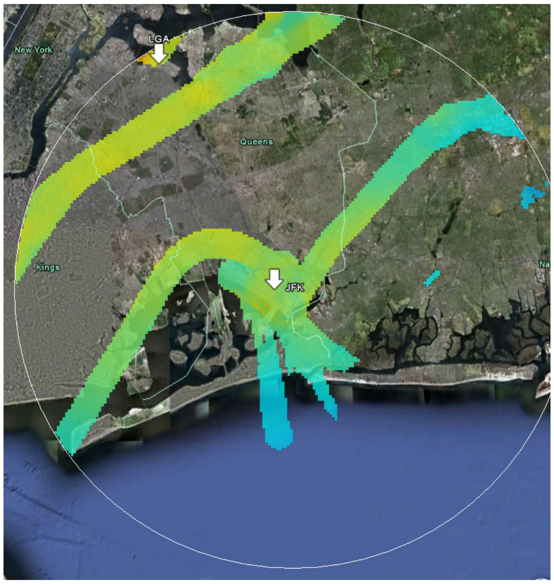
The fourth contributor to transponder utilization above 2% is heavily associated with the first three but specifically relates to a TCAS unit's initialization to full interrogation power when TCAS is first powered-on. This initialization value lengthens the amount of time required for a newly powered-on TCAS in a busy environment to decrease its power to the proper level. For example, it would take a TCAS unit 80 seconds (10 steps × 8 seconds) to reach maximum 10 dB attenuation in a busy terminal environment. While the TCAS unit is "frozen" between eight second steps, interrogations are sent to all aircraft within communication range, resulting in increased utilization of those aircraft transponders.

The fifth contributor to transponder utilizations above 2% is a factor that helps to correct for uniform-in-range TCAS aircraft distributions. Normally TCAS assumes a uniform-in-area distribution for NTA; however, uniform-in-range distributions are present around airports, including all sites covered in this paper. In order to adjust, a TCAS unit calculates the effect of the uniform-in-range distribution and corrects the surveillance parameters. The correction factor has minimum and maximum limits imposed which are appropriate for most situations. However, when an aircraft encounters an environment that is outside these bounds, transponder utilization may exceed 2%.

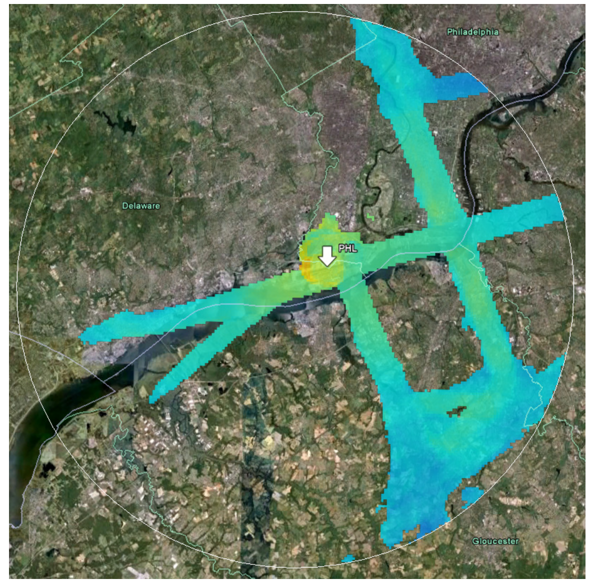
The results in Figure 10 are expected as interference limiting attempts to maximize surveillance range while keeping transponder utilization just below 2%. Placing the previously mentioned restrictions on interference limiting results in transponder utilization over the desired 2%. The restrictions exist to provide TCAS with reliable surveillance in a wide variety of environments. Greatest average utilizations of approximately 2.7% suggest that the interference limiting restriction parameters function remarkably well even in the most dense aircraft environments.

Future studies will explore tuning the interference limiting parameters noted above to dense environments within TRAMS coverage with the goal of reducing TCAS transponder utilization while maintaining or increasing surveillance range capability.

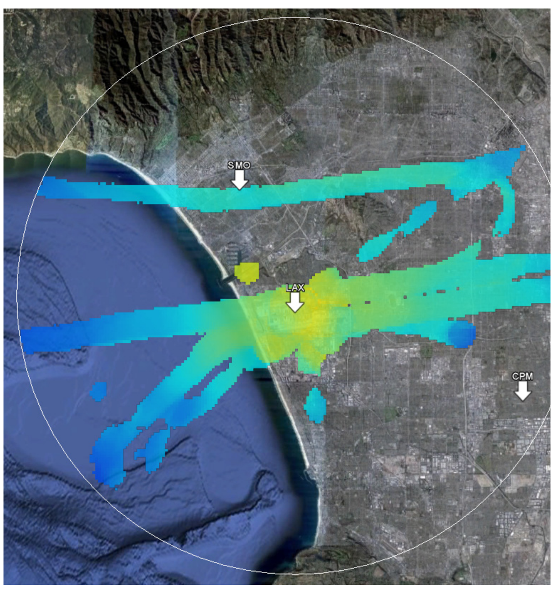
Figure 11 and Figure 12 show instantaneous transponder utilization distributions for TCAS aircraft within 10 NM of the radar. An instantaneous utilization is the transponder occupancy due to TCAS of an aircraft during a one second surveillance interval. At LAX, JFK, PHL, and DFW over 90% of TCAS utilizations are less than 3% and almost none of the aircraft ever reach a transponder utilization greater than 3.5%. LGB and ONT show almost no transponder utilization over 2% at any time.



(a) JFK



(b) PHL



(c) LAX

(d) DFW

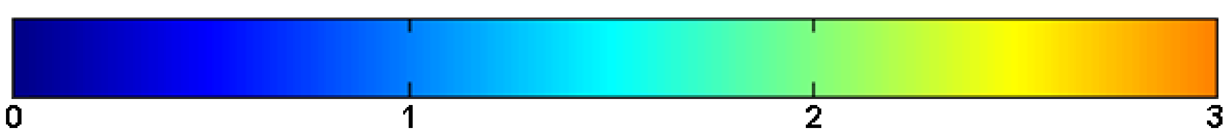


Figure 10. Average Transponder Utilization Due to TCAS (%)

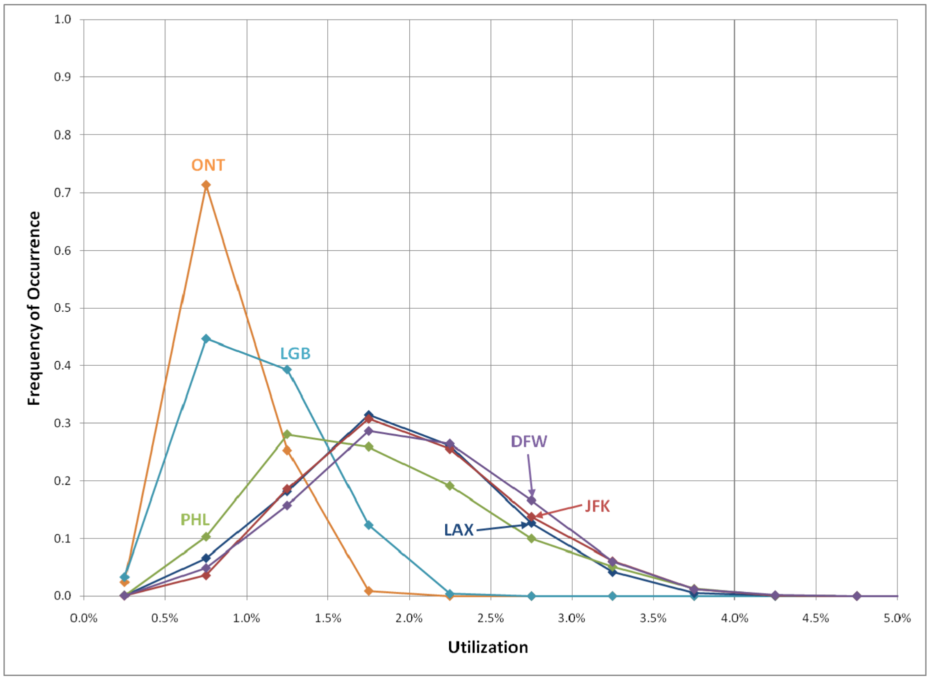


Figure 11. Normalized Distribution of Instantaneous TCAS Transponder Utilization

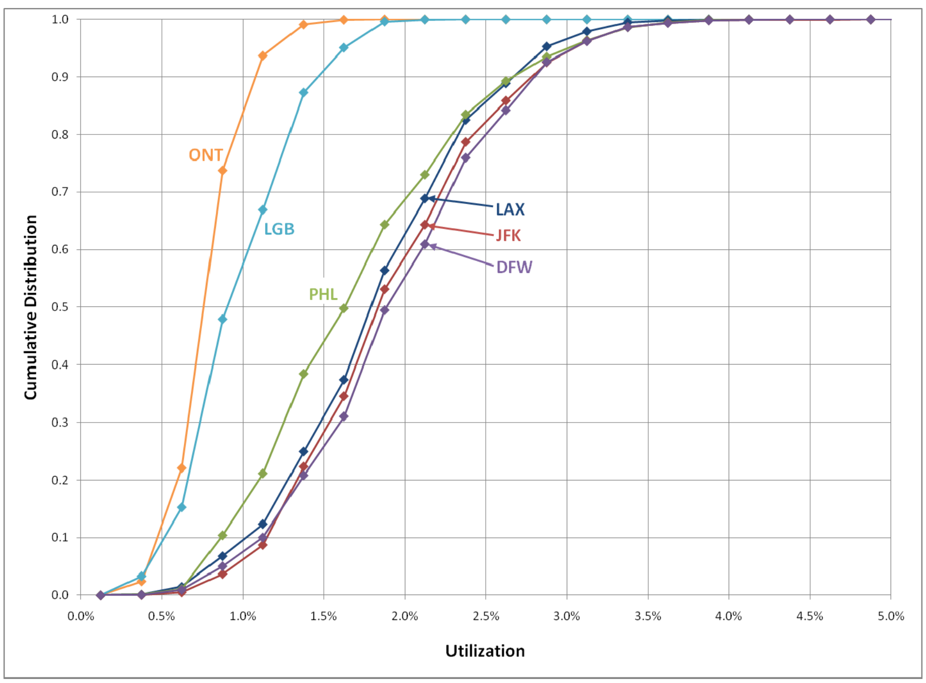


Figure 12. Cumulative Distribution of Instantaneous TCAS Transponder Utilization

4.1.2 Simplified Transponder Utilization Impact

The results displayed in Figure 11 and Figure 12 indicate that it is not unusual for transponder utilization to exceed 2% for individual aircraft in busy areas. The value 2% was used in the development of TCAS interference limiting, but it is not a hard limit, and our analysis shows 2% is not of particular significance in terms of radar performance.

Figure 13 shows how different values of TCAS interference will affect Mode S radar performance. TCAS interference is mostly due to transponder utilization from TCAS interrogations, but also includes some effect from the replies that are generated which result in FRUIT (False Replies Uncorrelated In Time) interference. Radar performance is characterized by the mean time between misses of a radar report, which results in a track being coasted for one scan. A missed report, or coast, caused by transponder utilization and other interference effects, occurs after a number of missed interrogation opportunities. For this analysis, a Mode S radar has 6 opportunities during the time the main beam is illuminating a Mode S equipped aircraft to obtain a reply and generate a report.

The horizontal axis in Figure 13 is the total of all non-TCAS interference effects, including interrogations from ground based radars and FRUIT interference on reception. Under typical conditions in the U.S., the total of all non-TCAS interference effects will be between 0-0.1. When the abscissa is less than about 0.2, the mean time between missed reports is more than 100 minutes, even with very high TCAS interference. Radar report misses will still occur at a higher rate for other reasons such as power fading and low antenna gains, while TCAS interference will have a negligible effect. In all cases the effects from TCAS are minor relative to the other effects.

A model of the JFK SSR and TCAS activity was constructed to estimate the TCAS impact on SSR performance. The calculated probability of an unsuccessful transaction without TCAS is 11% and the probability of unsuccessful transaction due to TCAS is 8%, resulting in a mean time between missed radar reports of over 2600 minutes or 44 hours. This result is indicated by a black x in Figure 13. Section 4.1.3 provides greater detail on the JFK model and results.

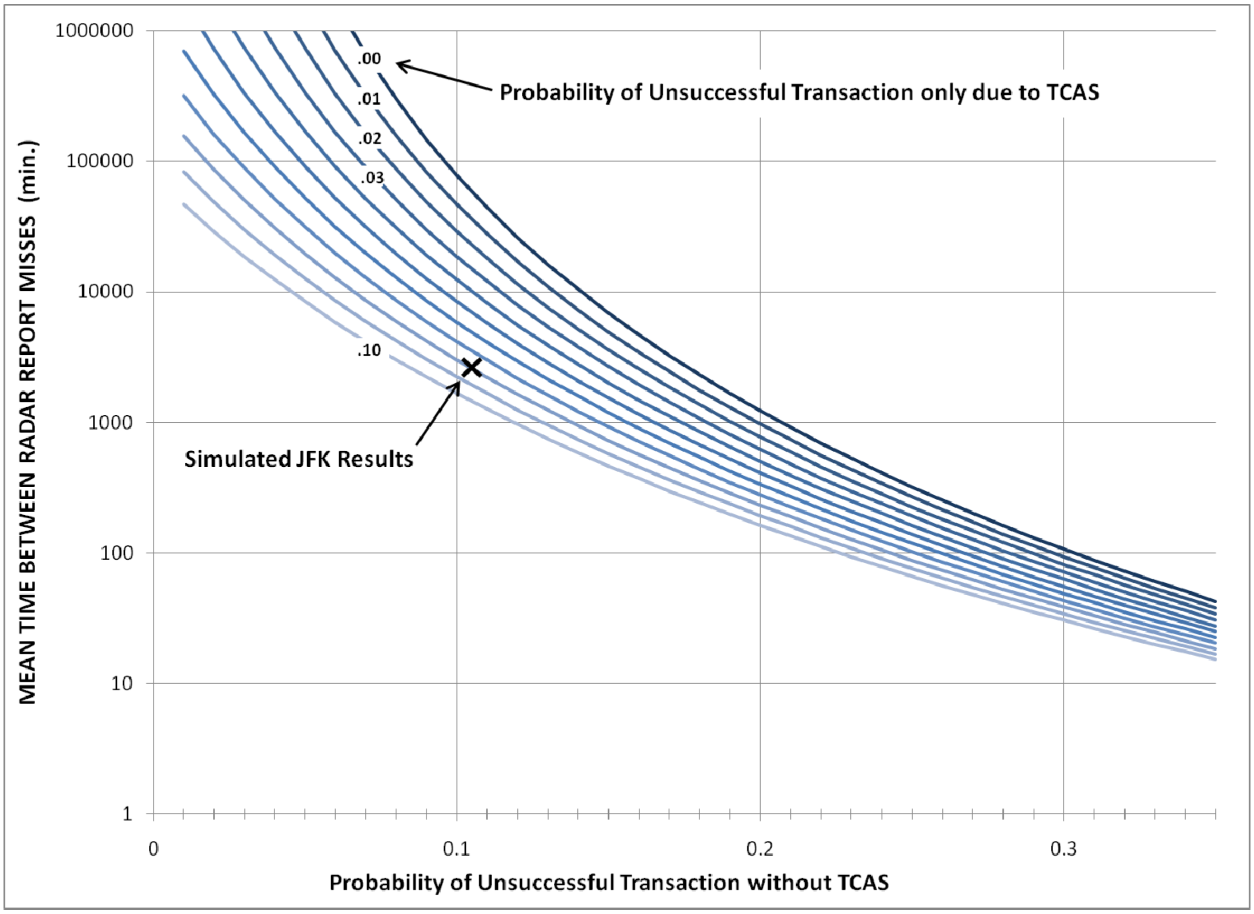


Figure 13. The Effect of TCAS Transponder Utilization on SSR Report Probability

4.1.3 Detailed Transponder Utilization Impact at JFK

This section will present a detailed analysis on the impact of transponder utilization due to TCAS. The transponder utilization from non-TCAS effects is calculated for the JFK area. This analysis will specifically investigate the track update probability at the JFK Mode S Secondary Surveillance Radar (SSR) given high transponder utilization due to TCAS. Prior results considered Mode S transponder utilizations on TCAS equipped aircraft. For completeness, this section will address probabilities for SSR track updates of both Mode S and ATCRBS. Worst case transponder utilization of 5% will be used to measure the TCAS impact. It will be shown that Mode S radars' use of monopulse means that there is essentially no degradation of tracking performance resulting from TCAS operation.

During a scan, the Mode S sensor attempts to obtain a position measurement on every ATCRBS and Mode S transponder. If the transponder is already in track, the measurement is used for track updating; otherwise it is applied to a track initiation process. A transponder is in track for the vast majority of scans during which it is within coverage range. Therefore, we focus on the probability of updating an existing track.

The use of monopulse by a Mode S sensor means that a position measurement having an accurate azimuth can be made from one successful interrogation/reply transaction. The interrogation/reply process is characterized by its round reliability, which is defined as the probability of interrogation times the probability of reply reception. In this report we only consider the effects of interference on these probabilities and ignore such things as insufficient power to reach the target.

Both the interrogation and reply reception process can be interfered with by other ATCRBS sensors, Mode S sensors, and TCAS. An interrogation by any one of these sensors just prior to an interrogation from the JFK sensor can result in a failure to reply to JFK, or the JFK sensor may fail to receive the reply because it was interfered with by a reply from another transponder (i.e., FRUIT).

Interrogations of various types occupy the transponder for associated time intervals; during those times the transponder is unavailable to other interrogations. Replies have various lengths and are modeled such that to receive a reply it must not be overlapped by another reply (except that a Mode S reply can be overlapped by a single ATCRBS reply). The product of the probabilities of interrogation, $p(i)$, and reply reception, $p(r)$, is the probability of a successful surveillance transaction, s.

For an ATCRBS track we assume that the probability of update on a scan, $p(u)$, is the probability that at least two of the six interrogations are successful, which is a binomial in s. For a Mode S track we assume that the probability of update is one minus the probability that six interrogations fail, each with failure probability $f = (1-s)$. For this analysis the assumption of six opportunities for a successful interrogation/reply transaction is used (i.e., if the first fails, the sensor has time to make up to five retries).

We estimate the terms $p(i)$, $p(r)$, s, and $p(u)$ for ATCRBS and Mode S equipped targets with and without TCAS. The assumptions, models, and estimates are shown in Appendix A, and the results are given in Table 5 below.

TABLE 5

Performance Probabilities, with and without TCAS

Without TCAS	**ATCRBS**	**Mode S**
$p'(i)$ successful interrogation	0.9623	0.9657
$p'(r)$ reply reception	0.9314	0.9270
$s' = p'(i)*p'(r)$ transaction	0.8963	0.8952
p'(update) w/o TCAS	0.9999	0.9999
p'(missed update) w/o TCAS	6.573 * 10^-5	1.325 * 10^-6
Including TCAS Utilization of 5%		
$p(i)$ successful interrogation	0.9142	0.9174
$p(r)$ reply reception	0.9111	0.8982
$s = p(i)*p(r)$ transaction	0.8329	0.8240
p(update) w/ TCAS	0.9993	0.9999
p'(missed update) w/o TCAS	6.728 * 10^-4	2.972 * 10^-5

Figure 14 shows the five tracks from the simulation that have the highest transponder utilization due to TCAS. For each track the utilization is almost 5% at times. The five tracks have a combined total of 640 radar scans on which an update by the JFK SSR should be made. Table 6 shows the expected number of scans, out of 640, on which a track update would not be made (i.e., the track would be coasted) because of transponder utilization or reply garbling, with and without TCAS for ATCRBS and Mode S targets. Included in Table 6 is the actual number of radar scans with a missed update as recorded by the JFK SSR. The calculated and actual numbers of missed updates agree very well; there were zero missed updates by the radar. Table 6 also shows the expected number of minutes between missed updates. The results show that a Mode S track would be expected to miss an update less than once per day due to the effects of TCAS in a very busy terminal environment.

The performance is largely driven by the Mode S sensor monopulse capability, which allows a track update on a single interrogation/reply. Monopulse enables low Mode S search Pulse Repetition Frequency (PRF) (relative to ATCRBS sliding window) which reduces transponder utilization and FRUIT. The performance also benefits from the Mode S sensor's ability to retry unsuccessful Mode S interrogation/reply transactions for targets in track. In conclusion, it can be seen that tracking performance remains excellent even for the very few tracks whose transponders might experience 5% utilization by TCAS for a brief period.

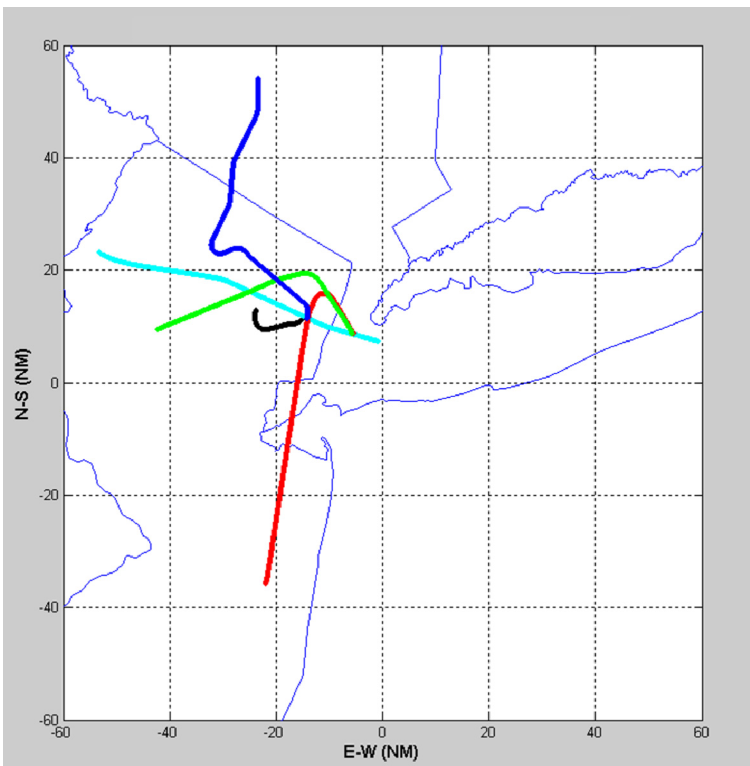


Figure 14. Five Tracks with the Highest Average Transponder Utilization Due to TCAS

Table 6

SSR Update Performance

	Missed Scans out of 640 (Number of Coasts)			**Hours between missed updates**	
Transponder	Simulated Without TCAS	Simulated Including TCAS	Observed from JFK SSR Data	Without TCAS	Including TCAS
ATCRBS	0.04	0.4	N/A	20	2
Mode S	0.001	0.02	0	986	44

4.2 SURVEILLANCE RANGE

Surveillance range is determined by the attenuation value interference limiting designates to reduce interrogation power and reception sensitivity. Figure 15 shows the relationship between the power attenuation value and surveillance range. As the interrogation power and reception sensitivity are reduced, the range at which a TCAS aircraft can interrogate a target and receive a reply is lowered. The likelihood of a successful interrogation at a given range and power is a probabilistic function and may be defined as: “reliable surveillance” (6 dB link margin), nominal or 50% surveillance (0 dB link margin), or “few targets reply” (-6 dB link margin).

The surveillance environments above and below 10,000 feet can differ greatly and consequently have separate MOPS requirements; therefore, the altitude bands are treated separately. For aircraft below 10,000 feet, “interference limiting hotspots” are defined as areas in which the surveillance range is reduced to the minimum allowed in the TCAS MOPS yet the power required to perform needed interrogations still exceeds that which interference limiting determines is available. For aircraft between 10,000-18,000 feet, “surveillance hotspots” are defined as areas in which the reduction in surveillance range no longer provides sufficient time for timely TCAS alerts.

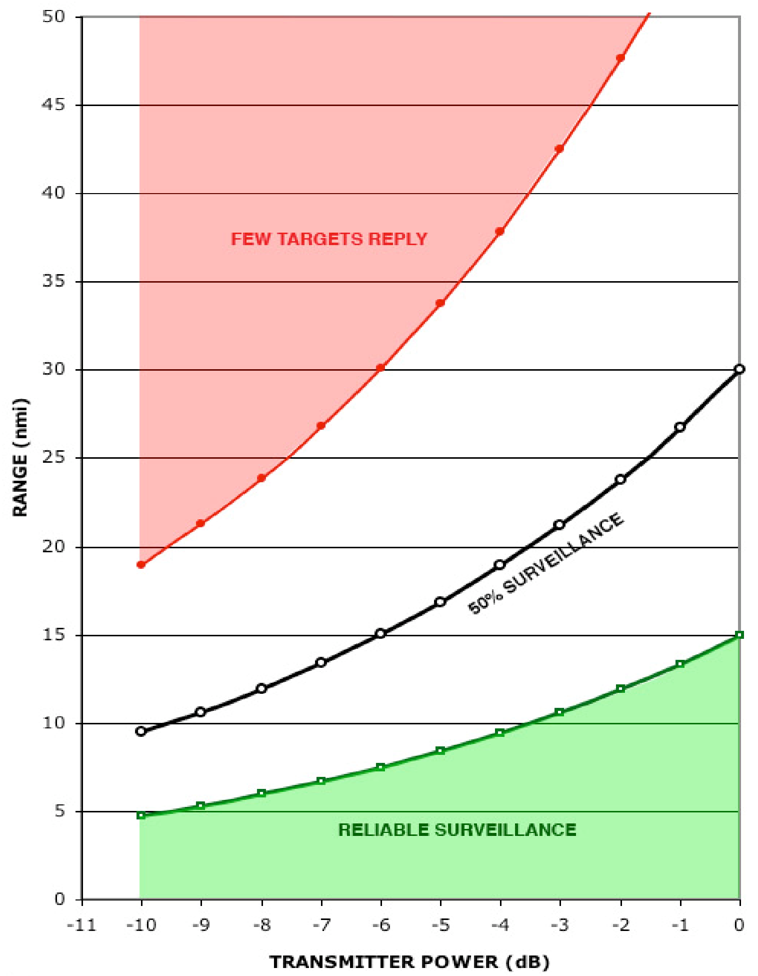
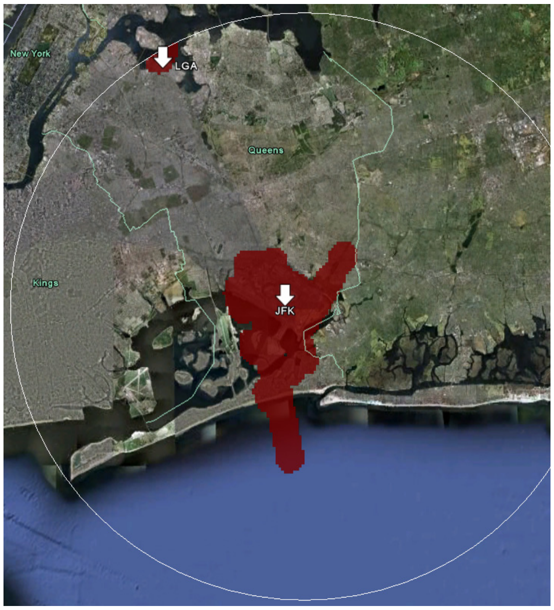


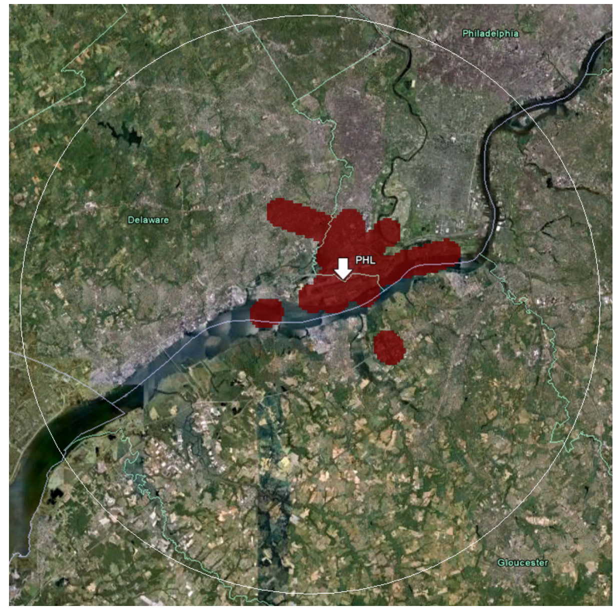
Figure 15. Surveillance Range vs. Attenuation

4.2.1 Interference Limiting Hotspots

Interference limiting hotspots are defined as areas below 10,000 feet where an aircraft is at maximum interrogation power attenuation, or the minimum allowed surveillance range, and the TCAS interrogation power sum still exceeds the allowed power sum provided by interference limiting. As an aircraft encounters dense airspace, interference limiting reduces maximum interrogation power to reduce surveillance range until it reaches the limit, at which point it continues transmissions even if interference limiting is not met. Accordingly, transponder utilization due to TCAS would be expected to rise over the designated 2% in these areas as surveillance range cannot be reduced any further to complement the dense environment. Figure 16 illustrates that all airports of interest exhibit hotspots near the runways. These hotspots are caused by TCAS aircraft on approach and takeoff patterns interacting with the dense environment. When compared to the average utilization intensity maps, the hotspots correlate to the areas with the highest constant transponder utilization.



(a) JFK



(b) PHL

(c) LAX

(d) DFW

Figure 16. Interference Limiting Hotspots – Low Altitude

4.2.2 Surveillance Hotspots

Surveillance hotspots are defined as areas between 10,000-18,000 feet where surveillance range may be insufficient for TCAS to provide the maximum warning time for a potential threat with a high closure rate. This has been an area of concern in the past, as there are no speed restrictions above 10,000 feet, yet TCAS is allowed to reduce surveillance to a range that is suitable for encounters with maximum closure rates of 500 knots. The potential for these areas to exist has been known since the time of the original TCAS development, although surveillance data available at that time did not confirm such areas.

The necessary surveillance range between 10,000-18,000 feet was calculated was using the TCAS Operational Performance Assessment (TOPA) [3] RA database and TCAS MOPS requirements for guidance. The MOPS (Table 2-13 [1]) contains the minimum RA alarm time for aircraft with different altitude levels. The minimum RA alarm time between 5,000-10,000 feet is 25 seconds. Speed restrictions for aircraft below 10,000 feet altitude limit aircraft to 250 knots, or a maximum closing speed between two aircraft of 500 knots. Equation 1 below shows that for a minimum surveillance range of approximately 5 NM and maximum closing speed of 500 knots; the minimum warning time is 35 seconds. This would provide 10 seconds for target acquisition and 25 seconds for RA response. Using the same method of minimum RA time plus 10 seconds, the minimum warning time for aircraft operating within 10,000-18,000 feet is 40 seconds.

$$Min\ Surveillance\ Range\ (nm) = \frac{min\ warning\ time\ (s) * max\ closing\ speed\ (knots)}{3600} \qquad (1)$$

Since there are no hard speed restrictions between 10,000-18,000 feet, the TOPA RA database was searched to find the worst case (greatest) closing speed recorded in the altitudes of interest: 850 knots. Equation 1 shows that for an 850 knot closing speed and minimum warning time of 40 seconds the minimum surveillance range is approximately 9.5 nm. Thus, from Figure 15, interrogations with greater than 4 dB attenuation may not provide adequate surveillance for TCAS encounters between 10,000-18,000 feet.

The surveillance hotspot maps show a range out to 30 NM from the radar. Range rings are located at 10, 20, and 30 nm. Surveillance hotspots are seen near JFK (Figure 17), PHL (Figure 18), and DFW (Figure 19). PHL demonstrates minimal potential hotspot areas, whereas DFW has a few possible hotspots mostly in the areas between airports in the region. JFK has potential hotspots northeast of the city along the approach from the north to Newark International Airport (EWR) and near Teterboro Airport (TEB).

Although these results are preliminary, the surveillance hotspots are a key finding and will require further work to fully characterize surveillance performance in these regions. Future work will include a detailed assessment of safety risks and potential mitigations. Specific changes to the TCAS MOPS interference limiting algorithms between 10,000-18,000 feet have been previously investigated and will be pursued if warranted by future safety risk studies.

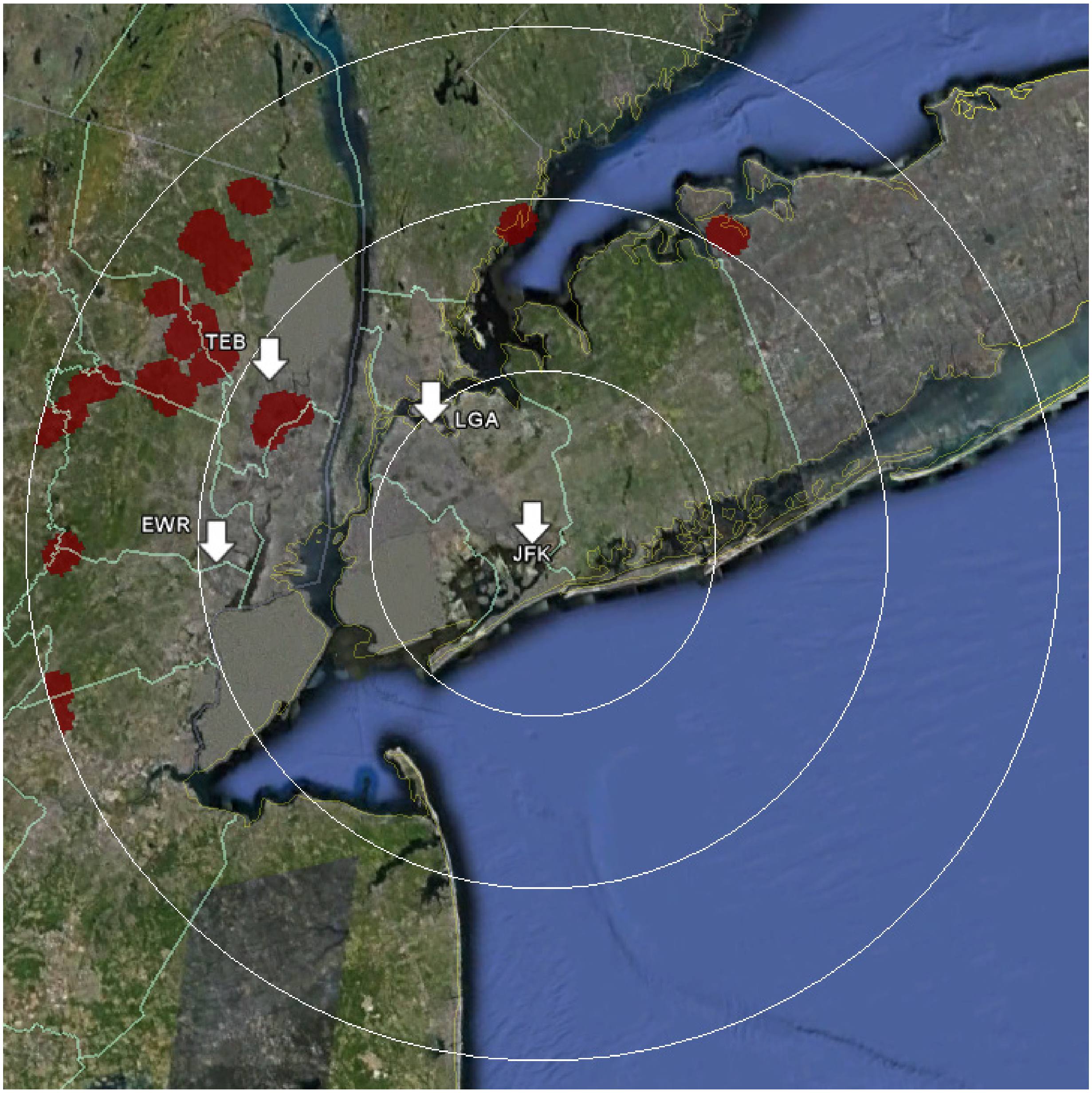


Figure 17. JFK Hotspots Map – High Altitude

Figure 18. PHL Hotspots Map – High Altitude

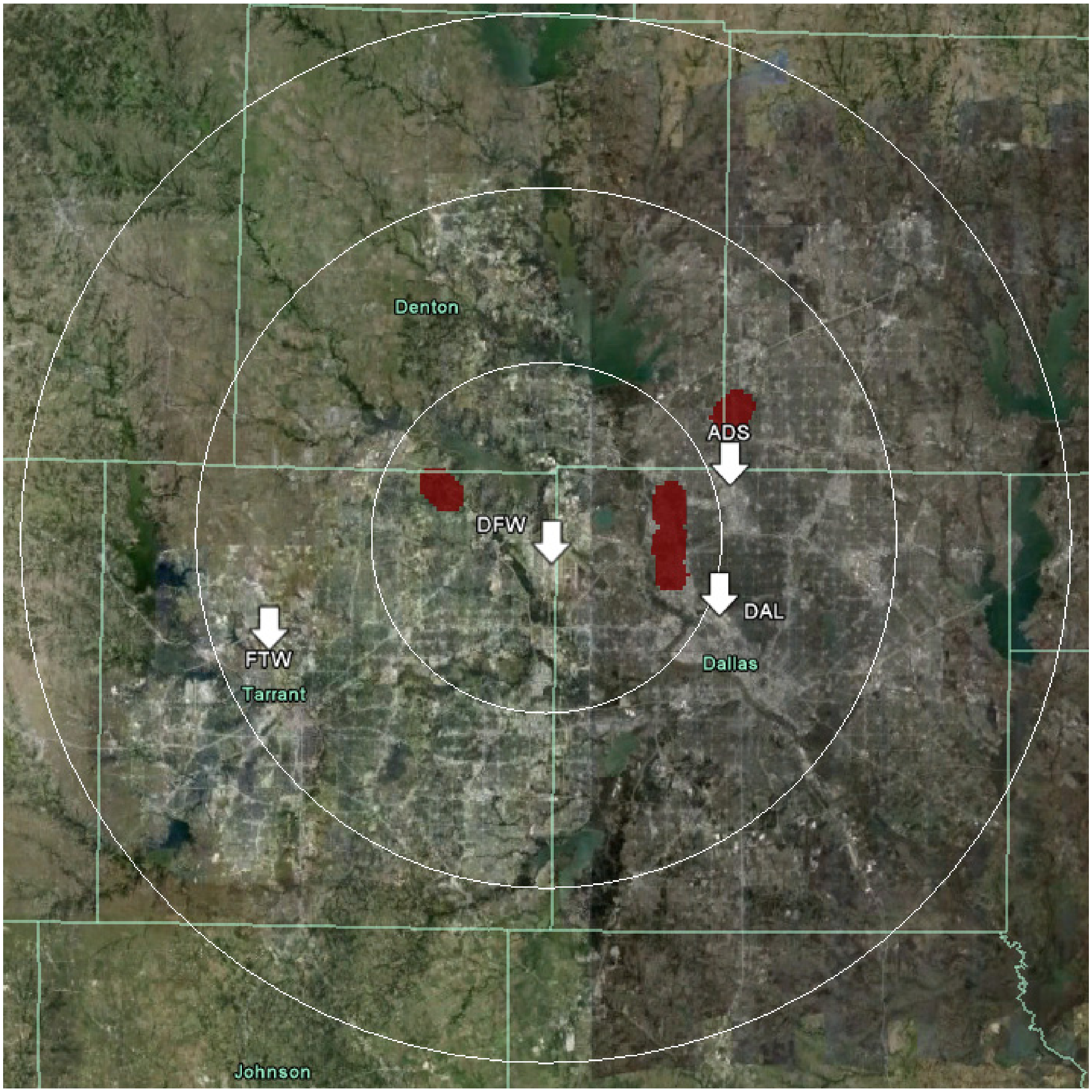


Figure 19. DFW Hotspots Map – High Altitude

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5. SUMMARY

The goal of this work was to determine how a MOPS implementation of TCAS v 7/7.1 surveillance functions in current, high-traffic terminal environments and to address potential areas of concern for investigation and TCAS MOPS changes. This was accomplished by characterizing the environment with respect to aircraft traffic and densities at six sites in the NAS. Comparisons were made to MOPS assumptions and previous density studies; results were consistent with the MOPS and prior measurements. A one hour period of very high activity from each site was chosen for analysis with a high fidelity TCAS surveillance simulation.

The main conclusions from this report are:

- A MOPS implementation of the TCAS surveillance logic performed as the requirements intended in the crowded areas. Interference limiting kept transponder utilization figures around 2%, and little or no activity measured above 3.5%.
- Analyses performed to assess the potential for ground ATC radar interference from TCAS indicate that transponder utilizations up to 5% have a negligible impact on U.S. ground radar performance.
- Surveillance hotspots were identified in a few areas but were not widespread. Future reports will include analysis to fully characterize these regions and present mitigations if necessary.

While results were in agreement with what was expected, this work marks a first in the ability to simulate TCAS surveillance performance in a wide variety of environments with great precision. Future efforts will focus on regions of concern and investigate requirements changes to maximize surveillance capability while minimizing potential TCAS interference with ground radar systems.

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APPENDIX A
EFFECT OF TRANSPONDER UTILIZATION DUE TO TCAS ON SSR PROBABILITY OF TRACK UPDATE NEAR JFK

A-1 SENSORS AROUND JFK

The estimates of *p(i)* and *p(r)* require knowledge of the sensors around JFK. Figures A-1 to A-3 show the deployment of Enroute and Terminal ATCRBS, and Terminal Mode S sensors. The numbers of sensors within 60 and 200 nm are used in the estimates. The 200 nm is the modeled range to which 1030 MHz transmissions will reach and still be above the transponder's minimum trigger level (MTL). The 60 nm is the tracking range of Terminal Mode S sensors, within which the sensor "locks out" Mode S transponders, which prevents them from replying to Mode S search interrogations. The inner circle is a range of 10 nm.

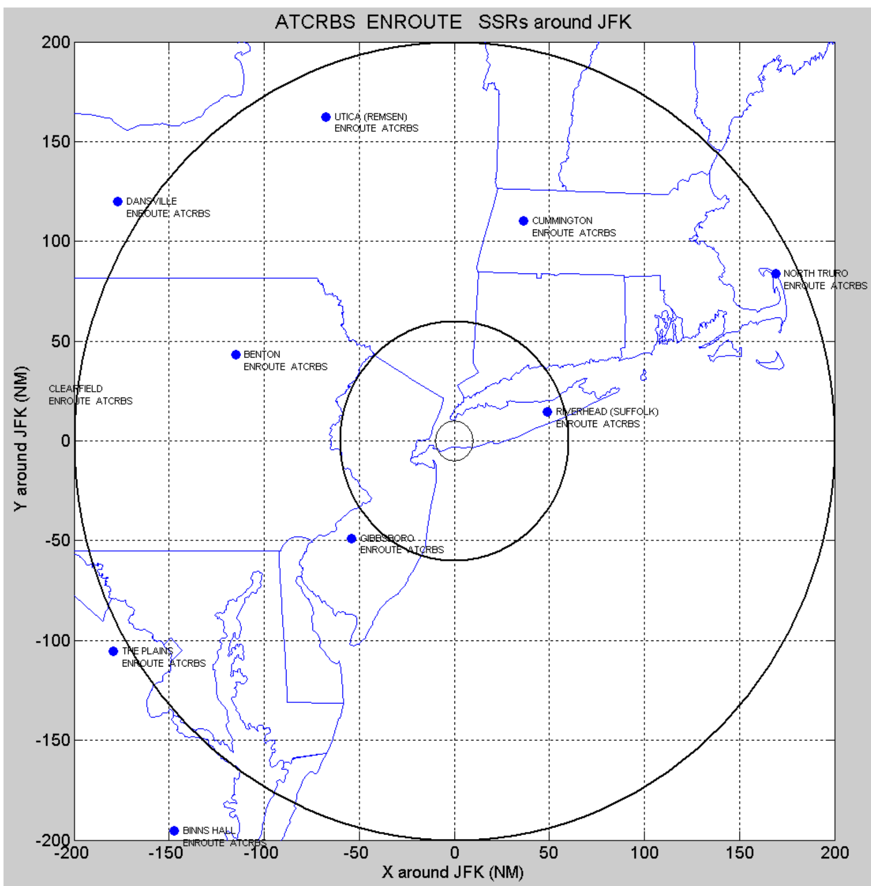

Figure A-1. Enroute ATCRBS Sensors around JFK

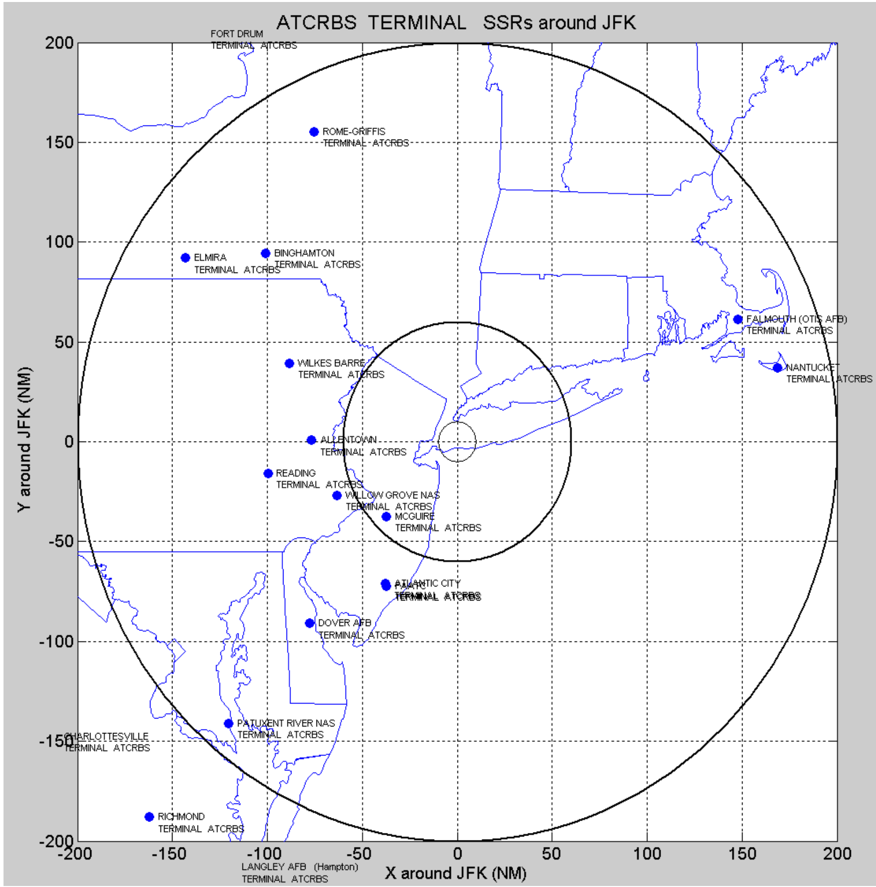

Figure A-2. Terminal ATCRBS Sensors around JFK

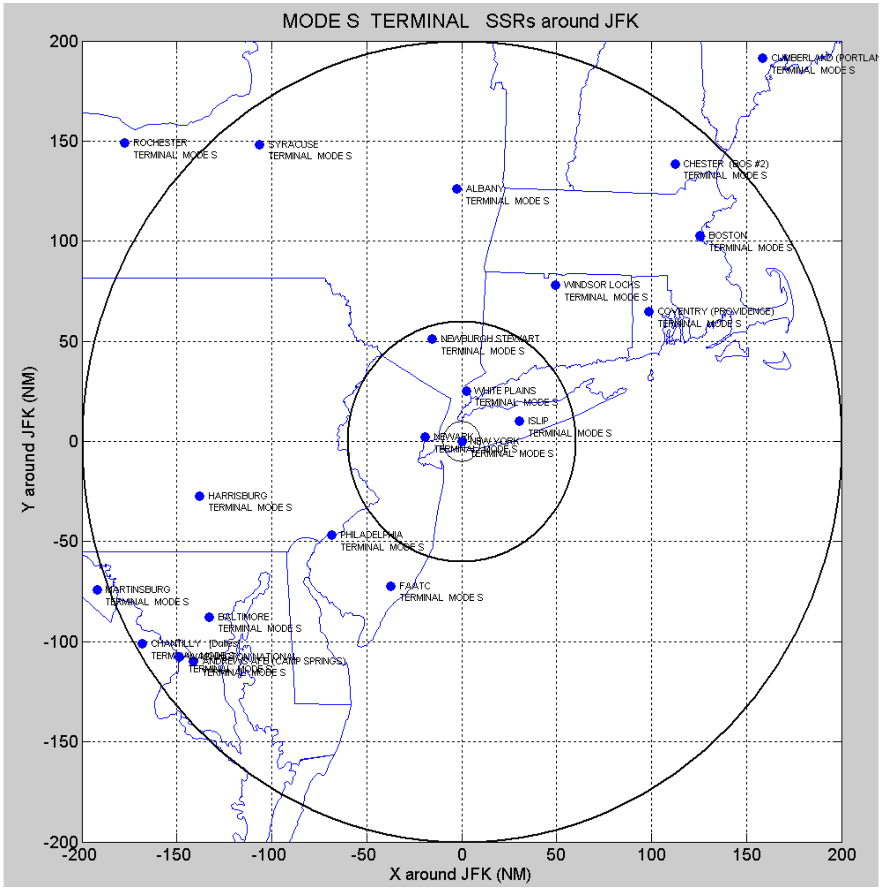

Figure A-3. Terminal Mode S Sensors around JFK

Table A1 shows the counts of the sensors in Figures A1 to A-3. The sensor counts in are with respect to a victim transponder that is within 10 nm of JFK.

TABLE A-1

Sensor Counts

Sensor Type	#
ATCRBS	
Main beam (<= 200 nm)	20
Sidelobe (<= ~5 nm) (1)	1
Mode S (not including JFK)	
Main beam (<= 200 nm)	18
Sidelobe (<= ~5 nm)	1
Tracks targets (<= 60 nm)	4
Does not track (60 to 200 nm)	14

(1) Actually, no target within 10 nm of JFK would be in the sidelobes of any sensor besides JFK. The count is set to 1 to represent a worst case.

A-2 AIRCRAFT DISTRIBUTION MODEL

The aircraft are modeled as being distributed uniformly in range with a density of three aircraft per nm in range. We model that 70% of the aircraft are Mode S equipped. There are 600 aircraft within 200 nm of each of the sensors shown in the previous section and 420 are Mode S equipped. To represent worst case performance, we model that all Mode S aircraft are equipped with TCAS and 1090ES.

TABLE A-2

Aircraft Distribution Model

Parameter	Value
Aircraft distribution model	Uniform in range
Aircraft density (aircraft per nm from sensor)	3 (aircraft/nm)
Percent of aircraft equipped with ATCRBS	30%
Percent of aircraft equipped with Mode S	70%
Percent of Mode S with TCAS	100%
Percent of Mode S with 1090ES	100%

A-3 PROBABILITY OF INTERROGATION WITHOUT TCAS, *p'(i)*

The probability of interrogation is the probability that the transponder is not being utilized by a prior 1030 MHz reception when the desired interrogation arrives. The prior reception could come from a Mode S sensor, ATCRBS sensor, or TCAS. The sensors are modeled with narrow mainbeams reaching to

200 nm in range, and an omni sidelobe/backlobe reaching to about 5 nm on average. The sensors make regularly scheduled search interrogations at a given pulse repetition frequency (PRF). We model that a Mode S transponder will not reply to Mode S searches when the transponder is within 60 nm of the sensor. Mode S sensors also make addressed interrogations.

The total 1030 MHz events (i.e., interrogations and suppressions) received by a transponder is modeled as a Poisson process. Different types of events utilize the transponder for different intervals. The probability that the transponder is available, i.e., the probability of interrogation, *p(i)*, is:

$$p(i) = \prod_{i=1}^{I} e^{-\lambda_i \Delta t_i} = \exp \sum \lambda_i \Delta t_i$$

Where:

λ_i = the arrival rate of 1030 MHz events of type i

Δt_i = the utilization time of transmissions of type i,

(which are different for ATCRBS and Mode S transponders)

Formulas A1. Probability of interrogation, *p(i)*

The 1030 MHz events and associated transponder utilization times are shown in the Table A-3 (in which R means the transponder (xpndr) replies, and S means the transponder suppresses; MB means mainbeam, and SL means sidelobe).

Table A-3

1030 MHz Events

Abbreviation	Event	Mode S utilization Δt (μs)	ATCRBS utilization Δt (μs)
ATCRBS search transmissions			
A(MB)	MB Mode A,C interr.	35 R	149 R
A(SL)	SL suppression	35 S	35 S
	Mode (Terra-fixed) S search [1]		
SAT(MB)	MB Mode A,C interr.	35 R	149 R
SAT(SL)	SL suppression	35 S	35 S
Mode S search interrogations			
ACL(MB)	MB UF11 All Call to locked out xpndr	45 S	35 S
ACL(SL)	SL UF11 All Call to locked out xpndr	45 S	35 S
ACU(MB)	MB UF11 to non-locked out xpndr	317 R	35 S
ACU(SL)	SL UF11 to non-locked out xpndr [2]		
Mode S track interrogations			
DA(MB)	MB UF4,5 to Addressed xpndr	317 R	35 S
DA(SL)	SL UF4,5 to Addressed xpndr [3]		
DN(MB)	MB UF4,5 Non-addressed xpndr	45 S	35 S
DN(SL)	SL UF4,5 to Non-addressed xpndr	45 S	35 S

(1) Terra-fix causes higher utilization and more fruit replies than normal operation, as shown below:

	Transponder		
Interrogation	ATCRBS	Mode S Unlocked	Mode S Locked out
Terra fix: P1,P3	F1,F2 (149 μs)	F1,F2 (45 μs)	F1,F2 (45 μs)
Terra fix: UF11	Suppress	DF11 (317 μs)	Ignore (45 μs)
Normal: P1,P3,P4	F1,F2 (149 μs)	DF11 (317 μs)	Ignore (45 μs)

(2) A transponder that is not locked out is beyond the range of the sidelobes.
(3) The sensor will not send an addressed interrogation to a target in the sidelobes.

We model ATCRBS searches with a PRF of 360, and Mode S searches with 130. Beamwidths are modeled as 3.6°. The contribution to transponder utilization by search interrogation is:

Where:

PRF	=	pulse repetition frequency
$BW_{Mainbeam}$	=	beamwidth of the mainbeam
$N_{SSR\,MB}$	=	sensors whose mainbeam covers victim transponder
$N_{SSR\,SL}$	=	sensors whose sidelobe covers victim

$$\lambda_{MB}^{Search} = N_{SSR\,MB} \frac{PRF * BW_{Mainbeam}}{360°}$$

$$\lambda_{SL}^{Search} = N_{SSR\,SL} \frac{PRF * (360° - BW_{Mainbeam})}{360°}$$

Formulas A-2. Rates of search interrogations

The contribution to transponder utilization by Mode S addressed interrogations is

Where:

$BW_{Mainbeam}$ = beamwidth of the mainbeam

$N_{MB\ or\ SL}^{ModeS,R\leq x}$ = mainbeam or sidelobe Mode S within x NM

$N_{Targets="ABCDEF"}$ = transponders with address = "ABCDEF" (i.e., 1)

$N_{Targets\neq"ABCDEF"}$ = transponders not = "ABCDEF"

$U_{DF4,5}$ = number addressed (interrogations/target)/scan

T_{Scan} = time for one scan (seconds)

$$\lambda_{to"ABCDE"}^{Addressed} = N_{MB}^{ModeS,R\leq 60} \frac{N_{Targets="ABCDEF"} * U}{T_{Scan}}$$

$$\lambda_{MB\,not\,to"ABCDE"}^{Addressed} = N_{MB}^{ModeS,R\leq 200} \frac{N_{Targets\neq"ABCDEF"} * U}{T_{Scan}} * \frac{BW_{Mainbeam}}{360°}$$

$$\lambda_{SL\,not\,to"ABCDE"}^{Addressed} = N_{SL}^{ModeS,R\leq 200} \frac{N_{Targets\neq"ABCDEF"} * U}{T_{Scan}} * \frac{(360° - BW_{Mainbeam})}{360°}$$

Formulas A-3. Rates of Mode S addressed interrogations

With the above definitions we obtain:

Table A-4

Rates of 1030 MHz Events

	Scheduled				
Code $_\iota$	N_{SSR}	*PRF* (sec^{-1})	*BW* (°)		λ_ι (sec^{-1})
A(MB)	20	360	3.6		72
A(SL)	1	360	360-3.6		356.4
SAT(MB)	18	130	3.6		23.4
SAT(SL)	1	130	360-3.6		128.7
ACL(MB)	4	130	3.6		5.2
ACL(SL)	1	130	360-3.6		128.7
ACU(MB)	14	130	3.6		18.2
ACU(SL)	na	na	na		
	Addressed				
Code $_\iota$	N_{SSR}	$N_{Targets}$	*Update Rate*	T_{Scan}	
DA(MB)	4	1	1.2	4.6	1.04
DA(SL)	na	Na	na	Na	
DN(MB)	18	(180-1)	1.2	4.6	8.5
DN(SL)	1	(180-1)	1.2	4.6	46.2

The event rates, λ_i , are combined with the utilization, Δt_i, for each event, *i*, using Formulas A1. The results for *p'(i)* without TCAS are:

Table A-5

Interrogation Probabilities, without TCAS

Code	λ (sec^{-1})	ATCRBS Δt (μs)	ATCRBS (μs/sec) λΔt		Mode S Δt (μs)	Mode S (μs/sec) λΔt
A(MB)	72	149	10,728.0		35	2,520.0
A(SL)	356.4	35	12,474.0		35	12.474.0
SAT(MB)	23.4	149	3,486.6		35	819.0
SAT(SL)	128.7	35	4,504.5		35	4,504.5
ACL(MB)	5.2	35	182.0		45	234.0
ACL(SL)	128.7	35	4,504.5		45	5,791.5
ACU(MB)	18.2	35	637.0		317	5,769.4
ACU(SL)						
DA(MB)	1.04	35	36.5		317	330.8
DA(SL)						
DN(MB)	8.5	35	295.8		45	330.8
DN(SL)	46.2	35	1,618.0		45	2080.3
		TOTAL	38,467.0		TOTAL	34,903.8
		sec/sec	0.038		sec/sec	0.035
		p'(i)	0.9623		*p'(i)*	0.9657

A-4 PROBABILITY OF REPLY RECEPTION WITHOUT TCAS *p'(r)*

The probability that an ATCRBS reply is correctly received at a Mode S sensor is modeled as the probability that the reply is not garbled by a fruit reply. Any amount of overlap by a Mode S reply will cause garbling. Contrariwise, overlap by an ATCRBS reply must be such that the pulses overlap, i.e., interleaving of pulses will not cause garble.

The probability that a Mode S reply is correctly received is modeled as the probability that it is not overlapped by any Mode S fruit or by two or more ATCRBS fruit. The Mode S receiver is capable of decoding the Mode S reply if it is overlapped by a single ATCRBS fruit. The fruit arrivals are modeled as Poisson processes, so the probability of reception, *p(r)*, is shown in Formulas A-4:

Where:

$p(r)$	= probability that reply is ungarbled
λ_x	= arrival rate of replies of type x
Δt_{ATCRBS}	= length of ATCRBS replies, 20.75 us
$\Delta t_{ATCRBS} / 3$	= effective length of ATCRBS replies, 20.75 us divided by ~(1.45/0.45)
$\Delta t_{ModeSshort}$	= length of Mode S short replies, 64 us
$\Delta t_{ModeSlong}$	= length of Mode S long replies, 120 us

Then:

$$p(r)_{ATCRBS} = e^{-\lambda_{ATCRBS}(\Delta t_{ATCRBS}+\Delta t_{ATCRBS})/3} * e^{-\lambda_{ModeSshort}(\Delta t_{ModeSshort}+\Delta t_{ATCRBS})} * e^{-\lambda_{ModeSlong}(\Delta t_{ModeSshort}+\Delta t_{ATCRBS})}$$

$$p(r)_{ModeS} = [1+\lambda_{ATCRBS}(\Delta t_{ATCRBS}+\Delta t_{ModeSshort})] * e^{-\lambda_{ATCRBS}(\Delta t_{ATCRBS}+\Delta t_{ModeSshort})} * e^{-\lambda_{ModeSshort}(\Delta t_{ModeSshort}+\Delta t_{ModeSshort})} * e^{-\lambda_{ModeSlong}(\Delta t_{ModeSlong}+\Delta t_{ModeSshort})}$$

Formulas A-4. Probability of reception, *p(r)*

The fruit rate estimates can be derived from aircraft density in Table A-3 combined with interrogation rates in Table A-4.

Table A-6

Fruit Rates without TCAS

ATCRBS fruit rate into JFK receiver				
Code	λ per aircraft	Number of aircraft	ATCRBS fruit	
A(MB)	72	600	43,200	
SAT(MB)	23.4	600	14,040	
Total from 200 nm incident at JFK			57,240	
Main beam sees 1%			572	
Sidelobe at -15 dB reaches 5 nm (1/40)			1,431	
Total ATCRBS fruit into JFK receiver			2,003	
Mode S fruit rate into JFK receiver				
Code	λ per aircraft	Number of aircraft	Mode S Short fruit	Mode S Long fruit
ACL(MB)	5.2	420	2,184	
ACU(MB)	18.2	420	7,644	
DA(MB)	1.04	420	437	
1090ES	6.2	420		2,604
Total from 200 nm incident at JFK			10,265	2,604
Main beam sees 1%			103	26
Sidelobe at -15 dB reaches 5 nm (1/40)			257	65
Total Mode S short fruit into JFK receiver			360	91

With these fruit rates we apply Formulas A-4:

Table A-7

Probability of Reception without TCAS, *p'(r)*

Probability of ATCRBS reply reception (Δt_{ATCRBS} = 20.75 μs)			
	Rate (λ_i)	Duration (Δt_i μs)	Exponential term
ATCRBS	2003	20.3	0.9727
Mode S short	360	64	0.9700
Mode S long	91	120	0.9873
		ATCRBS *p'(r)*	0.9314
Probability of Mode S reply reception (Δt_{ModeS} = 64 μs)			
	Rate (λ_i)	Duration (Δt_i μs)	Exponential term
ATCRBS	2003	20.3	0.9871
Mode S short	360	64	0.9550
Mode S long	91	120	0.9834
		Mode S *p'(r)*	0.9270

A-5 PROBABILITY OF SUCCESS WITHOUT TCAS, *s' = p'(i) * p'(r)*

The probability of a successful interrogation/reply transaction, without TCAS is:

Table A-8

Probability of Success without TCAS, *s*

	Probabilities		
Transponder	*p'(i)*	*p'(r)*	*s' = p'(i)* p'(r)*
ATCRBS	0.9623	0.9314	0.8963
Mode S	0.9657	0.9270	0.8952

A-6 PROBABILITY OF TRACK UPDATE WITHOUT TCAS *p'(u)*

For an ATCRBS track we assume that the probability of update on a scan, *p(u),* is the probability that at least two of the six interrogations as the beam sweeps by are successful, which is a binomial in *s*. For a Mode S track it is the one minus the probability that six interrogations fail, each with failure probability $f = (1\text{-}s)$. This is because if the first fails the sensor has time to make up to five more interrogations.

Where:	
$p(i)$	= probability of interrogation, i.e., the transponder is not occupied
$p(r)$	= probability of reply reception, i.e., the reply is not overlapped by fruit
s	= probability of success, i.e., i.e., interrogation and reply are both successful
f	= probability of failure, i.e., no measurement is made
$P(Up)$	= probability a track is updated
	= For ATCRBS at least 2 successes in 6 pre-scheduled opportunities
	= For Mode S at least 1 successes in 3 as-needed attempts

Then:

$s = p(i) * p(r)$

$f = (1 - s)$

$$p(u)_{ATCRBS} = \sum_{r=2}^{6} \left(\frac{6!}{r!(6-r)!} \right) s^r \; f^{6-r} = 1 - (f^6 + 6\, s\, f^5)$$

$$p(u)_{ModeS} = 1 - f^6$$

NOTE: $p(i)$, $p(r)$, and s have different values for ATCRBS and Mode S

Formulas A-5. Probability of update, *p(u)*

The resulting probabilities of update for ATCRBS and Mode S are in Table A-9

Table A-9

Probability of Update without TCAS, *p'(u)*

Trans-ponder Type	s'	Update requirement	*p'(u)*
ATCRBS	0.8963	2 or more of 6 replies received	0.9999
Mode S	0.8952	1 reply received, allowing up to five retries [(1)]	0.9999

(1) The average number of interrogations to get a successful reply is 1/0.8460 = 1.18. This does not change the fruit rates. The increase in transponder utilization is only affected in the addressed part, not the scheduled part which dominates. Therefore, the increase due to retries is negligible.

A-7 PROBABILITY OF INTERROGATION INCLUDING TCAS, *p(i)*

Section 4.1 showed that several tracks had transponder utilization over 4%. Figure A-4 below shows the ground track of the five tracks having the highest utilization.

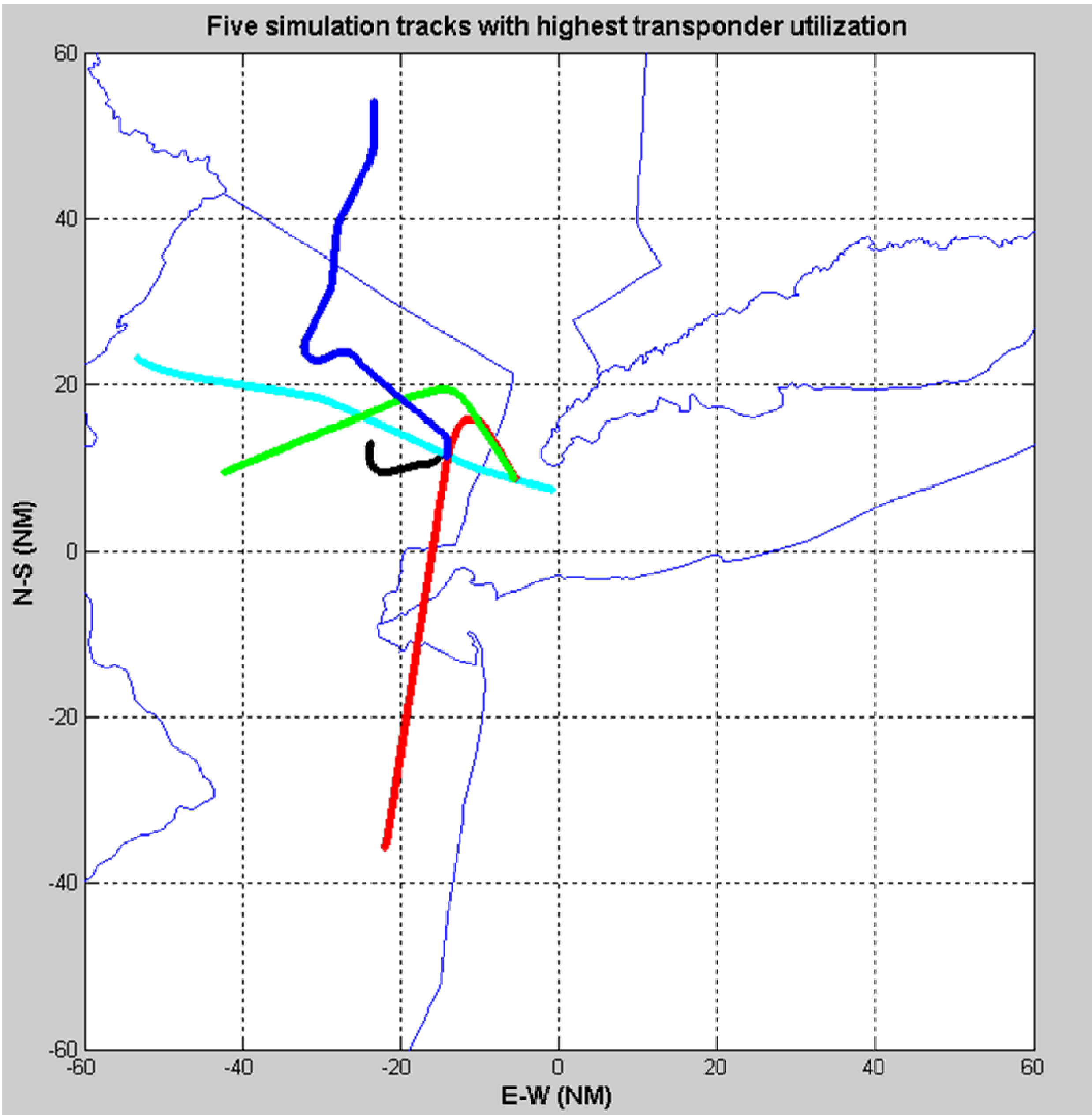

Figure A-4. Tracks with High TCAS Utilization

Figure A-5 shows the ATCRBS and Mode S utilizations vs. time for each of the tracks.

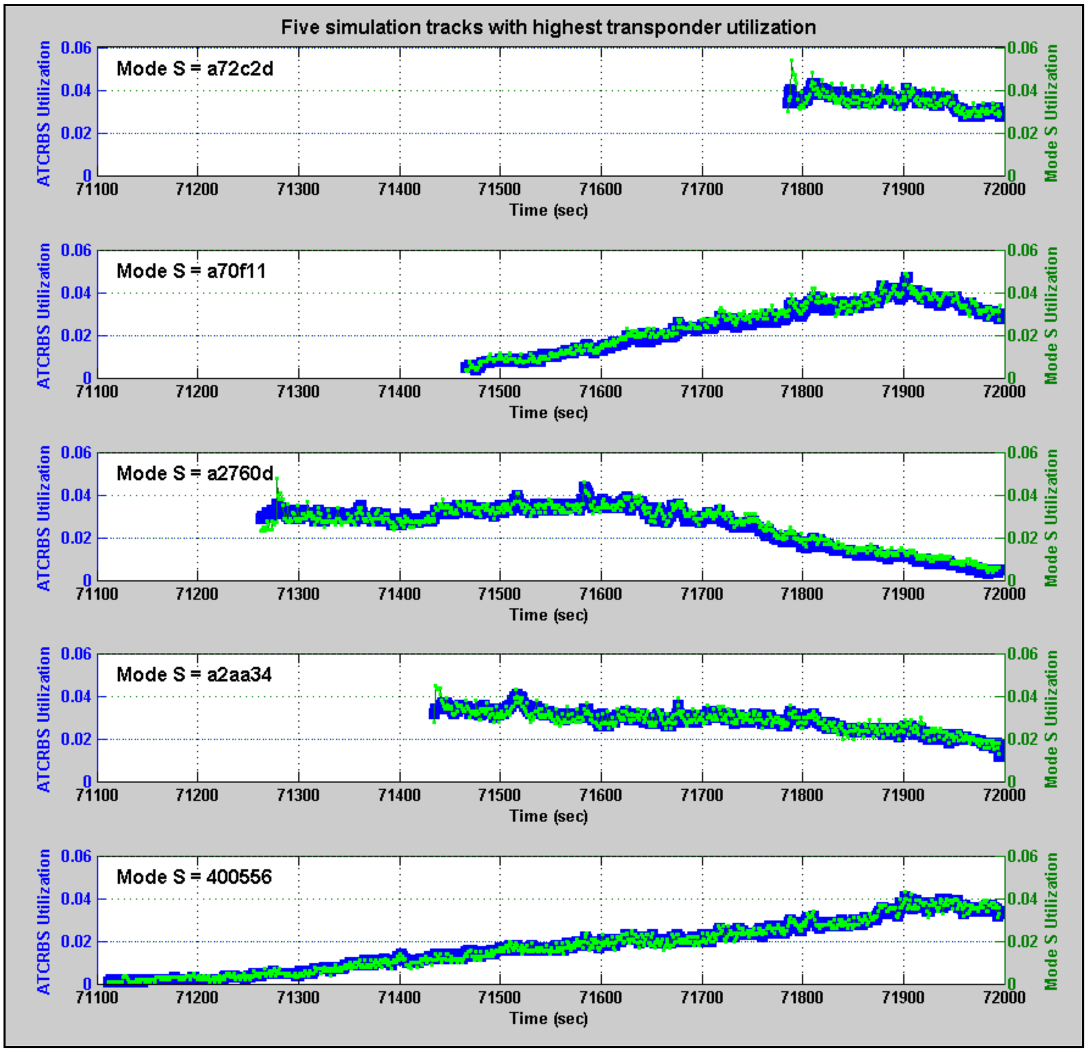

Figure A-5. Utilization for Five Simulated Tracks

To represent the worst case utilization we assume 5%. According to Formulas A1 the resulting availability including TCAS is that without TCAS times 0.95. The *p(i)* for ATCRBS and Mode S in Table A-10 are computed as 0.95 times the values for *p'(i)* previously given in Table A-5.

Table A-10

Interrogation Probabilities, Including TCAS, *p(i)*

	Probabilities		
Transponder	*p'(i)*	*TCAS impact*	*p(i)*
ATCRBS	0.9623	0.95	0.9142
Mode S	0.9657	0.95	0.9174

A-8 PROBABILITY OF REPLY RECEPTION INCLUDING TCAS *p(r)*

The intent of Interference Limiting Equation #3 is to limit the number of ATCRBS replies elicited by the aggregate of all the TCAS's to 40 replies per second. We therefore model that each of the modeled 180 ATCRBS transponders is emitting at that rate.

Interference Limiting Equation #1 limits the utilization of transponders, which implicitly limits the Mode S interrogations of Mode S transponders. We estimate the number of Mode S interrogations allowed by Equation 1 as shown.

For uniform in range target distribution around TCAS

Eq. #1 is:

$$\sum_{i=1}^{Imax} \sqrt{\frac{P_i}{250}} \le \frac{280}{NTA_{30NM} + 1}$$

The 0 dB margin range for omni antennas,

250 W interrogations and -74 dBm MTL is 30 NM. Thus,

$-74dBm = \frac{K*250}{30^2} = \frac{K*P_i}{R_i^2}$, so that:

$\frac{P_i}{250} = \frac{R_i^2}{30^2}$. Assume interrogations are with 6 dB uplink margin, 4 times nominal power

$\sum_{i=1}^{Imax} \frac{\sqrt{4}*R_i}{30} \le \frac{280}{NTA_{30NM}}$, where for simplicity we drop the "+1"

Let ρ = the range density of Mode S targets, all equipped with TCAS

The *ith* target out in range from TCAS is at the range:

$$R_i = \frac{i}{\rho}$$

$\sum_{i=1}^{Imax} \frac{i}{30*\rho} \le \frac{280}{2*NTA_{30NM}}$. But, $NTA_{30NM} = 30*\rho$

Assume 30% of the allocation is used by Whisper S, the remainder for Mode S

$$\sum_{i=1}^{Imax} i = \frac{Imax*(Imax+1)}{2} \le \frac{0.70*280}{2} = 98.$$

$$Imax*(Imax+1) \cong 196 =$$

$$Imax \cong 14$$

Formulas A-6. Mode S interrogation rate by TCAS

Each TCAS can interrogate about 14 Mode S targets at a 1 Hz rate. By symmetry, we assume that each of the 420 Mode S targets (which we also assume is TCAS-equipped) is being interrogated, and therefore replies, 14 times a second, plus one for the squitter.

Table A-11

Fruit Due to TCAS

				Received by JFK sensor		
Transponder type	Number transponders	Fruit rate per transponder	Total Fruit rate	Mainbeam (1%)	Sidelobe (1/40)	Total
ATCRBS	180	40	7.200	72	180	252
Mode S	420	15	6,300	63	157	220

The probabilities of reception without TCAS in Table A-6 are recomputed to include TCAS in Table A-12.

Table A-12

Probability of Reception Including TCAS, *p(r)*

Probability of ungarbled ATCRBS reply reception (Δt_{ATCRBS} = 20.75 μs)			
	Rate (λ_i)	Duration (Δt_i μs)	Exponential term
ATCRBS	2003+252	20.3	0.9693
Mode S short	360+220	64	0.9520
Mode S long	91	120	0.9873
		Product = ATCRBS *p'(r)*	0.9111
Probability of ungarbled Mode S reply reception (ΔtModeS = 64 μs)			
	Rate (λ_i)	Duration (Δt_i μs)	Exponential term
ATCRBS	2003+252	20.3	0.9839
Mode S short	360+235	64	0.9284
Mode S long	91	120	0.9834
		Product= Mode S *p'(r)*	0.8982

A-9 PROBABILITY OF SUCCESS INCLUDING TCAS, *s = p(i) * p(r)*

The probability of a successful interrogation/reply transaction, including TCAS is:

Table A-13

Probability of Success Including TCAS, *s*

	Probabilities		
Transponder	*p(i)*	*p(r)*	*s= p(i)* p(r)*
ATCRBS	0.9142	0.9111	0.8329
Mode S	0.9174	0.8982	0.8240

A-10 PROBABILITY OF TRACK UPDATE INCLUDING TCAS *p(u)*

The resulting probabilities of update for ATCRBS and Mode S are:

Table A-14

Probability of Update Including TCAS, *p(u)*

Trans- ponder Type	s	Update requirement	*p(u)*
ATCRBS	0.8329	2 or more of 6 replies received	0.9993
Mode S	0.8240	1 reply received, allowing up to five retries (1)	0.9999

(1) The average number of interrogations to get a successful reply is 1/0.8240 = 1.21. This does not change the fruit rates. The increase in transponder utilization is only affected in the addressed part, not the scheduled part which dominates. Therefore, the increase due to retries is negligible.

A-11 COMPARISON WITH MEASUREMENTS

The FAA's William J. Hughes Technical Center (WJHTC) measured the Mode S transponder availability in the New York/New Jersey area at about 20,000 feet altitude in July of 2007 during a busy traffic period. The results include TCAS and mutual suppression, and are shown in Figure A-6. The values vary from about 85% to 95% which agrees well the estimated value of 0.9174 given in Table A-10.

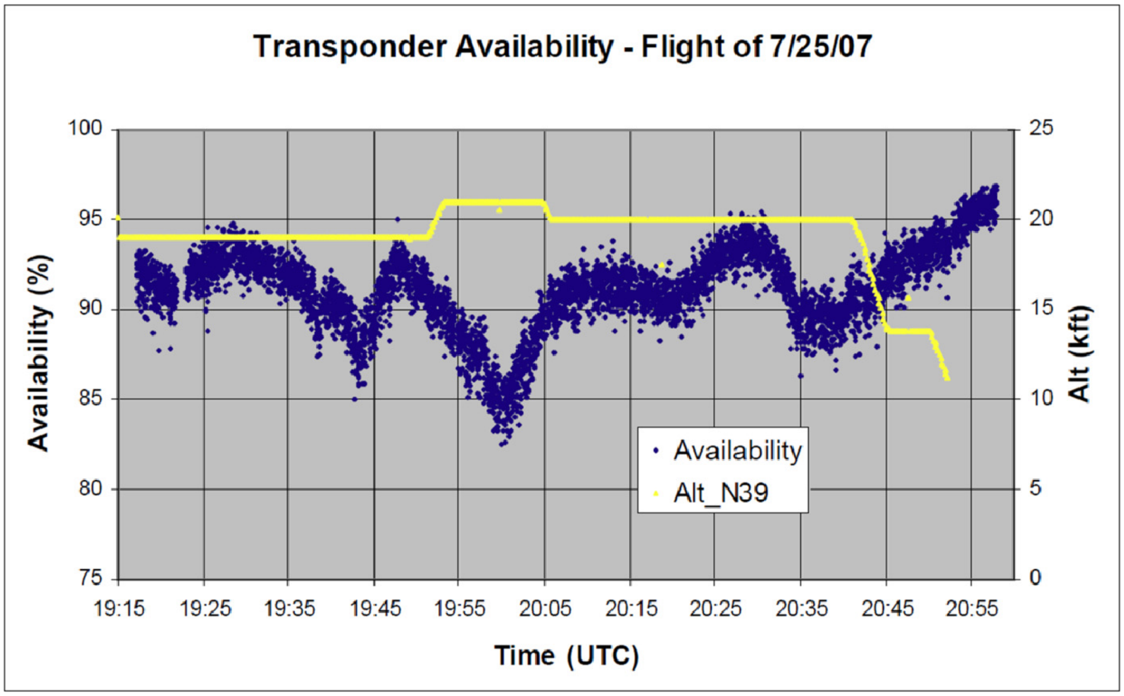

Figure A-6. WJHTC Measured Transponder Availability

WJHTC also measured the ATCRBS fruit rates versus power, shown in Figure A-7. The measurement is with an omni antenna, and the rate at -84 dBm was 25,931.

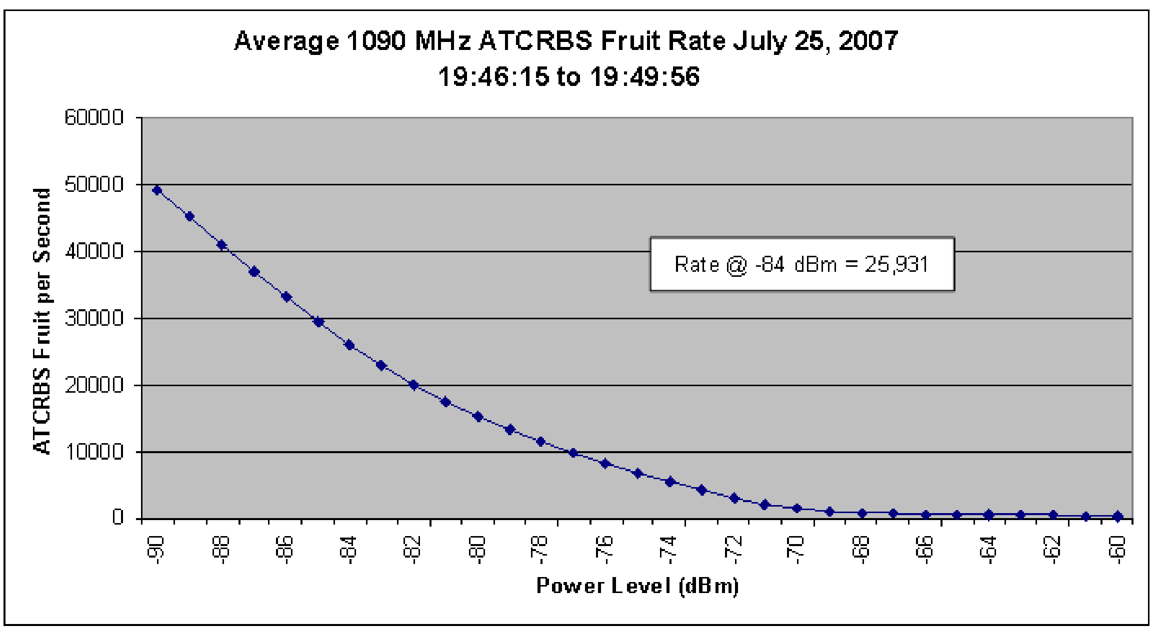

Figure A-7. WJHTC ATCRBS Fruit Measured in the Air

In a separate set of measurements, WJHTC measured the ATCRBS fruit at -84 dBm as seen from the roof of one of their buildings in Atlantic City during about a month, as shown in Figure A-8.

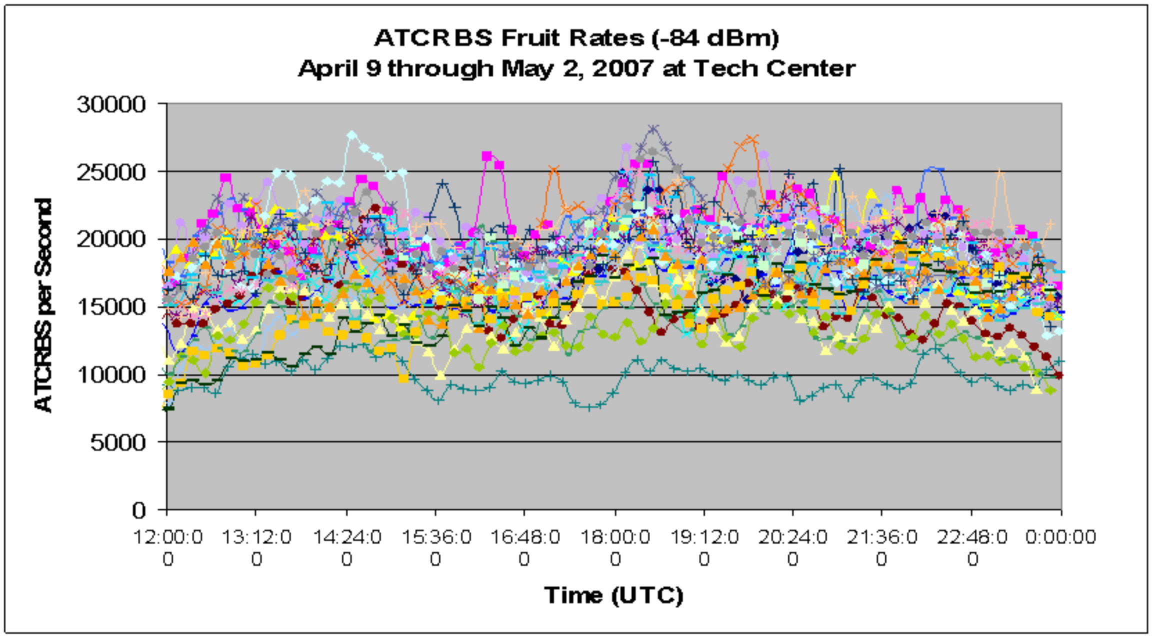

Figure A-8. WJHTC ATCRBS Fruit Measured on the Ground

The measurement occasionally reached 26,000, and we conclude that the fruit seen by an omni near the ground is similar to what is seen at high altitudes.

The cumulative value of nearly 50,000 at -90 dBm in Figure 7 corresponds roughly to a range of 200 nm, and agrees well with the sum of the values estimated in Tables A-6 and A-10 as shown in Table A-15.

Table A-15

Fruit Due to TCAS

	Estimated Fruit			Measured
Transponder type	Without TCAS (Table A-6)	Due to TCAS (Table A-11)	Including TCAS	WJHTC (Figures A-7 – A-10)
ATCRBS	57,240	7.200	64,440	50,000
Mode S	7,921[(1)]	6,300	14,221	8,000[(2)]

(1) This value is 10,265 less most of the estimated 1090ES shown in Table A-6, since there was little 1090ES equipage for the measurements 0.9*2,604

(2) We extrapolated up because decoding drops off as the MTL is lowered. It should be shaped more like the ATCRBS in Figure

Figures A-9 and A-10 show Mode S measurements by WJHTC in the air and on the ground. Again, it appears that the fruit received on the ground is similar to that received in the air. Table A-15 shows that the sum of the Mode S estimates shown in Tables A-6 and A-11 is about twice what WJHTC measured. The reason is not known, but the consequence is that the degradation estimated to be caused by TCAS on the JFK sensor is greater that what would be experienced in actuality.

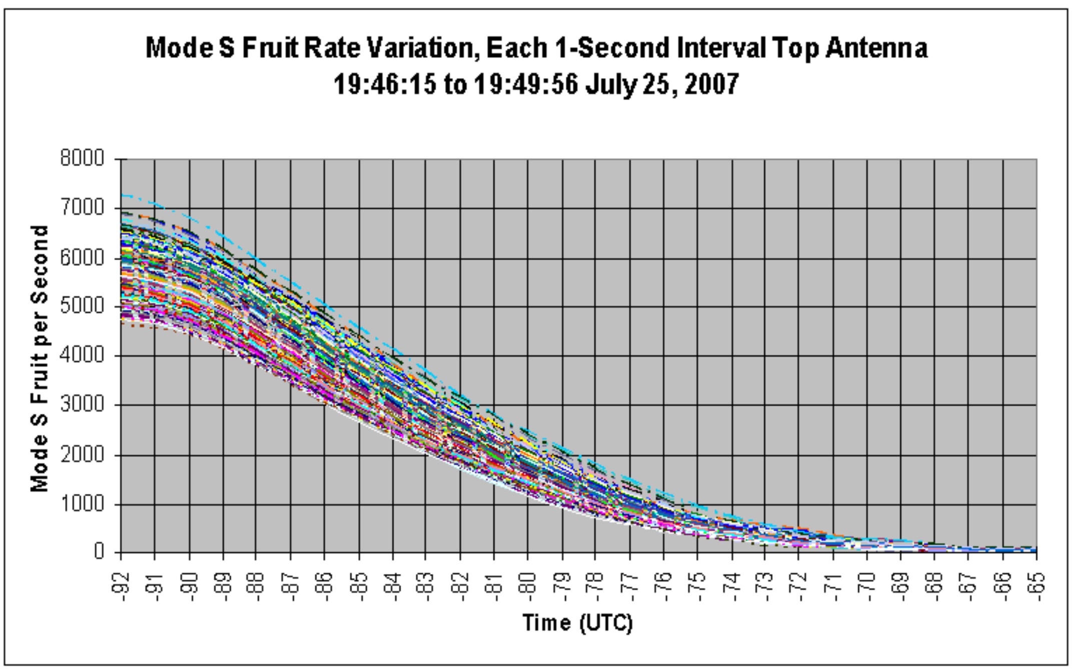

Figure A-9. WJHTC Mode S Fruit Measured in the Air

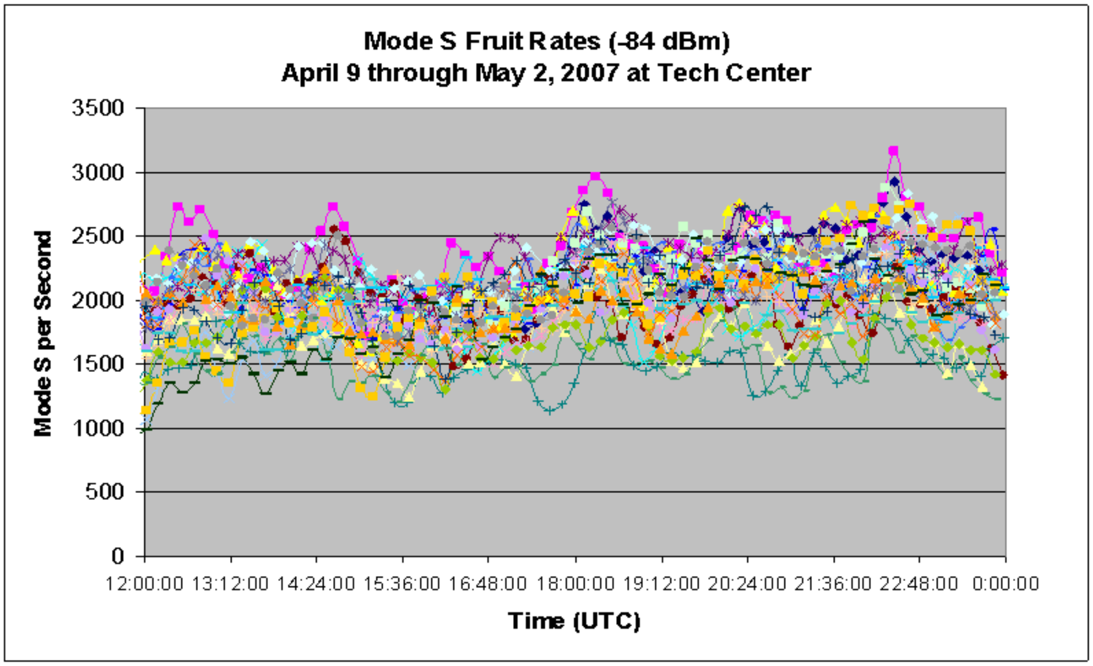

Figure A-10. WJHTC Mode S Fruit Measured on the Ground

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GLOSSARY

ADS	Addison Airport, Dallas, TX
AGL	Above Ground Level
ATCRBS	Air Traffic Control Radar Beacon System
CD2	Common Digitizer 2
DFW	Dallas Fort Worth Airport
EWR	Newark International Airport
FRUIT	False Reply Uncorrelated In Time
IL	Interference Limiting
JFK	John F. Kennedy International Airport
LAX	Los Angeles International Airport
LGB	Long Beach Airport
MOPS	Minimum Operational Performance Standards
NAS	National Air Space
NTA	Number of TCAS Aircraft
ONT	LA/Ontario International Airport
PHL	Philadelphia International Airport
RA	Resolution Advisory
SARPs	Standards and Recommended Practices
SSR	Secondary Surveillance Radar
TEB	Teterboro Airport
TOPA	TCAS Operational Performance Assessment
TRAMS	TCAS Resolution Advisory (RA) Monitoring System
UTC	Coordinated Universal Time
WJHTC	FAA William J. Hughes Technical Center

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