**Project Report**
**ATC-390**

# Measurements of the 1030 and 1090 MHz Environments at JFK International Airport

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16. Abstract

Measurements of signals in the 1030 and 1090 MHz frequency bands have been made by MIT Lincoln Laboratory in the last several years, previously in the Boston area and most recently in April 2011, at JFK International Airport near New York City. This JFK measurement activity was performed as a part of the Lincoln Laboratory Traffic Alert and Collision Avoidance System (TCAS) work for the Federal Aviation Administration (FAA) and is the subject of this report.

This report includes:

- Overall characteristics of the 1030/1090 MHz environments
- Analysis of the TCAS air-to-air coordination process
- Examination of 1090 MHz Extended Squitter transmissions for use in TCAS
- Assessment of the extent and impact of TCAS operation on the airport surface

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# EXECUTIVE SUMMARY

This is the third report of MIT Lincoln Laboratory 1030/1090 monitoring, performed as a part of the Lincoln Laboratory Traffic Alert and Collision Avoidance System (TCAS) work for the Federal Aviation Administration (FAA). The first two reports focused on measurements near Boston, MA; this third report is based on measurements at JFK International Airport in New York. The Lincoln Laboratory JFK measurement activity, using a ground-based omnidirectional receiver, was timed to coincide with airborne measurements carried out by the FAA Technical Center in the vicinity of New York City. This location is important because the New York City area is considered to have the highest density in the United States of Mode S equipped aircraft and TCAS equipped aircraft.

This JFK report includes all of the major topics covered in previous reports, allowing a comparison between the Boston and New York airspaces:

1. Overall analysis of the 1030/1090 MHz environments,
2. Analysis of the TCAS air-to-coordination process,
3. Examination of 1090 MHz Extended Squitter transmissions, i.e., the Mode S implementation of Automatic Dependent Surveillance-Broadcast (ADS-B).

This report also includes an additional new topic:

4. Assessment of the extent and impact of TCAS operation on the airport surface.

The Lincoln Laboratory measurements at JFK were recorded over an extended time period in April 2011, continuing 24 hours a day over 25 days. These were passive measurements (without any transmissions). Measurements of aircraft tracks by the FAA's ATC radar were also recorded simultaneously, allowing the omnidirectional receptions to be used together with the radar data to draw a number of conclusions about the mechanisms affecting the 1030 and 1090 MHz frequency bands.

The omnidirectional antenna was installed in a temporary location on the main control tower at JFK airport. The receiver used for omnidirectional receptions was made by Thales ATM, Inc. and is one of the standard receivers being used for the nationwide deployment of ADS-B. The main radar used for this analysis was the FAA's radar installed at JFK airport, although a number of other radars also provided data during the period of these measurements.

Findings included the following:

- Among the aircraft in the New York area, 88 percent are equipped with Mode S, a substantially higher percentage than in the Boston area (50 percent). Of the Mode S aircraft, 86 percent are also equipped with TCAS and 25 percent are also equipped with ADS-B. These are average values, computed over the entire data set. The corresponding Boston numbers for TCAS and ADS-B are 75 percent and 28 percent.

- Aircraft density was found to be concentrated at JFK, diminishing as a function of distance away from JFK. Expressed as a function of range, the cumulative number of aircraft grows linearly with range, having a rate of about 3 aircraft per NM of range away from the radar at JFK airport.

- Although on-ground TCAS operation is at variance with the spectrum approval of TCAS, many aircraft operate TCAS while on the airport surface at JFK. The measurements show that on most afternoons 20 to 30 aircraft are operating TCAS on the surface, and a maximum near 45 was observed. These large numbers help to explain why the Mode S reply rate is high in the JFK area and also why the TCAS count is often very high when flying in this area in view of the three major metropolitan airports.

  An analysis of the impact of on-ground TCAS operation shows that aircraft operating TCAS on the ground at the three major metropolitan airports increase the average number of TCAS messages received by an airborne aircraft within 30 NM of JFK by approximately 50% on 1030 MHz and 90% on 1090 MHz. In addition, these on-ground TCAS operations cause a doubling of the instantaneous TCAS count within 30 NM of JFK. This TCAS count is used in TCAS interference limiting algorithms to decrease the transmission power (and thus surveillance range) of nearby airborne TCAS units. Results from this analysis indicate that on average the surveillance range of airborne aircraft within the JFK area is reduced by 20%. It is possible that excessive operation of TCAS units on the airport surface could cause the surveillance range of airborne TCAS units in certain altitude volumes to be insufficient for TCAS to provide the maximum warning time for a potential threat with a high closure rate. This will be studied further.

- Among the different kinds of Mode S replies, the most common are TCAS replies, which make up 60 percent of all Mode S replies. This result was compared with similar measurements in the Boston area, and it is consistent with a higher population of TCAS aircraft in the New York airspace. Short (or ‘acquisition’) squitters represent about 10 percent of all reply types in the New York airspace. Extraneous short squitters (squitters transmitted beyond the expected 1 per second) were found to be about 5 percent of all reply types.

- An examination of ADS-B receptions shows that aircraft from many different countries appear in the New York airspace. For most of those countries (with the US being a notable exception), the majority of aircraft are equipped with ADS-B. These countries are listed, along with the number of aircraft detected from each country and the percentage that are equipped with ADS-B.

- TCAS coordination messages were recorded by the omnidirectional receiver, providing an opportunity to study coordination exchanges in TCAS-TCAS encounters. During the 25-day measurement period, 87 TCAS-TCAS encounters were observed, a TCAS-TCAS encounter rate four times greater than in the Boston area. In the most basic sense, TCAS coordination was successful in every case; the up/down maneuver sense was correctly communicated between the two aircraft, and when both aircraft selected Resolution Advisories, the two RAs were compatible. It was rare but there were cases (2 encounters) in which the up-down sense of the coordination was reversed after the initial coordination. Previously identified coordination anomalies were observed at JFK with similar frequency to observations made in Lexington MA. In one encounter a significant degradation in the communication link was observed which is of concern. Coordination analysis also helped reveal and analyze an encounter where the coordination process stopped (after initial sense was coordinated) due to a surveillance problem.

The results from this report are being used in a number of significant ways:

- Recorded JFK surveillance data is being used to support the work of RTCA SC-147 in developing revisions to TCAS standards documents.

    1. JFK data has been used to supplement radar recordings for building a comprehensive aircraft environment for input into the Lincoln Laboratory TCAS surveillance simulation. Simulation findings have led to proposed modifications which can dramatically reduce TCAS 1030/1090 MHz spectrum usage.

    2. First-time information about on-ground TCAS operation has led to proposed modifications requiring on-ground TCAS aircraft to limit their active interrogation power and to use passive ADS-B surveillance when possible.

- Data related to TCAS surveillance is being used in the development of surveillance algorithms for ACAS X, the next-generation collision avoidance system under development by the FAA TCAS Program Office.

- Examination of specific 1030 and 1090 transmissions has supported and will continue to support the FAA Certification Office in analysis of equipment anomalies.

- The understanding of the relationship between ground-based and airborne 1030/1090 measurements made possible by this data collection is expected to enable greater future use of ground-based measurements in place of the more expensive and time-limited airborne flight testing.

- Data recorded at JFK can provide an independent check of fruit models generated from airborne measurements and serves as a resource for FAA spectrum activities underway.

# ACKNOWLEDGMENTS

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 the 1030/1090 MHz monitoring is taking place.

In addition, we would like to thank Jerry Johnson and Mark Boguski of Thales ATM, Inc. for their technical expertise and support throughout our entire monitoring program.

Finally we would like to thank the following FAA personnel, who worked with Lincoln Laboratory personnel to install and test the 1030/1090 MHz data collection system at JFK International Airport:

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Paul Quick – FAA Technical Center

Kevin Fehr – FAA Technical Center

James Rambone – FAA Technical Center

Shelly Moskowitz – JFK

Charles Caravello – JFK

Steven Lo Verde – NY Operations Support Center

# TABLE OF CONTENTS

# TABLE OF CONTENTS
# (Continued)

**Page**

# LIST OF ILLUSTRATIONS

# LIST OF ILLUSTRATIONS
# (Continued)

# LIST OF ILLUSTRATIONS
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# LIST OF ILLUSTRATIONS
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# LIST OF TABLES

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# 1. INTRODUCTION

Measurements of signals in the 1030 and 1090 MHz frequency bands have been made by MIT Lincoln Laboratory in the last several years as a part of the Lincoln Laboratory Traffic Alert and Collision Avoidance System (TCAS) work for the Federal Aviation Administration (FAA). Previous measurements were made in the Boston area, and results are documented in [1] and [2]. In April 2011, measurements were made at JFK International Airport near New York City. The Lincoln Laboratory JFK measurement activity, using a ground-based omnidirectional receiver, was timed to coincide with airborne measurements carried out by the FAA Technical Center in the vicinity of New York City. This location is important because the New York City area is considered to have the highest density in the United States of Mode S equipped aircraft and TCAS equipped aircraft.

Both the Boston and New York measurements are intended to allow new and better understanding of the current conditions in the 1030/1090 MHz frequency bands. These bands are important because they are used by a number of systems: FAA radar and multilateration surveillance of aircraft, military surveillance of aircraft, TCAS, and Automatic Dependent Surveillance – Broadcast (ADS-B). The 2020 FAA ADS-B mandate is expected to increase use of the 1090 MHz frequency, and efforts are being made to ensure efficiency by all users.

In addition to understanding the 1030/1090 MHz environment, the JFK measurements allow detailed examination and analysis of various TCAS-related topics, including the performance of TCAS air-to-air coordination and the extent to which ADS-B information is available for use by TCAS. The placement of the receiver at JFK provides a clear view of the airport surface and allows for the first time a comprehensive measurement of on-ground TCAS operation. This JFK report includes all of the major topics covered in previous reports, allowing a comparison between the Boston and New York 1030/1090 MHz activity.

Results can also be compared with those of Los Angeles, another location associated with high aircraft density. Measurements in 1976 determined that at that time the maximum local density of aircraft was found in the LA Basin, higher by a factor of about 2 relative to other major cities [3]. However, the LA Basin area is limited in extent by mountains and the Pacific Ocean, and therefore the high density conditions do not extend far from LA itself. In contrast, New York City is not limited to that degree and is part of the large northeastern megalopolis.

The previous Boston area measurements of aircraft density and 1030/1090 MHz signals have resulted in the development of analysis techniques that can now be used in New York. The April 2011 measurements were undertaken to make use of these techniques to extend the information previously gathered about these frequency bands and the density of air traffic.

Section 2 gives a description of the Lincoln Laboratory measurement facilities, including placement and coverage of the receiver and measurement dates and times.

Section 3 is the most extensive section, discussing the 1030/1090 MHz environment in detail. Information is given on aircraft density, equipage type (ATCRBS, Mode S, TCAS, ADS-B), message reception rates, and relative rates of different downlink formats.

Section 4 examines TCAS operation on the airport surface. A companion document in Appendix B provides an analysis of the impact of on-ground TCAS operation on 1030/1090 MHz usage and on the performance of nearby airborne TCAS units.

Section 5 analyzes the TCAS air-to-air coordination process. It includes a review of the issues noted in earlier Boston data and compares the types and frequencies of Boston and New York anomalies. Statistics are given on various aspects of TCAS-TCAS encounters, and two sample encounters are explained in detail

Section 6 examines received ADS-B messages that would be of use to TCAS.

Section 7 gives a summary of key report findings and conclusions.

Appendix A discusses modifications Lincoln Laboratory made to the 1030/1090 MHz Thales receiver in preparation for the JFK measurements. Earlier measurements in the Boston area were focused primarily on examining and analyzing the content of received messages; thus the Thales receiver was originally configured to capture only those messages that were decodable and contained data useful to an end user. For the JFK measurements, it was desirable to also characterize the Mode S FRUIT (False Replies Uncorrelated in Time) environment. Doing so required modifications to the Thales receiver which allowed the hardware to additionally capture/count replies that were received but not decodable. These modifications resulted in the Lincoln Laboratory ground 1030/1090 MHz receiver being more similar to the FAA Technical Center airborne 1030/1090 MHz receiver, allowing both organizations to share and compare data at a later point, if desired.

Appendix B, as stated earlier, provides an analysis of the impact of on-ground TCAS operation on 1030/1090 MHz usage and on the performance of nearby airborne TCAS units.

# 2. MEASUREMENT FACILITIES

## 2.1 RECEIVER PLACEMENT

For the New York measurements, the Lincoln Laboratory omnidirectional receiving system was installed at JFK Airport near New York City (Figure 1). The FAA radar at JFK was also used for simultaneous measurements of aircraft tracks. The range limit of the radar is 60 NM, whereas omnidirectional receptions can be from much longer ranges. The radar data was recorded in a detailed format, which includes Mode S addresses and generally more information than what is currently used for air traffic control purposes.

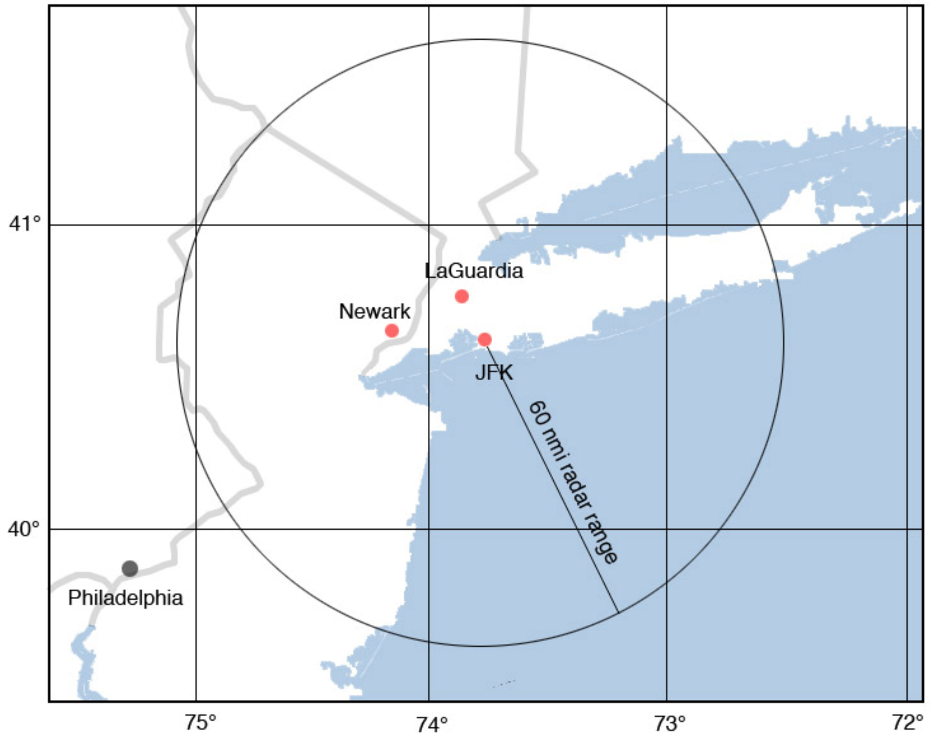


*Figure 1. Location of JFK measurements.*

The omnidirectional receiver was capable of detecting and recording receptions in both 1030 and 1090 MHz bands. The events recorded are signal detections in the form of a Mode S or ATCRBS signal. Along with each signal detection, the recording includes the received signal power and reception time. This receiver was obtained from Thales ATM, Inc., the manufacturer of the nationwide ADS-B ground stations. The Thales receiver includes a reply detector, and so the measurements available from the receiver are ATCRBS and Mode S replies detected by the Thales reply detector.

The omnidirectional antenna was installed in a temporary location on the main tower at JFK airport. The antenna is a 6.5-foot high vertical antenna, having a gain pattern that is omnidirectional in azimuth and shaped in elevation (model 5100A DME antenna made by dB Systems). The antenna gain pattern in elevation is shown in Figure 2.

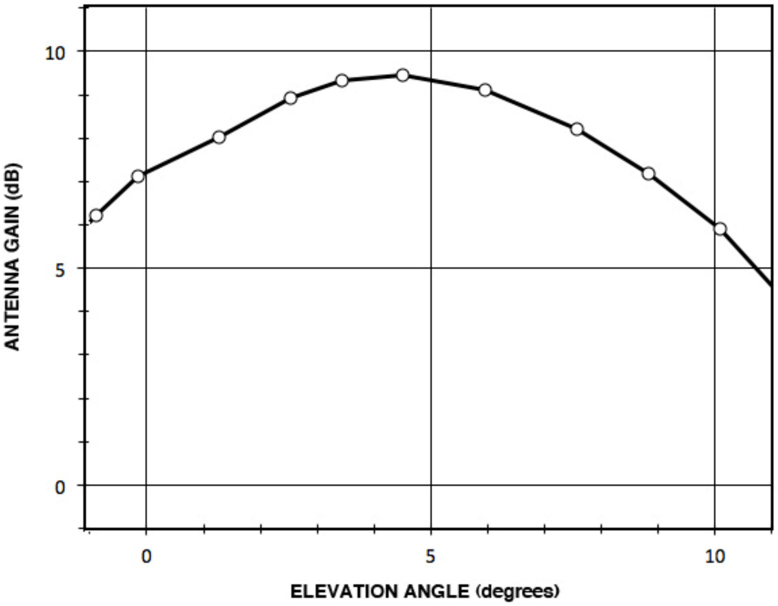


*Figure 2. Elevation pattern of the omnidirectional antenna.*

As indicated in Figures 3 and 4, the antenna location was near the top of the control tower, on a flat deck called the “antenna farm” where a number of other antennas are located. About 300 feet above ground level, this was an excellent location, providing a good view to the north and west. The view to the east was obstructed by the main section of the tower. Because the dimensions of the obstruction are well known, it is possible to account for the effects on reception rate. Section 3.2.3 provides an analysis of the amount of obstruction and gives adjusted values of reception rate as estimates of the full rates that would be received by an unobstructed omnidirectional antenna site.

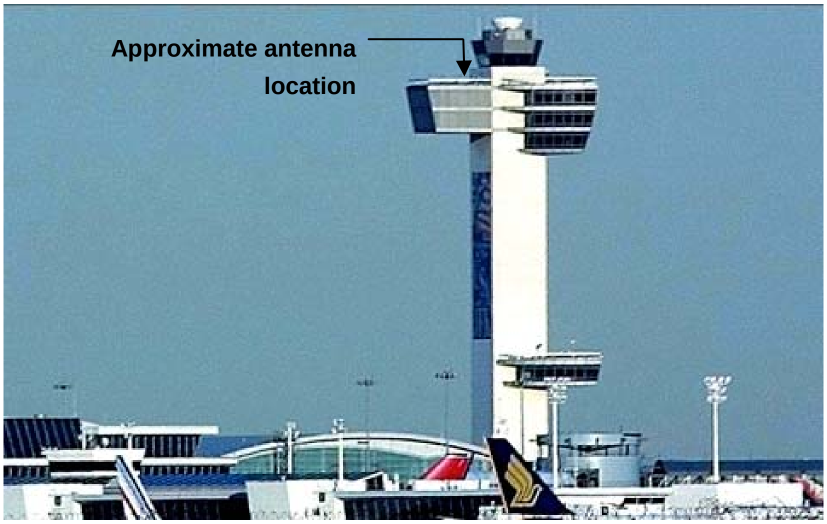


*Figure 3. Location of the omnidirectional antenna on the JFK tower.*

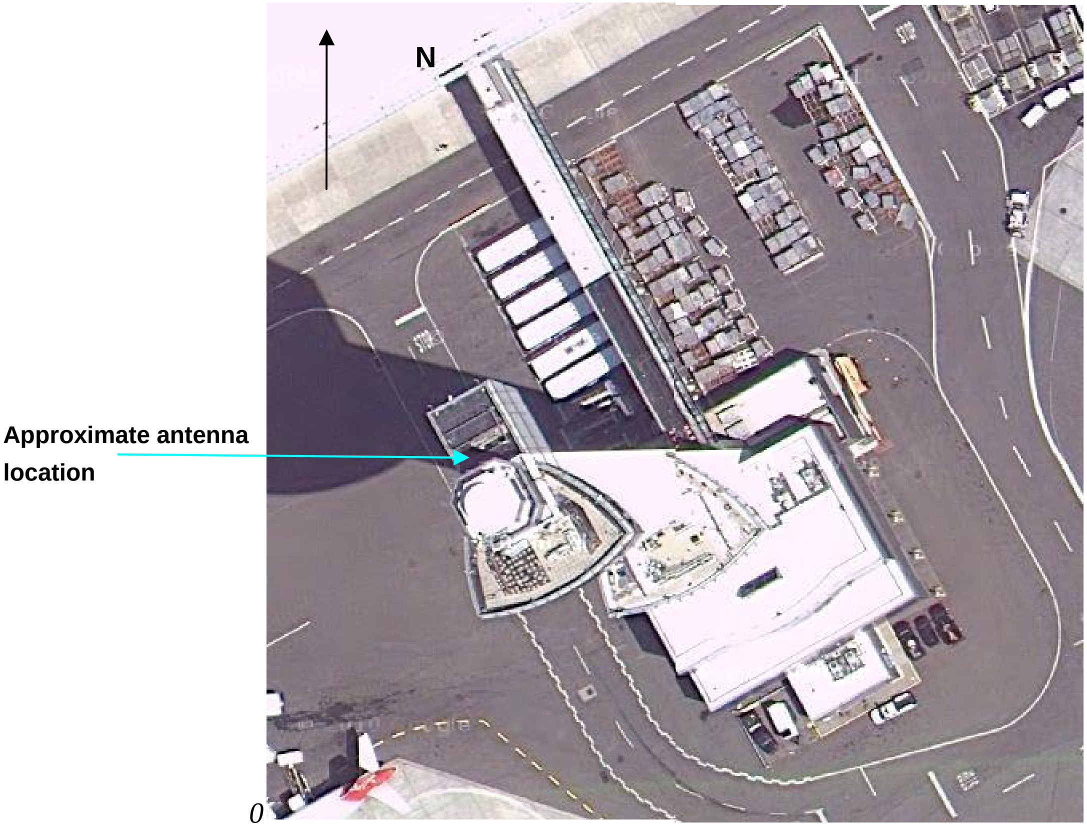


*Figure 4. Another view of the tower and antenna location.*

Panoramic photographs taken from the antenna farm are shown in Figure 5. The obstruction by the tower building appears clearly. Another panoramic view is in Figure 6, which was taken by a fish-eye lens. The photographs in Figure 5 were taken from a location somewhat farther away from the building, so the amount of obstruction is not exactly the same as for the antenna, whereas the fish-eye photo was taken from a location close to the omnidirectional antenna.

*Figure 5. Panoramic photos from the omnidirectional antenna location, ATC tower.*

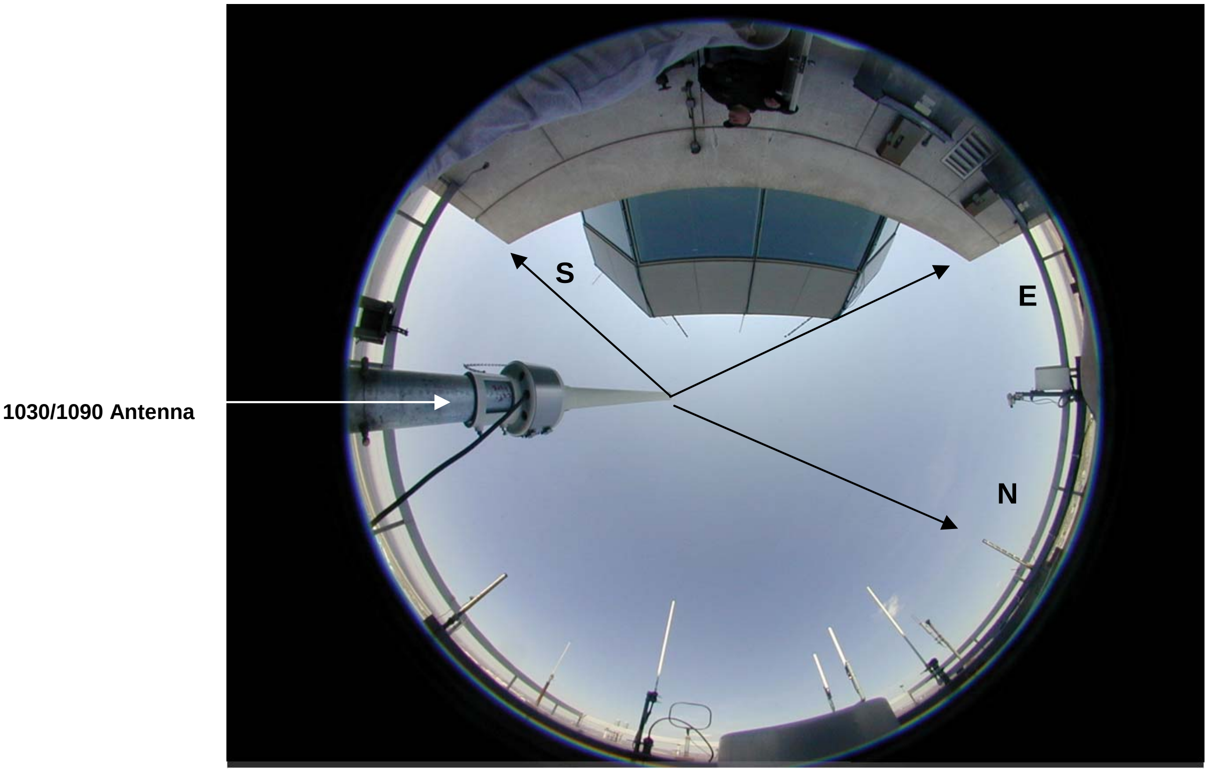


*Figure 6. 360 degree view from the omnidirectional antenna.*

To illustrate the effect of the obstruction on omnidirectional reception, Figure 7 shows a comparison between aircraft tracks measured by the JFK radar and omnidirectional receptions. This figure shows the receptions of short squitters (DF11 with II code = 0) during a 2000 second period. Each red point indicates the reception of a short squitter. The location of the aircraft at that time was determined by using the radar data. For each aircraft address detected by short squitters, the blue points indicate the location of the aircraft, even when there was no DF11 reception. Consequently, the preponderance of blue points southeast from JFK indicates that omnidirectional reception was blocked in those directions.

Seen from the installed antenna, the width of the obstruction is 116°. The building obstructs 32% of the desired 360° coverage. A simple characterization of the effect would be to reduce reception rate by the factor 0.68, and a rough estimate of the full reception rate from an unobstructed antenna would be higher by the inverse factor, which is 1.48. Fortunately however, the direction that is obstructed is mostly over ocean where the amount of air traffic is relatively low, as can be seen in Figure 7. Consequently, the reduction is not as significant. Section 3.2.3 provides a quantitative analysis of the obstruction factor, considering the traffic distribution, and showing how much of an adjustment could be applied to estimate the full reception rate for complete 360° reception. That more detailed analysis concludes that a factor of about 1.10 is appropriate for estimating the full reception rate.

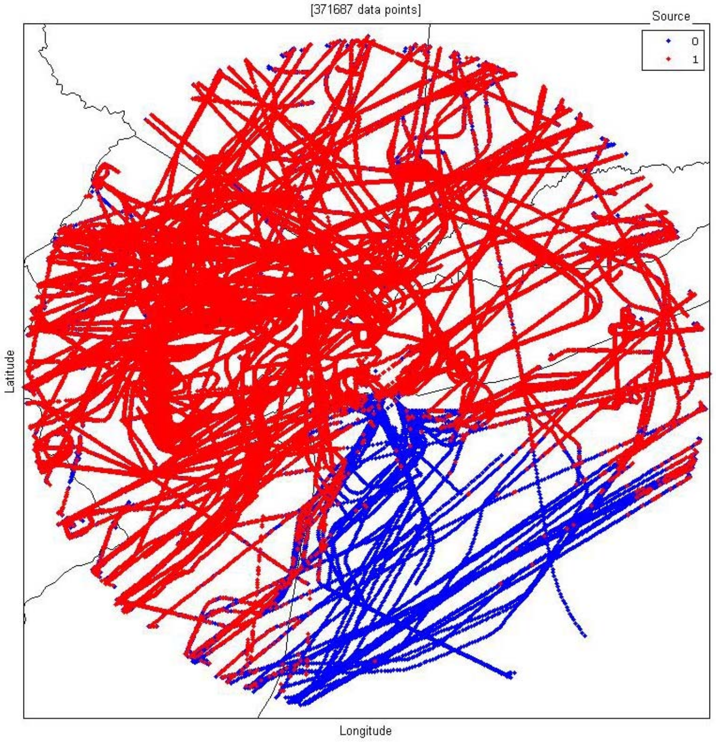
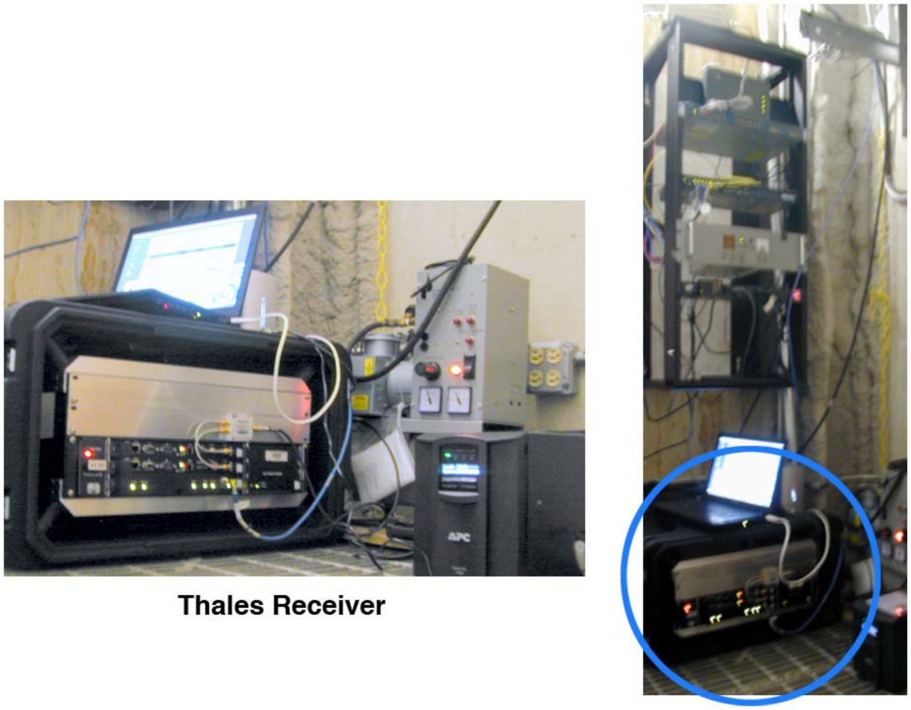


*Figure 7. Omnidirectional reception as affected by building obstruction. Red is omnidirectional reception; blue is radar report.*

FAA William J. Hughes Technical Center (WJHTC) and Lincoln Laboratory personnel installed and tested the 1030/1090 data collection system on Monday, 4 April 2011. WJHTC engineers provided the manpower to perform a professional installation of the RF cabling through existing conduits from a utility closet on the 16th floor to the antenna farm located on the northwest side of the air traffic control tower (Figure 3). During the installation and testing process (Figure 8), it was determined that GPS time synchronization used for the Thales equipment timestamps would be unreliable due to lack of GPS signal lock. The high RF attenuation due to a long GPS cable run resulted in low signal at the receiver. This was corrected by installing a higher-gain active GPS antenna prior to noon EDT on 7 April 2011.

The raw recordings of received power level are referred to the receiver input ports. Figure 9 provides a summary of the amount of power loss between the omnidirectional antenna and the receiver. The losses shown here can be used to present the measurements as the power levels at the antenna, which is done for the measurements reported in the following sections.



**Thales Receiver**

**Rack Mounted Receiver**

*Figure 8. Temporary receiver installation.*

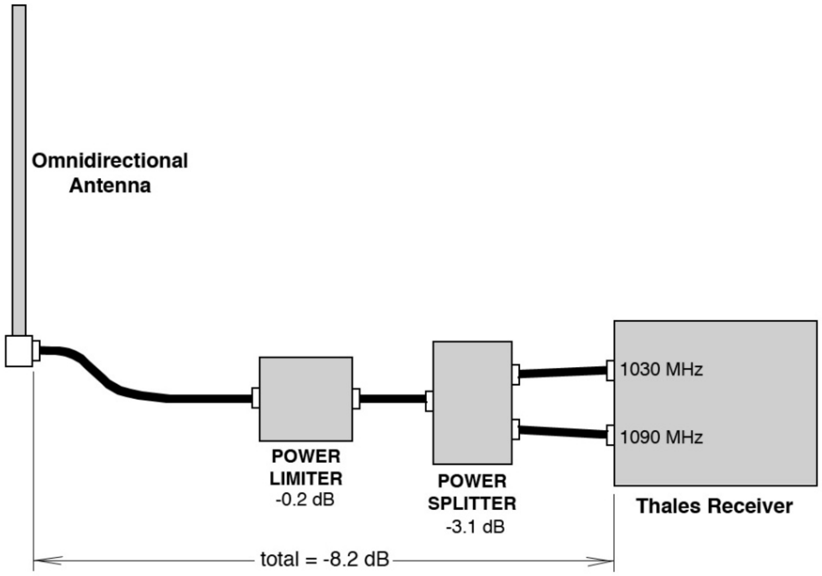


*Figure 9. Limiter and power divider between antenna and receiver.*

The Thales receiver used in these JFK measurements was a standard receiver of the type designed for the nationwide ADS-B deployment. Several adjustments were made to obtain maximum receiver performance for this data collection. These adjustments were made through consultation with engineers from Thales. Through these consultations, it was realized that an improved version of ATCRBS decoding on the Thales receiver had been developed. However, the receiver used for this data collection has not been upgraded to the improved ATCRBS decoding implementation. In the 1090 MHz band, the reception probability for Mode S signals is quite good, but that is not true for ATCRBS receptions. The receiver does detect and record some ATCRBS signal receptions, although a considerable percentage of them are not recorded. Consequently the measurements in the 1090 MHz band discussed in this report are limited to Mode S measurements in this New York program. The adjustments of the Thales receiver are described in Appendix A.

There are several notable differences between this receiver and other kinds of Mode S receivers. A TCAS II receiver includes basic bit detection and error correction; a high-end airborne ADS-B receiver includes enhanced bit detection and error correction. For this data collection, the Thales receiver was configured to include an enhanced form of bit detection, although without error correction, and a capability to record receptions having bit errors.

Between the previous measurements in the Boston area and these measurements at JFK, the receiver configuration was changed. Error correction was used previously but disabled for the JFK measurements. The reason for this change was to enable reception of a greater number of signals including messages having bit errors. As a result of the change, it was possible to acquire more data, although it was not possible to use error correction. The change in receiver configuration is described in more detail in Appendix A.

## 2.2 MEASUREMENT DATES AND TIMES

The measurements at JFK airport in New York cover a 25-day period in April 2011, continuing day and night over that time. Measurements began on the afternoon of Monday, 4 April 2011, and continued into the morning of 29 April. The 25-day time period is shown in the form of a calendar in Figure 10, which is a plot of aircraft counts over the measurement time period. This is a plot of radar data from the FAA radar at JFK Airport. Each point is a 1-hour average, and the vertical lines indicate midnight local time (Eastern Daylight Time). The dates are shown as numbers along the horizontal axis. The six quantities plotted vertically indicate different ranges from the radar, 10, 20, 30, 40, 50, and 60 NM. Approximately 510 gigabytes of 1030/1090 MHz message traffic data was recorded over this time period.

During this period, airborne measurements were also made by the WJHTC. The airborne measurements were on

| | |
|---|---|
| Tuesday, 5 April | 14:30 to 16:15 EDT |
| Thursday, 7 April | 14:36 to 17:08 EDT |
| Thursday, 21 April | 14:36 to 16:00 EDT |
| Tuesday, 26 April | 14:40 to 16:30 EDT |

These time periods are marked with vertical red lines in Figure 10.

At the conclusion of the data collection, the low-loss coaxial cable for the 1030/1090 system as well as the GPS cable were labeled and left in place for any future collection campaigns.

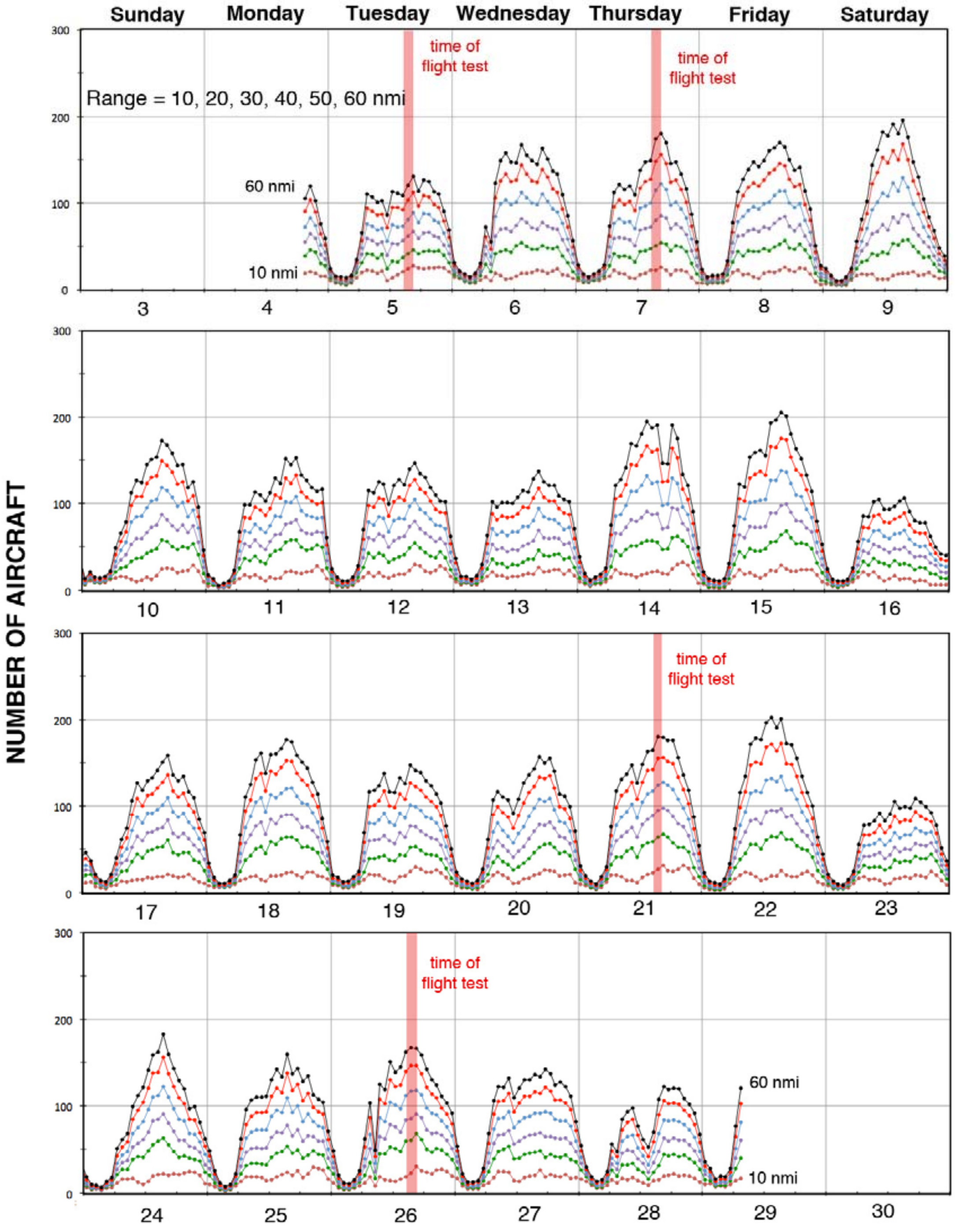


*Figure 10. Number of aircraft for different ranges from JFK over 25 days. Vertical lines denote midnight local time.*

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# 3. ANALYSIS OF 1030/1090 MHz ENVIRONMENTS

## 3.1 AIRCRAFT DENSITY

Figures 10 and 11 show the measured number of aircraft every hour of every day over the 25 day period in April 2011. Figure 10 is marked to show the dependence on range, and Figure 11 is marked to show the different counts for Mode S, ATCRBS, TCAS, and ADS-B aircraft. Each point is a one-hour average of aircraft counts measured by the JFK radar. The values in Figure 11 apply to the aircraft within 30 NM of the radar.

To determine the subset of all aircraft that are equipped with Mode S, it was only necessary to use radar data because each radar report indicates whether it is Mode S or ATCRBS. To determine the subset that has TCAS, the analysis technique made use of omnidirectional receptions as well as radar. A list of TCAS aircraft was created using TCAS broadcasts (1030 MHz) and also using the RI (Air-to-Air Reply Information) field in replies to TCAS (as described in Section 4). That list of addresses was then used with the radar data to count the subset of aircraft operating TCAS. The same technique was also used to count ADS-B aircraft using ADS-B receptions.

The plots in Figure 11 are in a cumulative format in which the upper points show the total of all transponder equipped aircraft, the next lower points are the subset that are equipped with Mode S transponders. Therefore, the separation between the upper two points (marked green in the upper plot) indicates the number of aircraft equipped with ATCRBS transponders. The number of ATCRBS aircraft is seen to vary considerably from day to day. Figure 11 shows that there was an increase in ATCRBS traffic on Saturday, 9 April, probably because it was a good-weather weekend day. The following Saturday was completely different, having less ATCRBS traffic than the two days before. Comparisons with weather are presented in more detail in Section 3.2.2.

There is an obvious day-night pattern in the two figures. By midnight every day, the number of aircraft dropped to a small number. The minimum number of aircraft occurred about 3 AM local time on most days. The data also indicates that there was a steeper rise in the morning than the drop-off at night. The two figures also indicate that there were considerable day-to-day differences, as mentioned above.

The data in Figures 10 and 11 also indicates some week-to-week differences. On the first Saturday (9 April) air traffic was not as low as on the other two Saturdays. Behavior like that might be a consequence of weather differences. Some weather data is presented in Section 3.2.2 below.

It is interesting to see that on certain days, nearly all the aircraft were equipped with Mode S and TCAS. In other words, there were nearly zero aircraft without Mode S and TCAS. Furthermore, the total number of aircraft was relatively low. That happened on Saturday, 16 April, and several other days. It seems likely that this condition was caused by bad weather.

The data in Figure 11 indicates that the number of aircraft that are equipped with ADS-B is about 18 percent of Mode S aircraft. Similarly, TCAS aircraft constitute about 86 percent of Mode S aircraft.

Figure 11 also indicates that the number of ATCRBS aircraft is only about 12 percent of the total. That percentage can be compared with Boston-area measurements reported in [2]. The number of ATCRBS aircraft seen in the Boston area was about 50 percent of the total, much higher than the percentage seen in New York. The reason for the difference may be simply that airline traffic in New York is quite high, and all airliners are equipped with Mode S.

These percentages can be summarized as follows. These values are averages calculated from the radar data over the entire period of 25 days.

Mode S aircraft / all aircraft = 88%
ATCRBS aircraft / all aircraft = 12%
TCAS aircraft / Mode S aircraft = 86%
Extended Squitter aircraft / Mode S aircraft = 20% *
Position Squitter aircraft / Mode S aircraft = 18%

**Note that this 20% value differs slightly from the 25% value given in the Executive Summary and in Section 6, "Analysis of 1090 MHz Extended Squitter." The 20% value is calculated from combined radar data and omnidirectional data and represents aircraft within 60 NM of the radar. The 25% value is calculated from aircraft within the larger range of the omnidirectional receiver.*

The aircraft counts in Figure 10 are shown using six values of range. The vertical spacing is approximately uniform, which would not be true if aircraft were distributed uniformly in area. The data indicates that the range distribution of aircraft is approximately uniform-in-range. In other words, the local density of aircraft per square NM is higher near the center, JFK. This is a common behavior we have observed in most high density areas [Ref. 1, page 68; Ref. 5, page 18; and Ref. 6, page 4].

Note that radar measurements are limited by the curvature of the earth. Aircraft at long range and low altitude are below the line-of-sight of the radar. At 60 NM range, the line-of-sight limit is about 2400 feet in altitude.

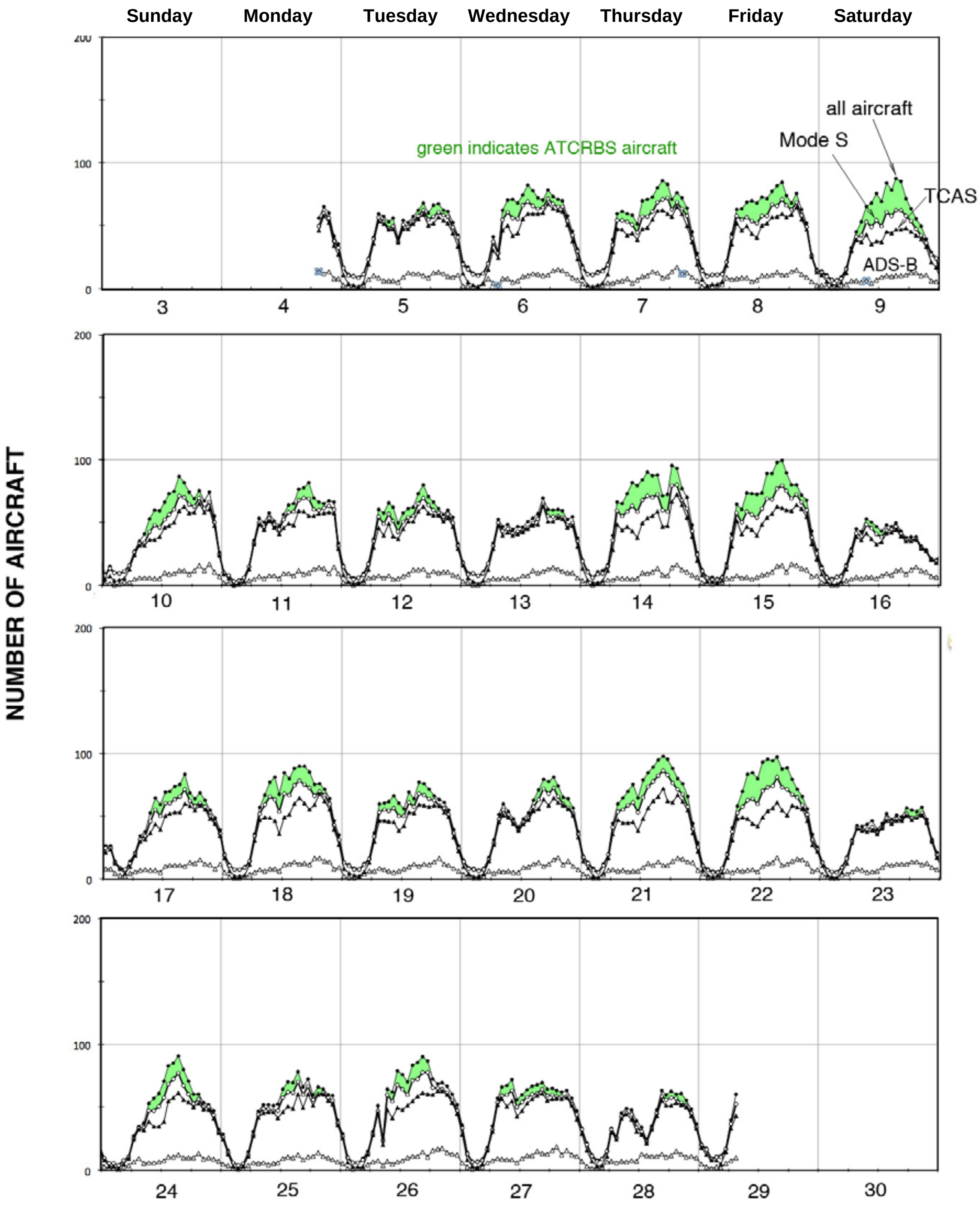

*Figure 11. Number of aircraft within 30 NM. Vertical lines denote midnight local time.*

Figure 12 shows the range dependence of aircraft density directly, in a cumulative plot of aircraft count vs. range. These points apply to a one-hour period during the flight test on Thursday, 7 April, 15:00 to 16:00 EST. The uniform-in-range characteristic can be summarized simply by saying that the range distribution is approximately a uniform rate of 3 aircraft per NM of range.

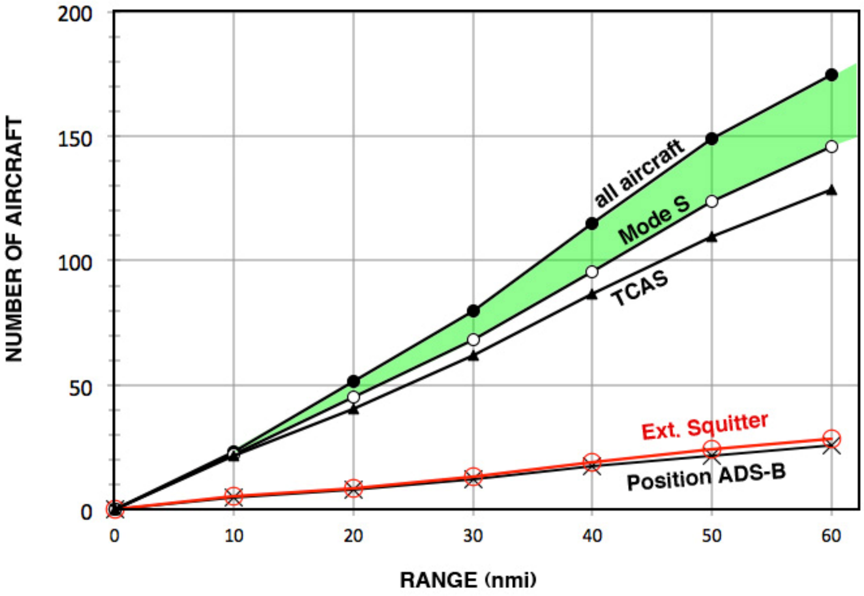

*Figure 12. Range distribution of aircraft.*

## 3.2 OMNIDIRECTIONAL RECEPTION RATES

### 3.2.1 Direct Measurements

The omnidirectional reception rates in the two frequency bands are shown in Figure 13 (1030 MHz) and Figure 14 (1090 MHz). In both cases the receiver threshold is –74 dBm referred to the signal-in-space. This would be the power level received by an ideal 0 dB omnidirectional antenna, whereas the actual antenna has gain of about +7 dB. To make the adjustment from receiver power measurements to the corresponding signal-in-space power, the antenna gain was subtracted (using 7.0 dB in this adjustment), and the ohmic losses were added (using 8.2 dB in this adjustment).

Setting a threshold of –74 dBm means that all stronger receptions are counted and weaker receptions are not. For 1030 MHz receptions, the normal context is that they are received by a transponder on an aircraft. The aircraft antenna gain nominal value is 0 dB, and the nominal value of receiver Minimum Triggering Level (MTL) is –74 dBm referred to the antenna end of the antenna-to-transponder cable. This is the reason for using the value –74 dBm in Figure 13.

For 1090 MHz receptions, normally these are received by a TCAS on an aircraft, for which the nominal MTL is also –74 dBm referred to omnidirectional reception and the antenna end of the antenna-to-TCAS cable. Also, 1090 MHz receptions are relevant for ADS-B reception on an aircraft. For over-ocean environments, an ADS-B receiver can make use of an MTL value more sensitive than –74 dBm, but for ADS-B uses in the most dense environments, such as New York, the ADS-B uses are limited to air-to-air ranges of about the same as TCAS, and therefore a threshold of –74 dBm is appropriate in these conditions.

The 1090 MHz results in Figure 14 are given for Mode S receptions and not for ATCRBS. The reason is that the Thales receiver configuration used for this data collection was optimized for Mode S reception, and as a result ATCRBS reception is degraded. These receiver modifications are described in Section 2 and in more detail in Appendix A. For 1030 MHz receptions, ATCRBS is similarly degraded, although less so because of the overall lower rate of signals in the 1030 MHz band. The ATCRBS rates are included in Figure 13 as an approximation to the actual rates.

Omnidirectional reception rate depends on the receiver threshold. Figure 15 shows the same data as in Figure 14 except for two values of receiver threshold.

Comparing the reception rates in Figure 15 for the two values of receiver threshold, the difference is a factor of about 2.5. In other words, the rates for the more sensitive receiver threshold are higher by factor of about 2.5.

The measurements in Figures 13 through 15 indicate that, with few exceptions, the variation of reception rate during each whole day reached a maximum in the afternoon. The maximum for a particular day can be very different from the maximum on a different day. The overall maximum values for the 25 days of data in Figure 15 are

Max. rate = 1180/second (1090 MHz, Mode S Short, –74 dBm)
= 2379/second (1090 MHz, Mode S Short, –84 dBm)

Rates near these maximum values occurred for only a tiny fractions of all the measured values. The 95 percentile maximum values during daytimes are

Max. (95%) rate = 1002/second (1090 MHz, Mode S Short, –74 dBm)
= 2173/second (1090 MHz, Mode S Short, –84 dBm)

More specifically, the measured rates were less than these values for 95 percent of the measurement points plotted in Figure 15, limiting attention to the daytimes, between 9 AM and 9 PM local time.

In understanding the performance of TCAS in this JFK environment, it is appropriate to consider the conditions that affect TCAS risk ratio. Risk ratio is defined as the probability of a midair collision with TCAS divided by the probability without TCAS. It is extremely rare for an encounter that would be a midair or near midair collision in the absence of TCAS, but it could happen at any time of day or night. Because the likelihood of a TCAS encounter tends to vary as the square of aircraft density, and because Mode S reception rate tends to mirror aircraft density, it follows that the effective value of interference is given by the root-mean-square (RMS) value of all the measured values of interference. Restated, if TCAS performance were to be judged by a single value of interference rate, then an appropriate rate would be the RMS value of the different rates experienced over time. For the entire time period plotted in Figure 15, the TCAS risk ratio is a result of the following RMS value of reception rate.

RMS rate = 619/second (1090 MHz, Mode S Short, –74 dBm)

This value was calculated from all of the 1-hour average rates over the entire 25-day measurement period.

Within each 1-hour period, there was additional variability of reception rate and a higher peak value. Typically the maximum and minimum values were higher and lower than the average by a factor of about 1.17.

The highest recorded Mode S reception rates during this data collection occurred on Thursday, 14 April 2011. Among the measured 1-minute average rates on that day, the maximum values were

Max. rate = 772/second (1030 MHz, Mode S, –74 dBm)
= 1820/second (1030 MHz, Mode S, –84 dBm)
= 1308/second (1090 MHz, Mode S, –74 dBm)
= 2607/second (1090 MHz, Mode S, –84 dBm)

In this data also (1-minute average rates), the maximum rates occurred briefly. Following is a comparison of absolute peak value with the daytime 95 percentile value and the RMS value. These results apply to the 1-minute measurements on 14 April 2011, Mode S Short signals, and –74 dBm received power level.

Max. rate = 1214/second
Max.(95%) rate = 1154/second
RMS rate = 694/second

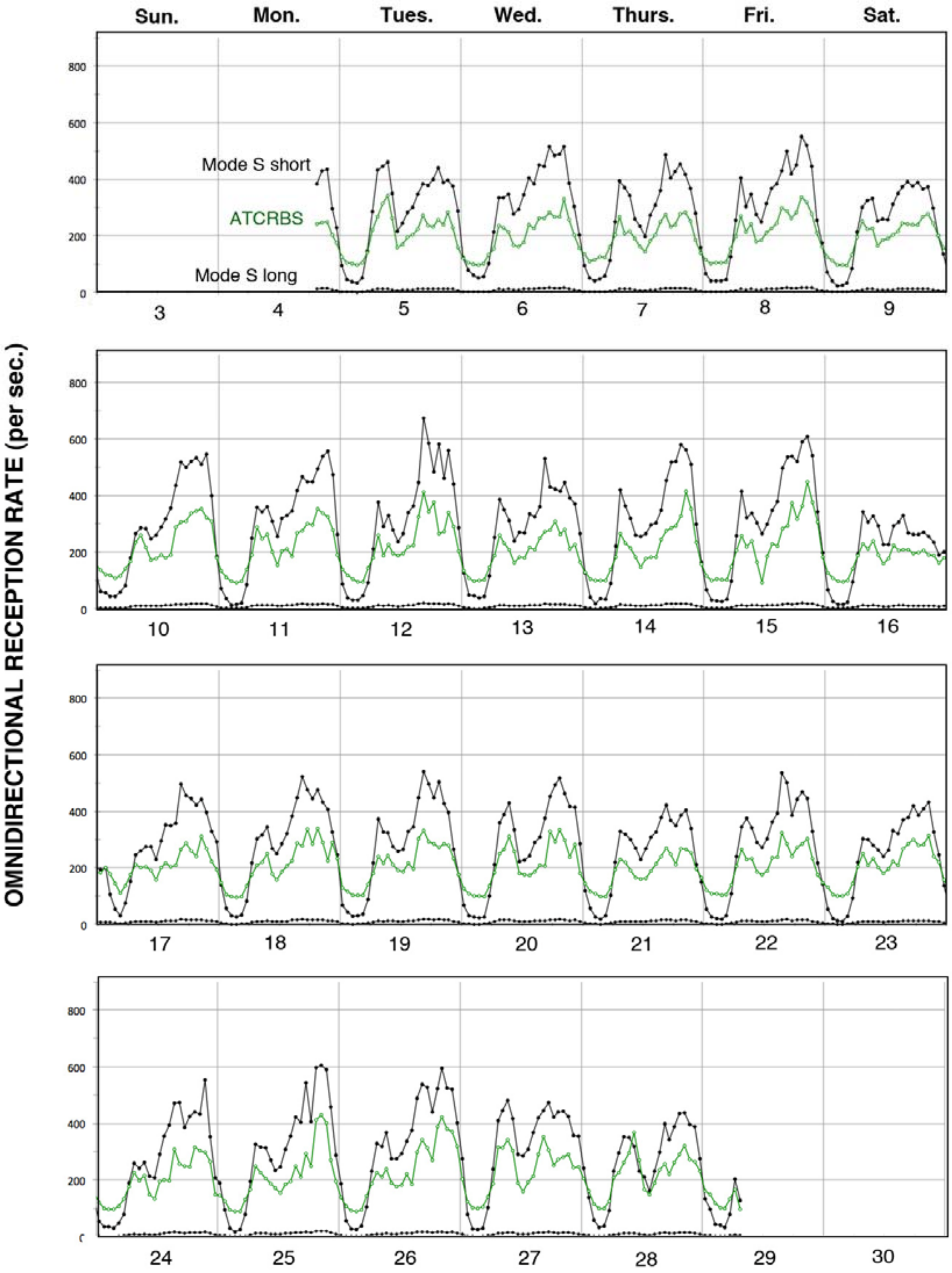

*Figure 13. Omnidirectional reception rate, 1030 MHz. Threshold = –74 dBm referred to signal-in-space. Vertical lines denote midnight local time.*

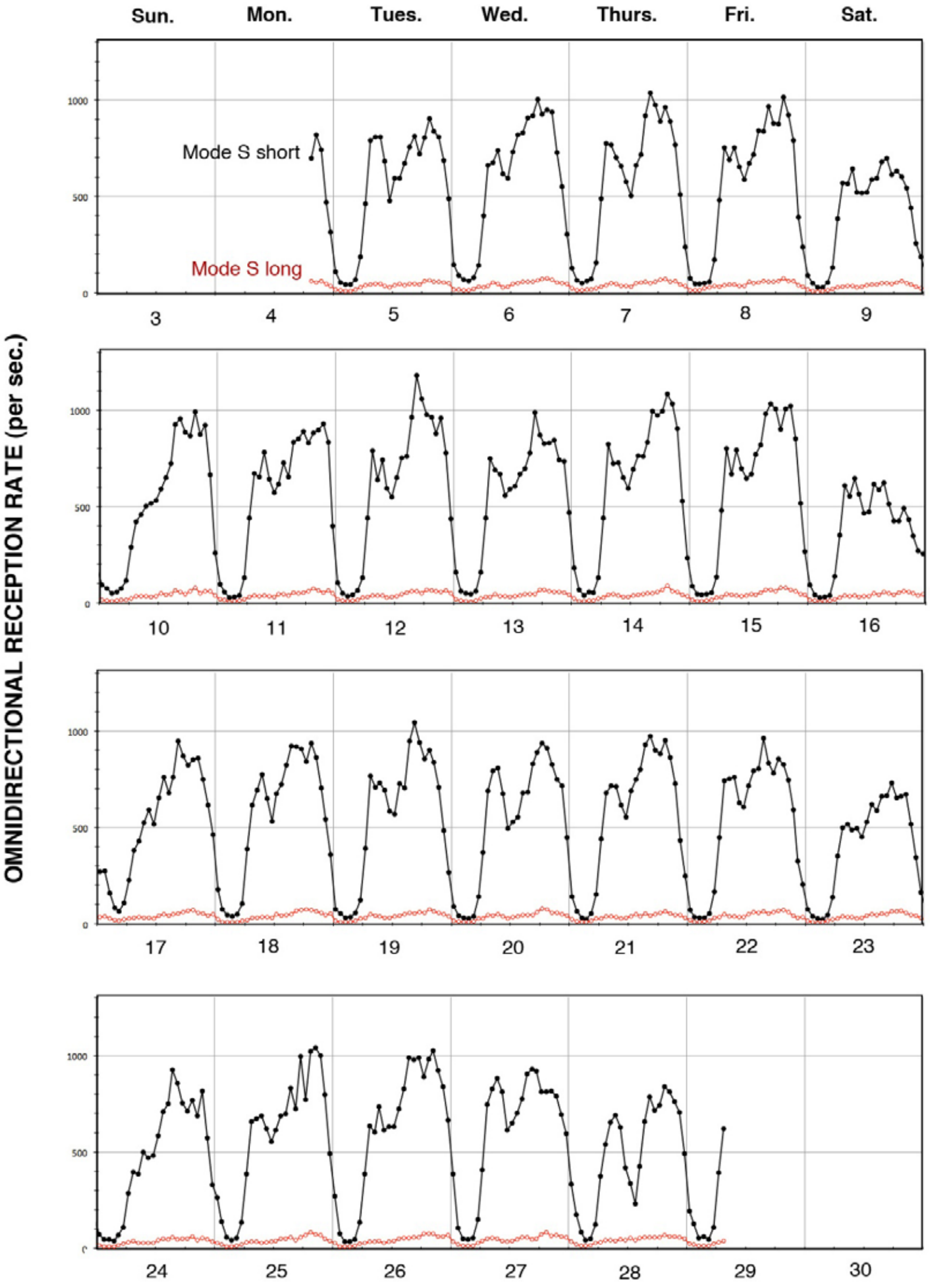

*Figure 14. Omnidirectional reception rate, 1090 MHz. Threshold = –74 dBm referred to signal-in-space. Vertical lines denote midnight local time.*

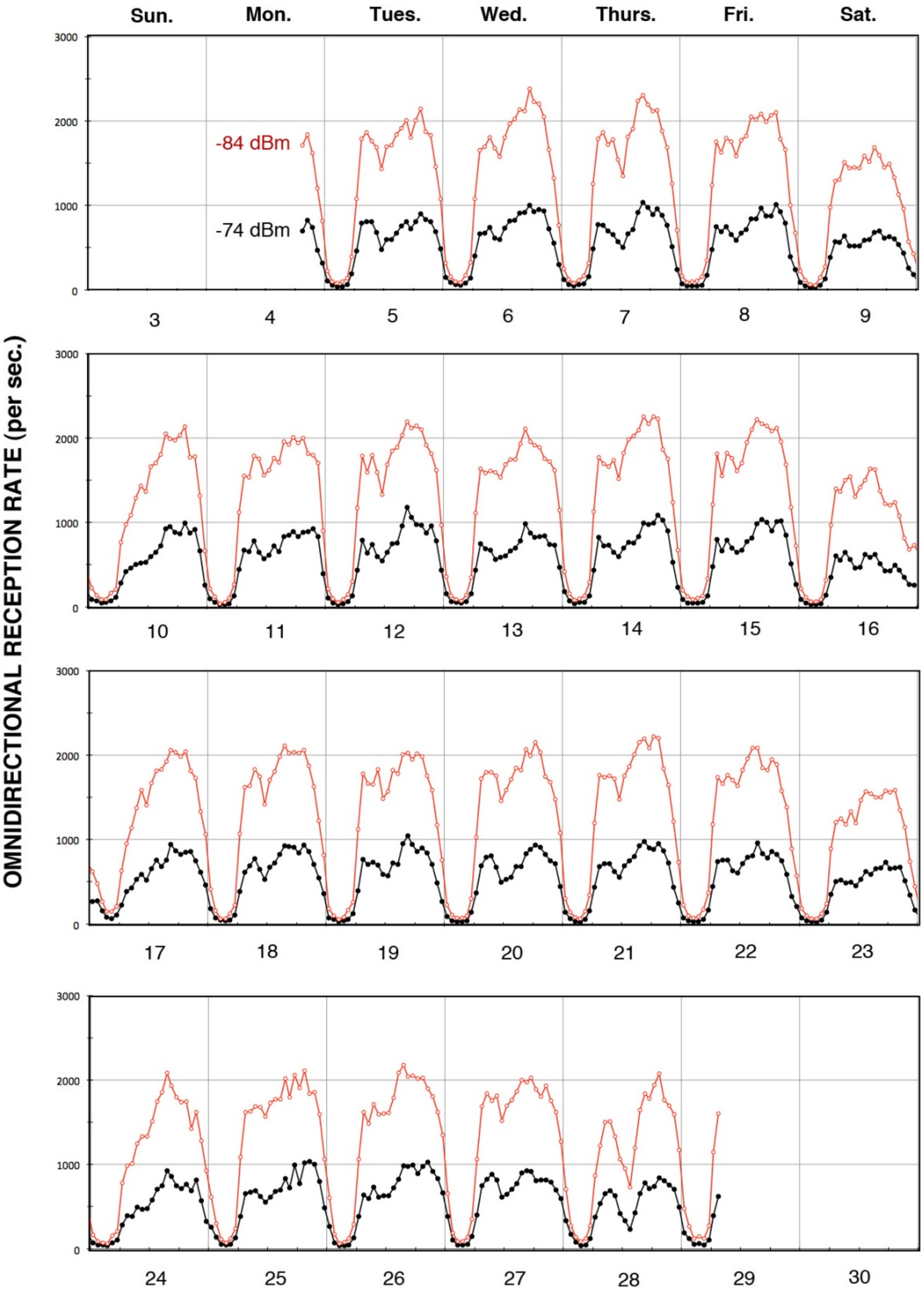

*Figure 15. Omnidirectional short Mode S reception rate, 1090 MHz, both –74 and –84 dBm.*

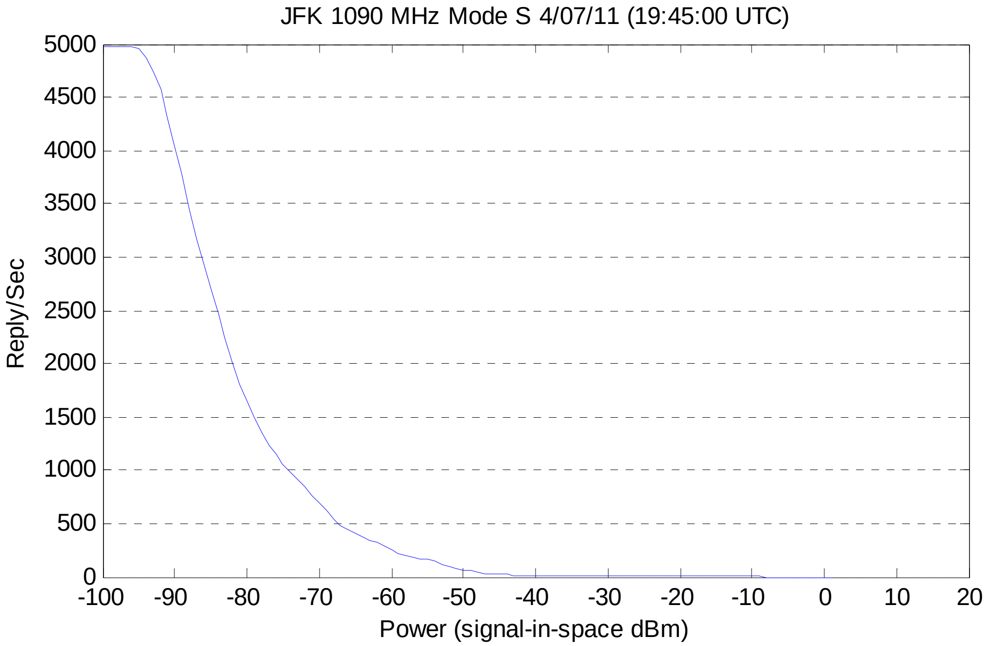

*Figure 16.  Cumulative omnidirectional Mode S reception rate, 1090 MHz.*

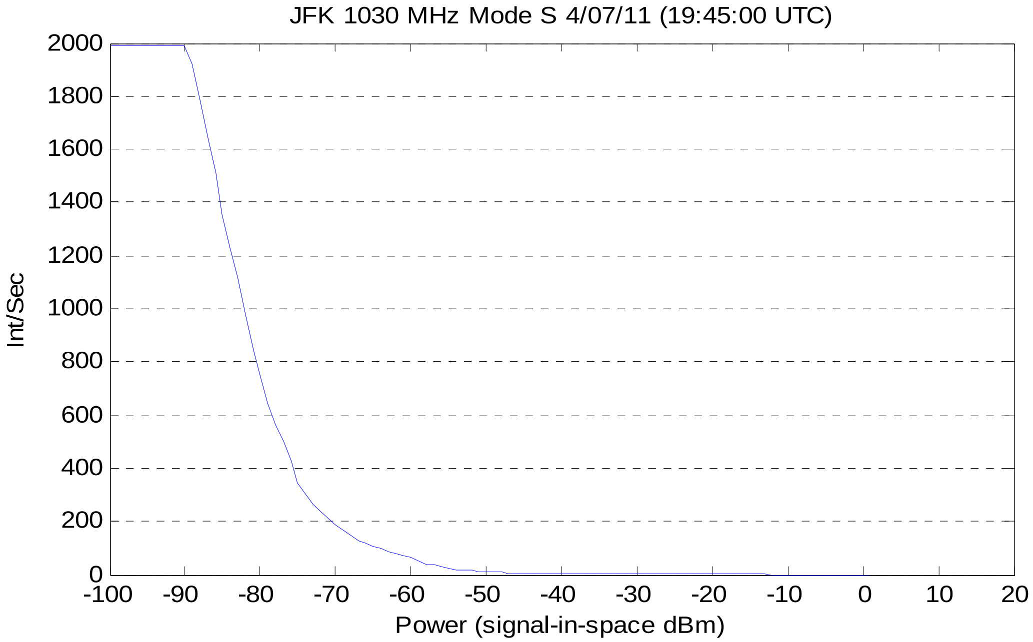

*Figure 17.  Cumulative omnidirectional Mode S reception rate, 1030 MHz.*

Figures 16 and 17 show the 1030 and 1090 MHz Mode S reception rates in a cumulative form. The plots are obtained from 10 seconds of long and short Mode S receptions at 15:45 EDT during the time when airborne measurements were being made. In this form, each point gives the total Mode S reception rate for all power levels equal to or above the abscissa value.

The rates plotted in Figures 14 through 17 include error-free receptions and also receptions that have some bit errors. Figure 18 illustrates the relative number of receptions with and without bit errors. This is a 1-hour period, 15:00 to 16:00 EDT on Thursday, 7 April, during the time when airborne measurements were being made. The portion of receptions having no bit errors is 85% of the total, and the remaining 15% are received with one or more bit errors. Additional signals generally arrive at the antenna but cannot be received at all because of overlap by other signals, as illustrated by dashed lines in the figure. This behavior is true in general although the percentages vary in different cases. The proportions shown in Figure 18 were determined by analysis of DF11 receptions using a receiver threshold of –74 dBm. In the case of DF11 messages, 24 parity bits are included in the message making it possible to determine if the message was received error free. Most of the other DF message formats do not include directly observable parity bits, and for that reason, the messages rates in Figures 14 through 17 were counted without applying error detection, although detailed examination during Lincoln Laboratory analyses have led to a conclusion that the receptions counted are, in fact, essentially all Mode S messages.

It should be noted that this analysis does not include messages which are not detected by the reciever. Additionally, as the sampling and hardware implementation of the reciever differs from that of a transponder, it cannot be assumed that a message received correctly in this analysis would be received correctly by a standard transponder or TCAS.

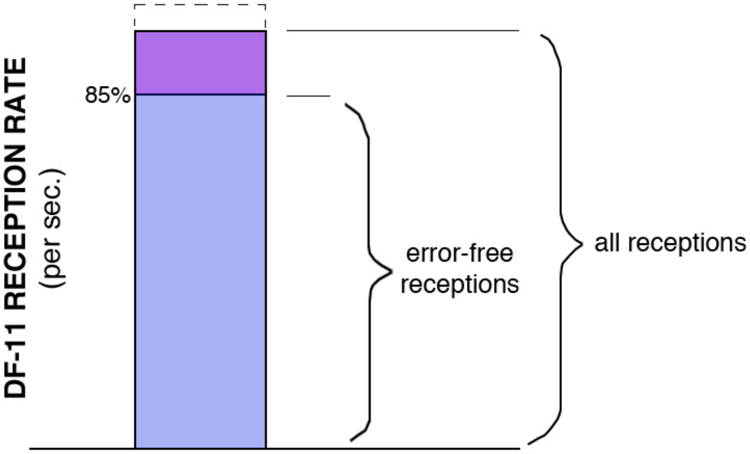

*Figure 18. Percentage of receptions having bit errors.*

The presence of messages with parity errors can be used to indirectly infer the extent of message interference occuring in the enviorment. As the number of Mode S messages transmitted increases, it is increasingly likely for two messages to overlap when received, causing a parity error. At lower powers, more messages are received (since messages received originate from a larger area) which increases the likelihood of overlap at lower power. Additionally, long Mode S messages have a higher probability of overlap since the message duration provides a longer oppurtunity for overlap. Figure 19 shows the percentage of long (DF17) and short (DF11) 1090 MHz Mode S messages received with correct parity for MTLs of –74 and –84 dB for each hour of a complete week. The total reception rate at –84 dB is also included to provide an indication of the overall spectrum usage durring the week.

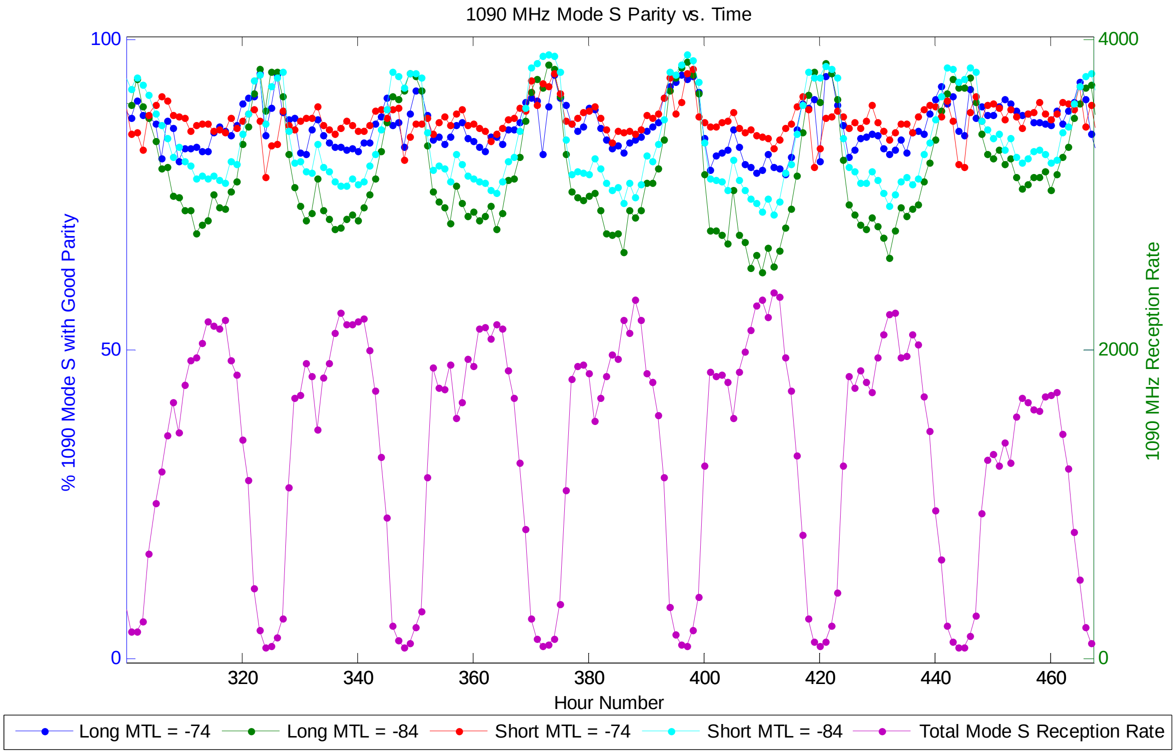

*Figure 19. 1090 MHz reception rate and percent of messages received with correct parity.*

As expected, a clear mirror pattern is observed in these plots; as the total reception rate increases, a higher percentage of messages are received with a parity error. It is also clear that a higher percentage of error-free short messages are received than long messages. Additionally, the percent of error-free messages is reduced at –84 dB compared to –74 dB. This makes sense as it is less likely for the overlap of a high power message with a low power message to cause an error in the high power message.

Figure 20 shows the correct parity percentage for each hour plotted against the total Mode S reception rate durring that hour. This plot includes data points from the entire 25 days of recording at JFK. The results are remarkably consistent. The portion of 1090 MHz Mode S messages received with correct parity comprises about 95% of messages during recording times with low reception rates. This percent of messages with correct parity falls off linearly as the number of transmissions observed in the environment increases. As expected, percentage of error-free long messages falls off more quickly than short messages, and messages with a lower MTL power fall off more quickly than high MTL power messages. During times with the highest level of omnidirectional Mode S receptions, almost 85% of short Mode S messages are received with an MTL of –74 dB without error on 1090 MHz. 65% of 1090 MHz long Mode S messages with an MTL of –84 dB are received without error.

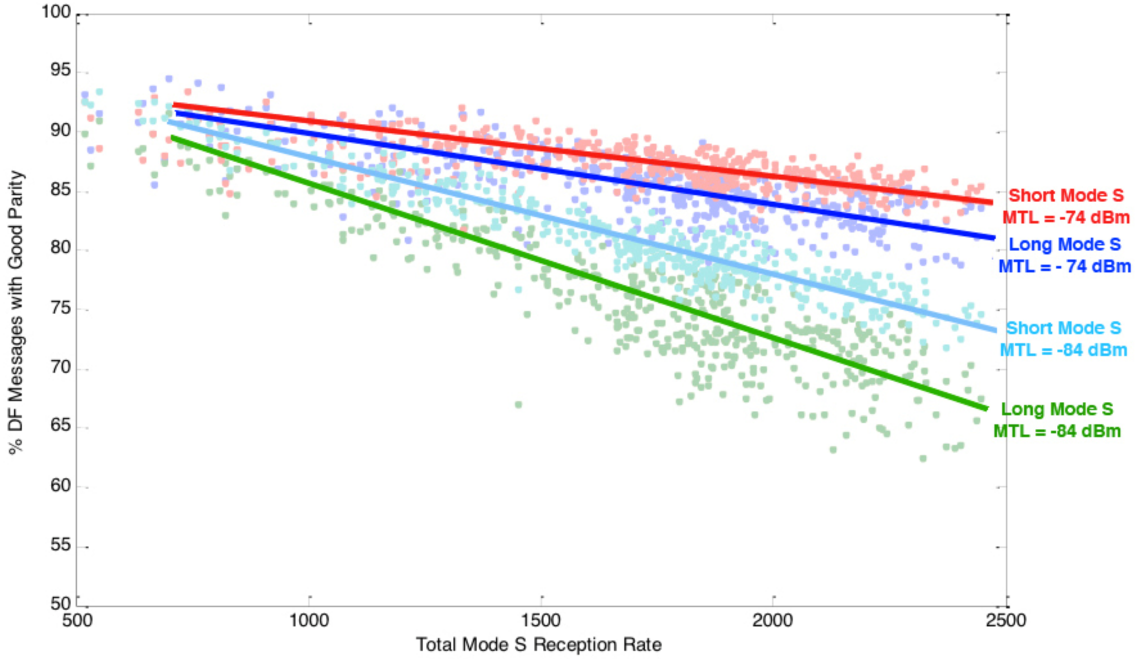

*Figure 20. Percent of 1090 MHz receptions with correct parity versus 1090 MHz reception rate.*

A similar analysis can be performed for Mode S interrogations on 1030 MHz. In general, interrogations on 1030 MHz are less common than replies on 1090 MHz. However, it remains important to understand the performance of the channel since the encoding differs (DPSK versus PPM), the messages are shorter, error correction is not used, and air traffic control operations rely on SSR based interrogations.

To carry out the corresponding analysis for 1030 MHz, it is necessary to apply error detection using the 24-bit parity-check code. That cannot be done directly for the short-format messages because the 24 parity bits are overlaid with the unique address of the aircraft for which the message was intended. The majority of long messages on 1030 MHz are TCAS Broadcast messages (UF16 UDS-32), which are used for TCAS interference limiting algorithms. Broadcast messages use 'FFFFFF' (also known as the 'broadcast address') as the intended recipient address and can be received by any aircraft. This is equivalent to having the parity bits available in the received message. Therefore, a parity check can be done for the long-format TCAS Broadcast messages (Uf16 USD-32).

To perform this analysis for 1030 MHz short-format messages, an address-list technique was used. A list of valid Mode S addresses for each hour was created using 1090 MHz DF11 messages received with correct parity. Mode S addresses tracked by ground based radars are also included in the list when a sufficient number of their replies to ground surveillance have been observed. If the address decoded from short 1030 MHz interrogations appears on the valid address list, the message is considered to have passed the parity check.

The results of this analysis are shown in Figure 21, which is a plot of the percentage of 1030 MHz receptions with correct parity versus the total 1030 reception rate for every hour of the collection at JFK.

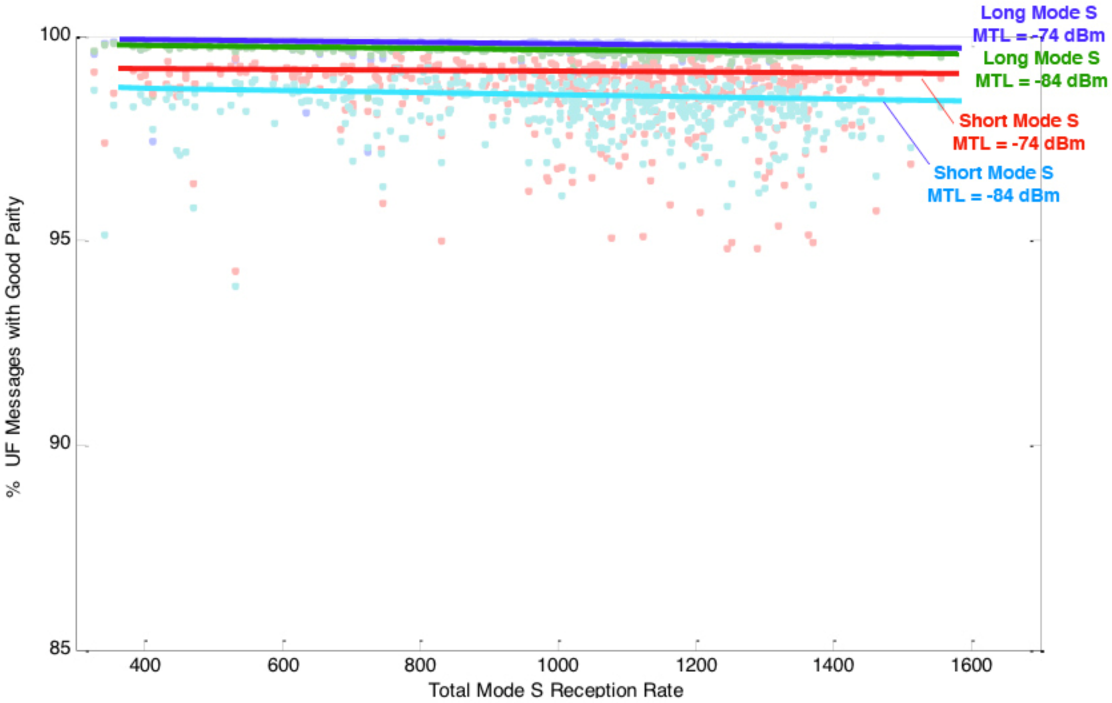

*Figure 21. Percent of 1030 MHz receptions with correct parity versus total 1030 MHz reception rate.*

Overall, the probability of received messages having correct parity is significantly higher on 1030 MHz. The majority of 1030 Mode S messages are received with correct parity even during recording times with high reception rates. The percent of messages with correct parity is relativly consistent and gently falls off linearly as the number of transmissions observed in the environment increases. Messages received with an MTL of –84 have a slightly higher percentage of parity errors. In this analysis, it appears that long messages have a lower percentage of parity errors than short messages.

This discrepency, however, is explained by the generation of the list of valid Mode S addresses. Furthur investigation has shown that many of the short Mode S interrogations marked as having ‘incorrect parity’ appear to be valid Mode S addresses of distant aircraft located below the line of sight of the reciever. In otherwords, the interrogations orginate from airborne aircraft that are interrogating low altitude aircraft. While the replies from the targets are not visable, preventing the address from being included as ‘valid’, the airborne interrogations are received. Therefore, it is reasonable to to say the the percentage of short interrogations on 1030 MHz with correct parity is similar to or higher than that of long interrogations on 1030 MHz. Durring times with the highest level of omnidirectional Mode S receptions, almost 99% of long Mode S messages are received with an MTL of –84 dB without error on 1030 MHz. Short messages on 1030 MHz are also believed to have been received with at least 99% correct parity.

### 3.2.2 Reception Rate Compared with Aircraft Density

It is interesting to compare the 1090 MHz reception rates in Figure 14 with the number of aircraft in Figure 11. One might expect that the day-to-day variations would be very similar simply because the 1090 MHz signals were all transmitted by aircraft. A larger number of aircraft would be expected to cause a proportionally larger 1090 MHz reception rate. Indeed the results agree with that expectation in many ways. The day-night pattern appears clearly in both figures. Looking in more detail, it is seen that Saturday, 16 April, had significantly fewer aircraft than the other days of that week, and the corresponding 1090 MHz reception rates have the same pattern. That was also true on the following week.

On the other hand, there are some notable exceptions to the proportional behavior of 1090 MHz receptions with number of aircraft. On Saturday, 9 April, the 1090 MHz reception rate was significantly lower that the preceding weekdays, but that was not true for the number of aircraft. For some reason, Saturday, 9 April, was different from the two Saturdays that followed.

This behavior can be examined in more detail by dividing the reception rate by the number of aircraft to estimate the per-aircraft transmission rate. For the reception rates in Figure 14, the receiver threshold was –74 dBm, which corresponds to an air-to-air range of about 30 NM [3]. Of the aircraft counts plotted in Figure 11, the counts within 30 NM would be appropriate for being associated with the –74 dBm reception rates. The results are shown in Figure 22. Each point is the short Mode S reception rate from Figure 14 divided by the number of Mode S aircraft from Figure 11. These values approximate the per-aircraft rate for short Mode S transmissions.

The per-aircraft results in Figure 22 help to explain where there are some differences in pattern between the omnidirectional 1090 MHz reception rates and the number of aircraft. Looking at the week of Saturday, 23 April, we see that the per-aircraft rate on Saturday was essentially the same as it was on the preceding weekdays. Therefore, because the number of aircraft was much smaller on Saturday, it follows that the 1090 MHz reception rate would be lower that day—which indeed happened. The behavior during the preceding week followed the same patterns, but there was a difference on the Saturday before that, 9 April. On that Saturday, the per-aircraft rate (Figure 22) dropped lower than the weekday rates. The number of aircraft remained high, unlike the two Saturdays that followed, and the per-aircraft rate dropped, unlike the two Saturdays that followed. The result was an exception to the proportionality that generally appears for 1090 MHz reception rate and number of aircraft.

Of course weather is another major variable. Weather conditions that affect air traffic are summarized in Figure 23 for the three weekend periods. Each row shows the 3-day period, Friday–Saturday–Sunday. Plotted vertically is visibility at the JFK airport. The default value for excellent visibility is 10 NM, and the data in Figure 23 show that the weather was excellent during many of the days, but there were several periods of poor visibility. The weather map for the full United States is shown in Figure 24 for Saturday, 16 April, late in the day. This is the time when visibility dropped suddenly. The weather map shows a major storm located at New York at that time. The poor weather on Saturday the 16th and Saturday the 23rd seems likely to be the reason for the significant drop in aircraft counts on those days. By comparison, Saturday the 9th had very good weather in the afternoon. The good weather on a Saturday afternoon might have resulted in a higher number of aircraft equipped with Mode S but not TCAS. This seems to be a likely explanation for the fact that Saturday the 9th was different from the other two Saturdays.

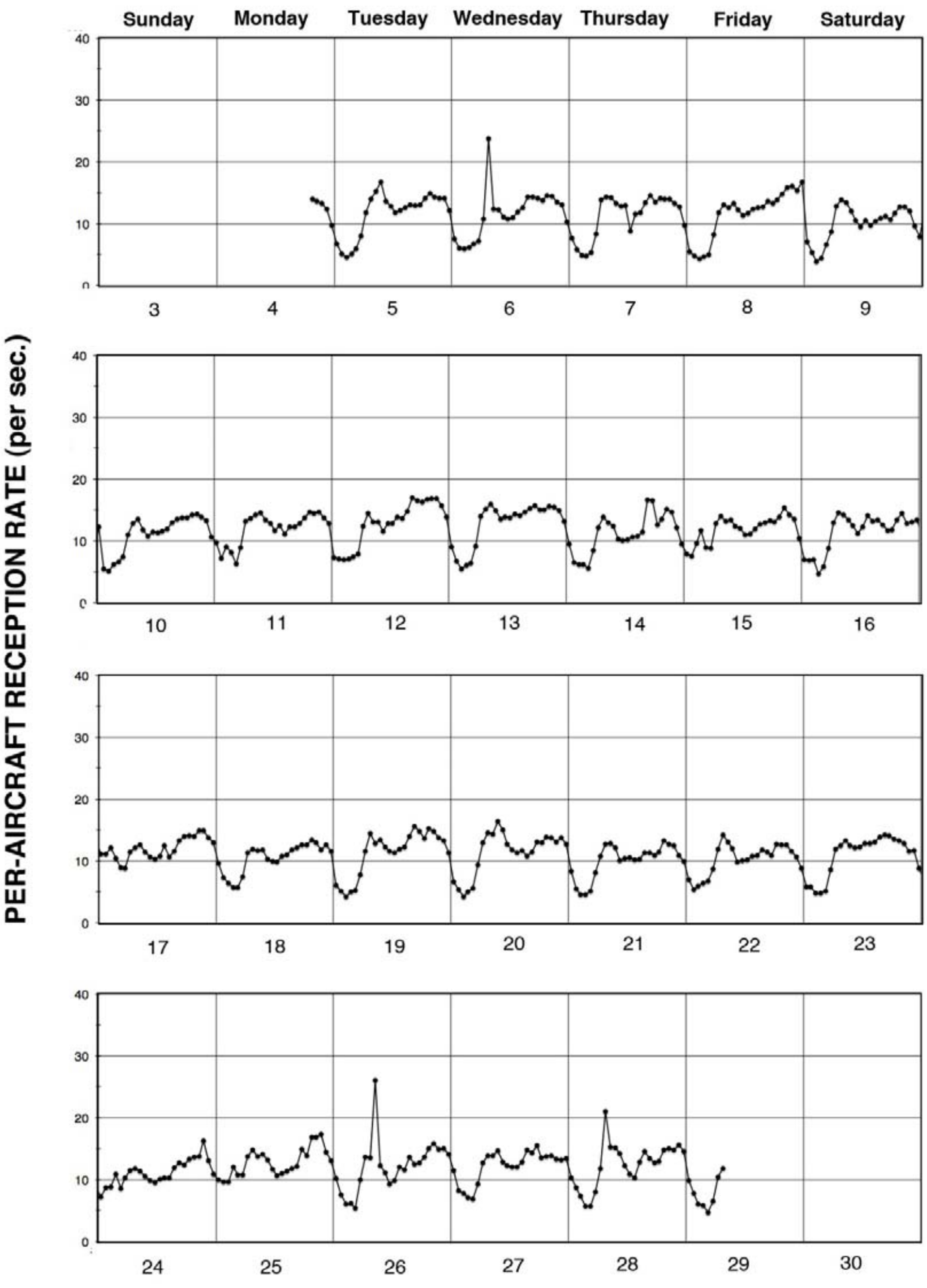

*Figure 22. Per-aircraft transmission rate. This applies to short Mode S transmission at 1090 MHz.*

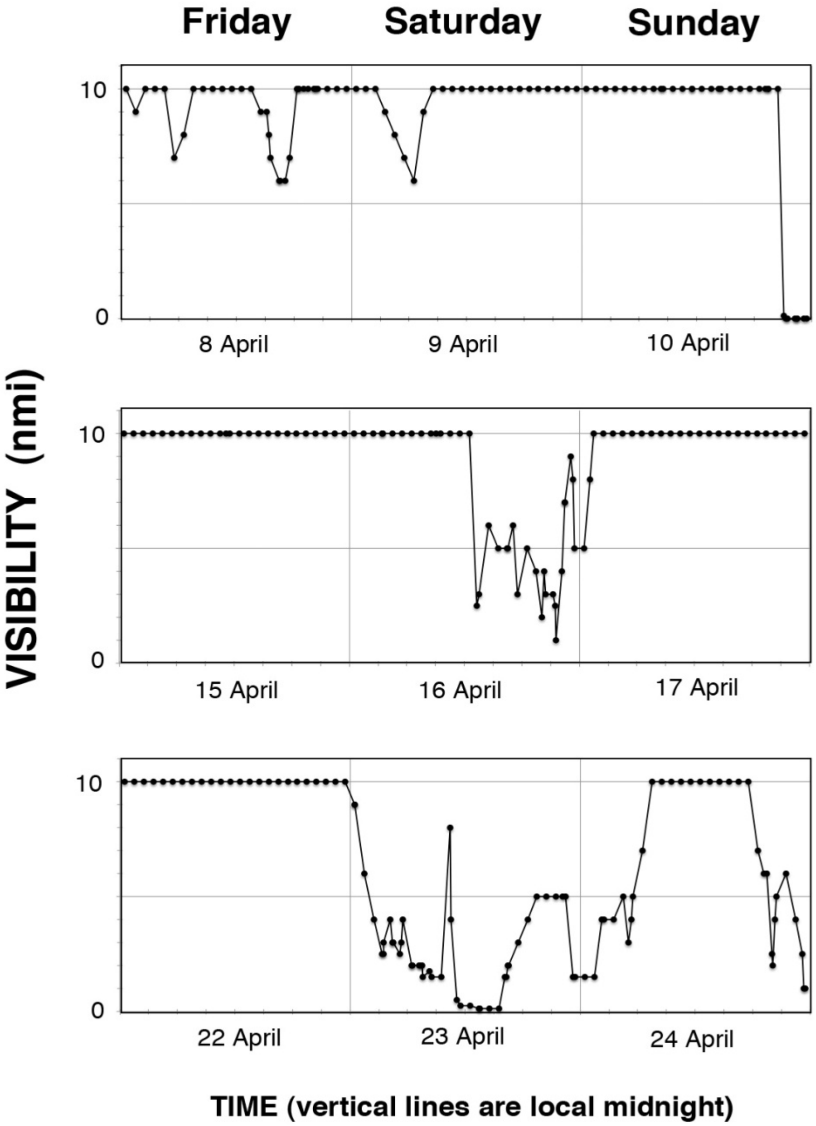

*Figure 23. Aviation visibility during three weekends.*

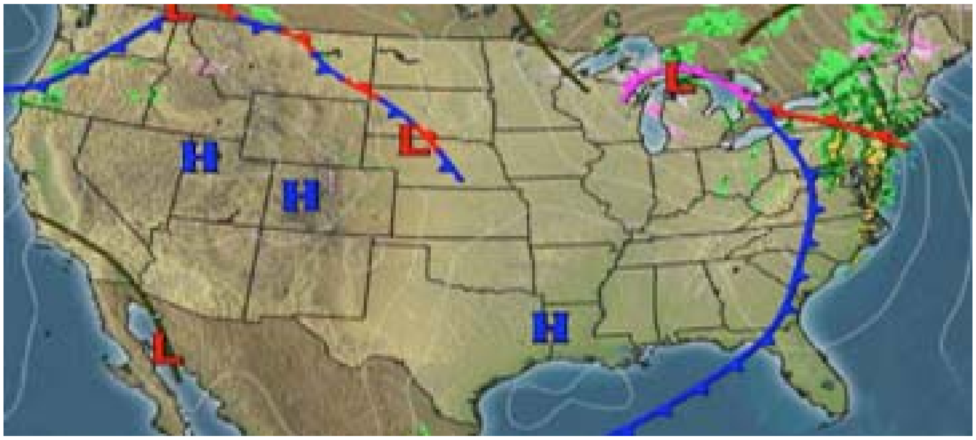

*Figure 24. Weather conditions on Saturday, 16 April 2011.*

The absolute values of the per-aircraft rates in Figure 22 are also of interest. The average daytime rate is about 14 short Mode S signals per second, with nearly all the samples being between 10 and 17 per second. These New York measurements can be compared with the TCAS simulation being used by Lincoln Laboratory. This simulation is based on actual aircraft tracks measured by the radar at JFK, and simulates all TCAS surveillance transmissions. When the simulation is run for a busy time period in the New York area, the per aircraft transmission rate of short Mode S replies is 13 per second. The agreement is good between the measurements reported in this document and the TCAS simulation.

Occupancy. In the 1090 MHz band, the measured Mode S reception rate with a threshold of –74 dBm was about 800/sec on average in most days. The max value was 1200/sec, which occurred briefly on one day. The timeline occupancy during that peak was

(1200/sec) * (64 microsec) = 0.077 (short Mode S)

Long Mode S receptions add about 0.005 more making the total about 8 percent. Making that calculation for the full week when the peak occurred, the results are shown in Figure 25. This is the fraction of the time line that is occupied by the short Mode S and long Mode S receptions, as received by an omnidirectional antenna of 0 dB gain.

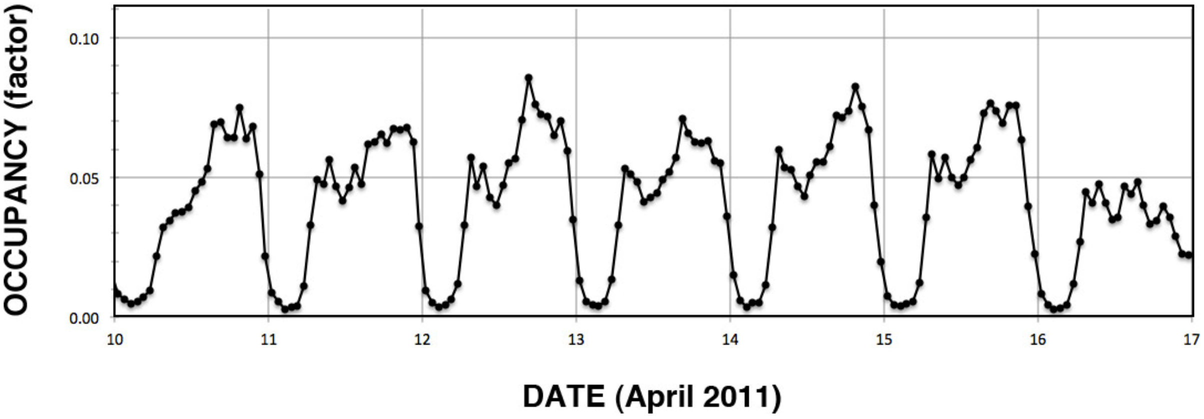

*Figure 25. Time occupancy of short and long Mode S receptions.*

Therefore, about 7 percent of the timeline is occupied by short Mode S receptions. ATCRBS receptions will also add to the total occupancy. Note that when receiving a Mode S signal, a single ATCRBS overlap can usually be tolerated, and also an ATCRBS signal is not as dense as Mode S, so the interference effect from an ATCRBS reception is less.

### 3.2.3 Obstruction Analysis

As described in Section 2, the 1030/1090 MHz receiver was located on the control tower of JFK airport for this data collection. The antenna was placed in the antenna farm on the northwest side of the tower. The tower itself created a 116° blockage in azimuth of omnidirectional receptions from the southwest. While high power receptions received from aircraft close to JFK were still received at lower powers, most transmissions from aircraft in the blockage were not received. An aircraft flying above JFK airport, however, would still see these messages, and therefore these transmissions are still of interest and should be accounted for. Blockages are an expected challenge of ground based monitoring, and in this section we discuss a method to account for known blockages using an additional source of data. In this case radar data is used to account for an azimuthally blocked antenna; a similar approach could be used to account for other types of blockages.

To compensate for the reduction in measured reception rate due to the blockage, we would like to develop a factor that can be multiplied by the measured rate to provide estimates of what the omnidirectional reception rates would be if we had a perfect omnidirectional site. The visible obstruction is 116°. Therefore, the simplest calculation is that our reception rate is diminished by the factor

$$\text{factor} = (360\text{–}116) / 360 = 0.678.$$

Therefore, full omni reception rate would be higher by the reciprocal, which = 1.48. But we see that there are fewer aircraft to the southeast, so the adjustment is not as large. By considering where most aircraft are located in the airspace, we can make a better estimate of the factor by which our measurement rates are diminished. The Mode S radar co-located at JFK has a view of the airspace out to 60 NM with few blockages. Using TCAS RA Monitoring System (TRAMS) data extracted from the JFK radar, a ratio is calculated of Mode S aircraft traffic (based on radar reports) within the unblocked azimuths[1] to all aircraft traffic tracked by the radar.

*Ratio A= Radar reports from unblocked azimuths / all radar reports*

This ratio makes two assumptions that should be noted. The first assumption is that the aircraft traffic distribution outside of radar coverage is similar to the traffic within radar coverage. This assumption is not necessarily true, and therefore the factor calculated is most valid when applied to measured data within radar coverage. The second assumption is that there is a complete blockage of receptions within the blocked azimuths, and no blockage outside those azimuths. The receiver successfully decoded messages sent at high power from close to JFK, despite being behind the blockage. In addition, at the edge of the blocked azimuths, the reception probability is degraded rather than blocked completed.

A second factor is introduced to adjust for receptions that are received from within the blocked azimuths or degraded despite being outside the blocked azimuths. The factor is calculated using ADS-B airborne position squitters to find the ratio of position squitters received from within the unblocked azimuths to all position squitters received.

*Ratio B= Position Squitters from unblocked azimuths / all Position Squitters*

This ratio makes an assumption that the azimuthal distribution of all Mode S receptions is similar to that of ADS-B receptions.

Finally, a blockage factor is formed using the two ratios A and B:

*Factor = B/A*

This factor was calculated for each hour of data collected at JFK. During peak times in the morning and late afternoon, the factor falls between 1.05 and 1.3. Over the 25 days data was collected, the average factor was about 1.11 in the morning, and 1.10 in the evening.

It is important to note that this factor is lower than the factor found using a simple calculation. Additionally, the ratio A is the dominant term in the factor calculation. In general, the characteristics of

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[1] The blocked azimuths are estimated using omnidirectional receptions.

the calculated factor are highly dependent on the direction of the blockage (traffic density in blockage) and the characteristics of the airspace.

Figure 26 shows the total 1090 Mode S reception rate over the first six days of recording with and without the blockage factor applied. The blockage factor is calculated for each hour of omnidirectional data. Factors are calculated and applied to the reception rates using MTLs of –74 dB and –84 dB.

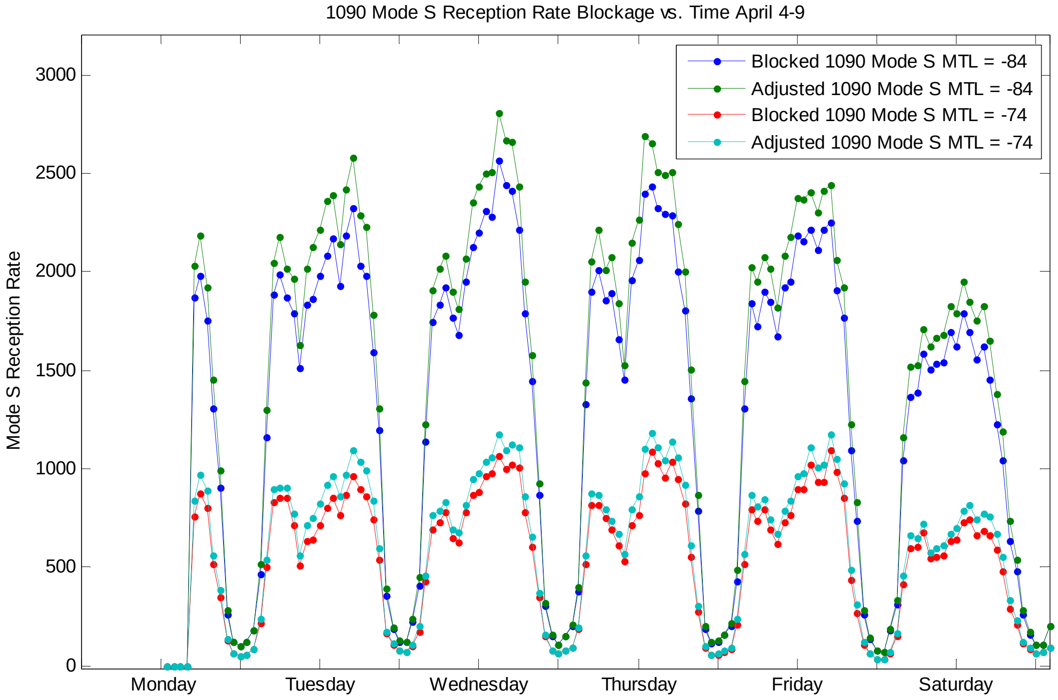

*Figure 26. 1090 MHz Mode S reception rate blockage versus time, 4–9 April 2011.*

### 3.2.4 Reception Probability Analysis

Received ADS-B Position messages can be used to measure the reception probability, because the transmission rate is known to be 2 per second by each aircraft. Furthermore, received Position squitters have 24 parity bits which can be used to determine whether the messages were received with no bit errors. Figure 27 shows the results of an analysis of received error-free Position squitters.

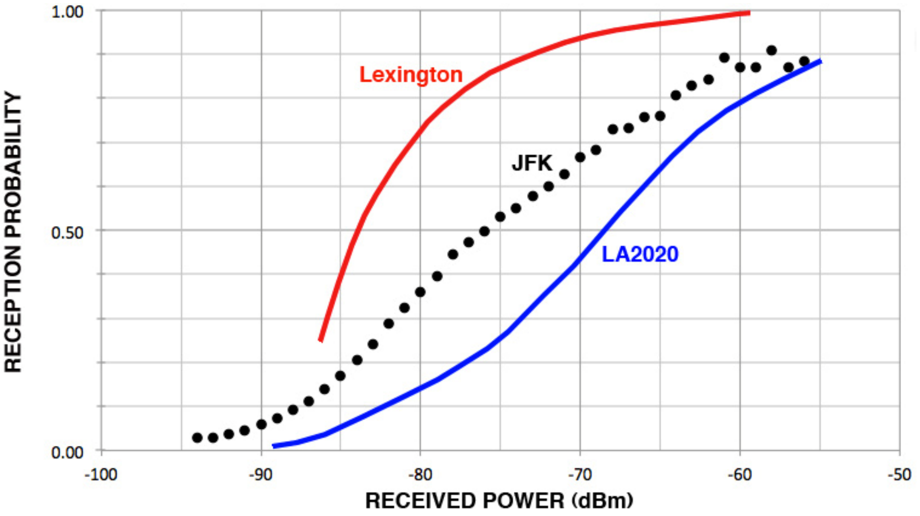

*Figure 27. Error-free reception probability of position squitters as a function of received power level. JFK reception used enhanced techniques but not error correction.*

Of the three curves in this plot, the middle curve was derived from the data recorded in New York. The other two curves, described below, are from existing publications.

In this analysis, Position squitter receptions were sorted by address and divided into 20-second periods. Each result is one data point, consisting of the average power over 20 seconds and the fraction received correctly, which was calculated as the number of Position squitter receptions divided by 40. All such points over a one-hour period (15:00 to 16:00 EDT on Thursday, 7 April) were sorted into 1-dB bins of power and then averaged in each bin, resulting in the probability values plotted in Figure 27.

Some consideration was also given to the 2-level variation in received power sometimes seen, which can be attributed to the top and bottom antennas on the transmitting aircraft. Banking of an aircraft can cause one of the two antennas to be shielded, resulting in weaker received power. To minimize that effect, a power-variation test was also used, and receptions during each 20-second period were ignored if the variation was large.

The upper curve in Figure 27 is a measurement from Lexington [Ref. 2, page 13]. The lower curve marked LA2020 is a calculated curve documented in the ADS-B MOPS, DO-260B [Ref. 7, page P-25]. This LA2020 curve applies to a hypothetical environment predicting the future in the Los Angeles Basin in the year 2020.

In addition to differences in location and date, the reception conditions are not identical for these three curves. The JFK curve applies to receptions that are error free without error correction, whereas the Lexington and LA2020 curves apply to error free receptions after error correction has been applied. Another difference is that the Thales receiver uses decoding hardware features beyond what was assumed to obtain the LA202 curve.

Viewed in relation to the other two curves, the JFK curve appears reasonable. Relative to Lexington, JFK has poorer performance, which could be attributed to the higher density of aircraft and signals. LA2020 has still poorer performance, which could be attributed to the higher density of aircraft and signals in that hypothetical environment. If error correction were added to the JFK performance, the JFK curve would be higher.

In analyzing the JFK data, it was also possible to calculate the fraction of DF11 and the fraction of DF17 receptions that were error-free. That is possible because 24 parity bits are available to check in DF11 and DF17 receptions. The results are shown in Figure 28, in the upper plot.

The reciprocal of the fraction that were received error-free can be considered to be the factor by which the rate of all receptions exceeds the rate of error-free receptions. Putting that result together with the JFK curve from Figure 27, the result is the reception probability as a function of received power level, including all receptions, with and without bit errors. The two forms of reception probability are shown together in Figure 28 in the lower plot.

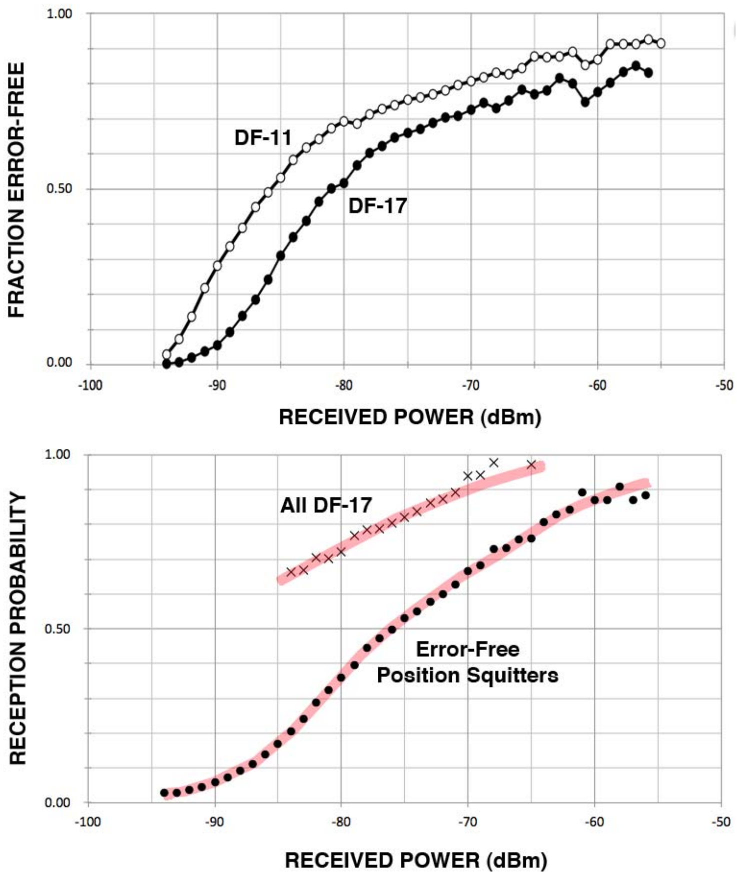

*Figure 28. Reception probability with and without bit errors. Using enhanced reception techniques but not error correction.*

### 3.2.5 Relative Rates of Different Downlink Formats

Every Mode S reception in the 1090 MHz band begins with a 5-bit DF value, which indicates the format of the message that follows. The most common values include:

DF = 0, reply to TCAS

DF = 4 or 5, reply to a ground based Mode S radar

DF = 11, short squitter (spontaneous transmission announcing the Mode S address)

DF = 11, also used for All Call reply to a ground based Mode S radar

DF = 17, ADS-B (spontaneous transmission of position and other ADS-B information)

The two kinds of DF11 messages are normally distinguished by the II code in the message. Short Squitters have II = 0, and replies to radars have non-zero values of II (with some exceptions).

The omnidirectional receptions at JFK have been analyzed to determine the relative rates at which different DF values were received. The results from Thursday, 7 April 2011, 15:00 to 16:00 local time, during the flight test period, are plotted in Figure 29. The upper two plots show the results from JFK, and similar results in the lower plot were obtained from measurements in Lexington, MA [Ref. 2, Figure 23]. For the results in the upper plot, the receiver threshold was –74 dBm, referred to the signal-in-space (as defined in Section 3.2.1). For the middle plot, the threshold was –84 dBm. For the lower plot (Lexington), the values apply to all receptions, including some weaker than –84 dBm.

DF11 messages include parity bits so that a receiver can make a parity check to determine if there was any bit error in the reception. For DF0, DF4, and many of the other formats, parity bits are not readily observable, and parity checking cannot be done for those receptions without an extensive analysis process. For that reason, the rates shown in Figure 29 include receptions without parity checking, just reading the DF value in the received message. Detailed examinations by Lincoln Laboratory analysts have led to a conclusion that the rates shown here are good estimates of the actual reception rates including messages that may contain one or more bit errors. It can be expected, however, that additional messages were arriving at the antenna that were not received at all because of overlap by other signals, and therefore that the total rates are somewhat higher than the rates plotted in Figure 29.

Figure 29 indicates that the subset of DF11 receptions having II = 0 is 61% for the higher threshold and 34% for the lower threshold. These percentages were calculated using only error-free receptions, although they are marked here as the same percentage of all DF11 receptions.

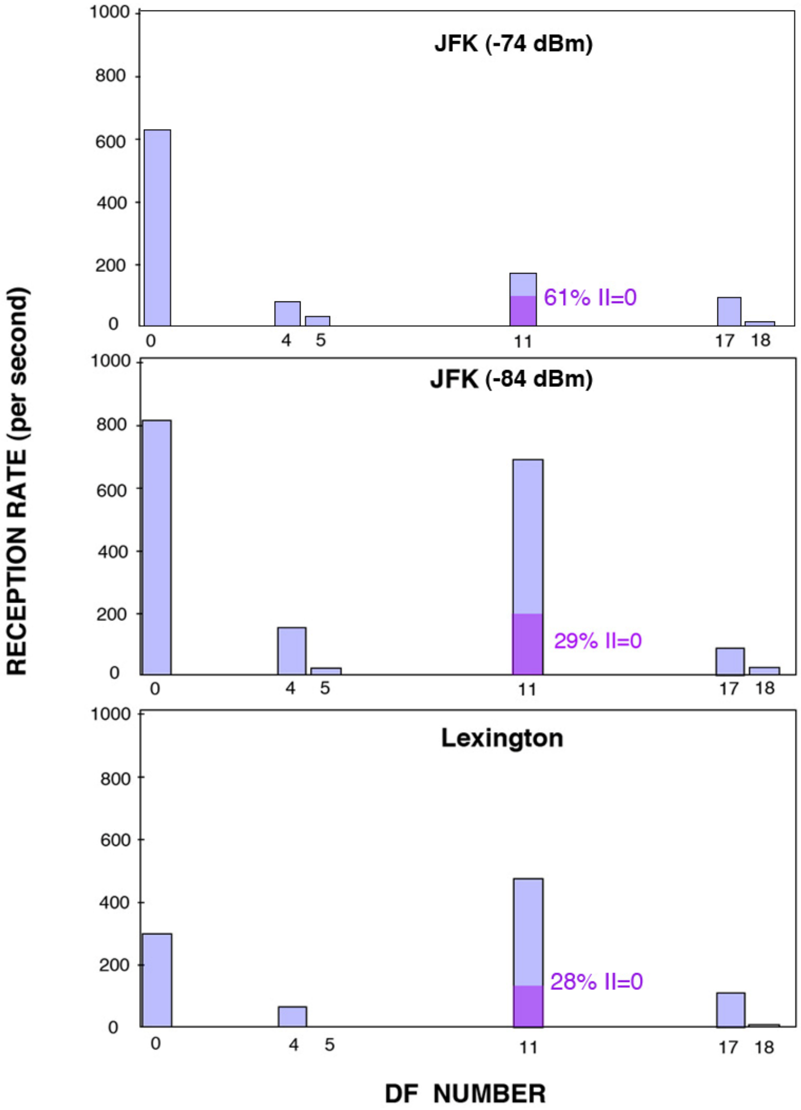

*Figure 29. Relative rates of different DF values.*

The three bar charts in Figure 29 have much in common. The DF0, DF4, DF11, and DF17 values stand out clearly in both the New York and Lexington environments. The two most common messages are DF0 (TCAS) and DF11 (short squitters and All Call replies). Among DF11 messages, the percentage that were short squitters was 61 percent in the immediate New York environment, 34 percent in the larger environment received using the very low threshold –84 dBm, and 28 percent in the Boston environment. In both locations, replies to TCAS significantly exceed DF4 and DF5 replies to radars. In the New York environment, replies to TCAS (DF0) constitute 60 percent of all Mode S reply types. It seems reasonable that TCAS replies are the most common kind in New York, because of the higher density of TCAS equipped aircraft generally expected in the New York area.

The conditions for determining the New York rates and the Lexington rates in Figure 29 were substantially different, and for that reason it would be best to avoid drawing conclusions from a comparison of absolute rates. The major difference is that the Thales receiver was modified and improved in the time between these measurements, as described in Section 2 above and in Appendix A.

The rate of DF11 with non-zero II can be compared against DF4 and DF5 rates. The DF11, non-zero II replies are used for initial detection of an aircraft, whereas DF4 and DF5 replies are used for the ongoing surveillance after the initial detection. It might be expected, therefore, that the rate of acquisition replies would be only a small fraction of the ongoing surveillance reply rate, but that is seen to be not true in the results in Figure 29.

The reason for the relatively high rate of DF11 with non-zero II code can perhaps be understood by considering the All Call process of Mode S radars. As each aircraft address is acquired by a radar, the radar locks out that aircraft from replying to further All Call interrogations. The lockout is, however, limited in range to the surveillance range of the radar, usually 60 NM. While the lockout is limited by range, All Call interrogations are detectable by aircraft at far greater ranges. It is the unwanted replies to those long-range All Call interrogations that can cause the All Call reply rate to be relatively high.

Figure 30 illustrates this mechanism by showing the locations and flight paths of aircraft transmitting All Call replies having a particular non-zero II code (II = 4 in this example). The points in the figure were generated from omnidirectional receptions in Lexington, MA. ADS-B Position messages were used to detect the addresses of aircraft equipped with ADS-B, and to mark their locations using cyan dots. Then DF11 receptions having the same address and containing II = 4 were used to plot the aircraft location as a red dot.

The results in Figure 30 clearly show two circles devoid of DF11 receptions. These are the 60 NM range extents of two radars, both using II = 4. Lockout is effective within the normal range of each radar, but clearly there are many unwanted All Call replies from greater ranges.

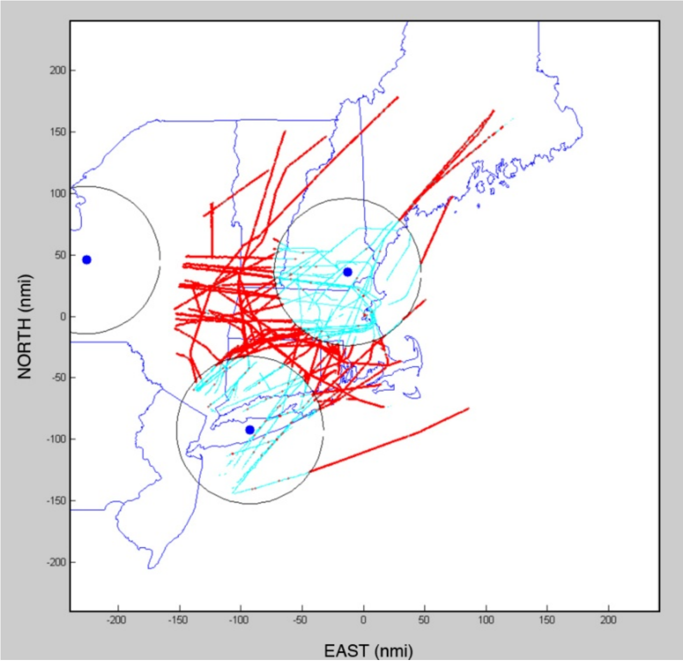

*Figure 30. Unwanted All Call replies (red) triggered beyond radar lockout range.*

Measurements of the different DF types were also made by the FAA Technical Center and documented in [4]. These were airborne measurements, flying in the New Jersey and New York area in 2007. The results in Ref. 4, section 9.1, are consistent with the results and conclusions given here. The analysis in [4] also explores mechanisms that can cause the transmission rate of Short Squitters to exceed the nominal rate of 1 per second. It was reported [4] that some aircraft when flying in some locations transmit Short Squitters at a much higher rate, as high as 18 per second in one case.

Although the Short Squitter transmission rate can greatly exceed the nominal 1 per second in some cases, the results in Figure 29 indicate that the total environment of Short Squitters is a relatively small fraction of the total environment of Mode S signals. Quantitatively, Short Squitters constitute only 10 percent of all Short Mode S receptions.

## 3.3 DF11 TRANSMISSION RATES

To better understand the source and effect of the additional DF11 II=0 messages, the location of aircraft transmitting these messages was studied. Using radar data and omnidirectional DF11 receptions, the DF11 II=0 transmission rate for each individual Mode S track during the time of the test flight was plotted in Figure 31. A three second moving average was applied to smooth the transmission rate along each track.

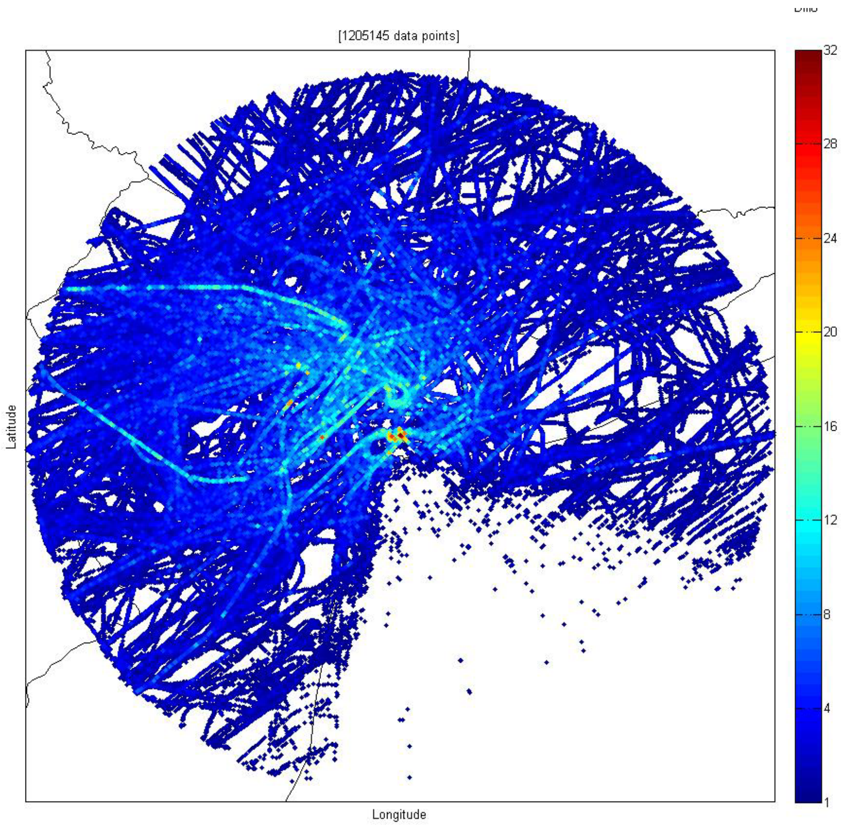

*Figure 31. DF11 II=0 per-aircraft transmission rates (error-free receptions).*

The plot shows that DF11 II=0 per-aircraft reception rates above the expected 1 squitter per second are observed across a large area. Higher than average rates are observed in the New York City area, and very high rates are observed near JFK airport and other airports. It should be noted that since the reception probability falls off with range, the II=0 rates are likely higher than the rates shown here for aircraft farther from JFK.

In Figures 32 and 33, the DF11 II=0 per aircraft transmission rates were broken up into aircraft below 5000 ft and aircraft above 5000 ft. We see that the highest peaks (~30 per second) occur only at low altitudes, and that they occur at major airports. This seems to fit with explanations of the additional transmissions involving multipath reflections. Figure 33 shows that high transmission rates (10–20 II=0 per second) are also seen farther from the terminals. Two aircraft (west and northwest of New York City) in particular have high II=0 rates despite being outside the densest region. This may suggest that some transponders are more susceptible than others to the causing mechanism.

Although the DF11 II=0 rates are sometimes much higher than the nominal 1 per second in certain circumstances, overall they do not make up a large portion of Mode S receptions on 1090 MHz. Taking the sum of DF11 II=0 beyond 1 per second from each aircraft during this two hour period, there is an average of 53 receptions per second at an MTL of –74 dBm. The total Mode S reception rate at –74 dBm on 1090 MHz during this time was 1032 receptions per second. Therefore, the additional DF11 II=0 messages account for ~5.1% of all Mode S receptions on 1090 MHz. A similar result is obtained for an MTL of –84 dBm. The inclusion of extra squitters at the surface of other airports would at most modify this value by a few percentage points. Although this issue does not constitute a debilitating spectrum problem, correcting the behavior would contribute to more efficient spectrum usage.

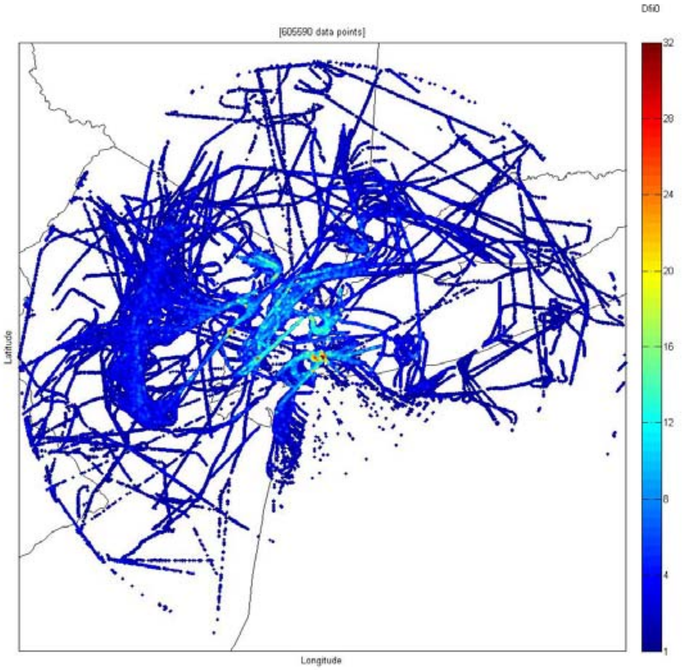

*Figure 32. DF11 II=0 per-aircraft transmission rates below 5000 ft.*

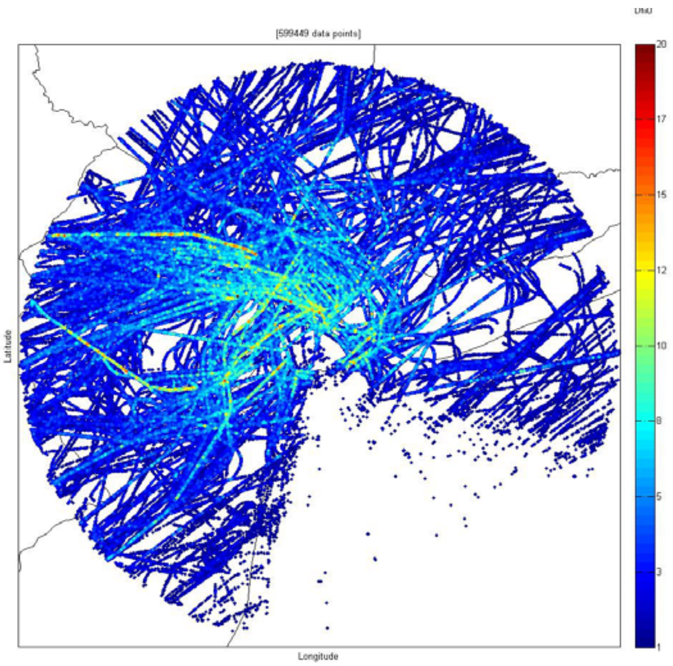

*Figure 33. DF11 II=0 per-aircraft transmission rates above 5000 ft.*

# 4. ANALYSIS OF TCAS OPERATION ON THE AIRPORT SURFACE

TCAS was designed as an airborne system to be activated when an aircraft enters the active runway for takeoff and turned off when exiting the runway following landing. Nevertheless, there is a perception that the number of aircraft using TCAS on the ground may significantly exceed what would be expected by proper use. FAA Technical Center personnel report that TCAS counts as high as 180 have been observed during test flights in the NYC airspace; such high TCAS counts can be partially explained by aircraft operating TCAS on the ground. On-ground TCAS operation is of concern for two reasons: (1) It unnecessarily contributes to both 1030 MHz interrogations and 1090 MHz replies, and (2) it adds to the TCAS count, and therefore it reduces the air-to-air surveillance range of TCAS.

In order to better understand the extent of on-ground TCAS operation, the number of aircraft operating TCAS on the ground at JFK was measured over the 25 days of data collection. The following methodology was used: The average number of TCAS operating on the ground was found for each 5- minute interval. This time interval was chosen in order to observe any peaks due to a backup of aircraft waiting to take off. For each interval, the Mode S addresses of aircraft reporting having been on the ground and having an active TCAS at some point during the time period were found using omnidirectional receptions from validated Mode S addresses. The following message fields and transmissions were used to determine on-ground and TCAS status:

On-Ground Status:

Capability (CA) in DF11 and DF17 transmissions: CA = 4 indicates on the ground

Flight Status (FS) in DF4 and DF5 transmissions: FS = 1 or 3 indicates on the ground

Vertical Status (VS) in DF0 transmissions: VS= 1 indicates on the ground

TCAS Operational Status:

TCAS Broadcast Interrogations (UF16-32): sent if TCAS operational

Air-to-Air Reply Information (RI) in DF0 transmissions: RI = 2 or 3 indicates operational TCAS

For each valid Mode S address, a status timeline was created using timestamps from the above messages. Short gaps between receptions were filled in, and questionable receptions were excluded. Radar data provided by the TCAS RA Monitoring System (TRAMS) was then used to verify that the aircraft was located at JFK when reporting on-ground. Finally the number of seconds each aircraft indicated being on the ground and having an operational TCAS were summed together and then divided by the seconds in the interval to find the average number of TCAS aircraft operating on the ground during that interval.

The data collected over 25 days of monitoring at JFK airport was analyzed using this process to determine the number of aircraft operating TCAS while on the ground. On average, during peak times, 20 to 30 aircraft are operating TCAS while on the ground. Daily peaks above 25 are observed, and a maximum close to 45 was observed.

Figure 34 shows the average number of TCAS operating on the ground at JFK airport during 5-minute intervals over a complete week. The results show that the number of aircraft operating TCAS on the ground at JFK peaks during the morning and evening.

Figure 35 shows a summary of the number of TCAS operating on the ground over the 25 days data was collected at JFK. For each hour in a day, the minimum, maximum, and average number of TCAS observed operating on the ground for all 5-minute segments of that hour across all 25 days is shown. For example, the maximum number of TCAS operating on the ground at 10 EDT was found by taking the highest 5-minute averages collected between 10–11 EDT over 25 days.

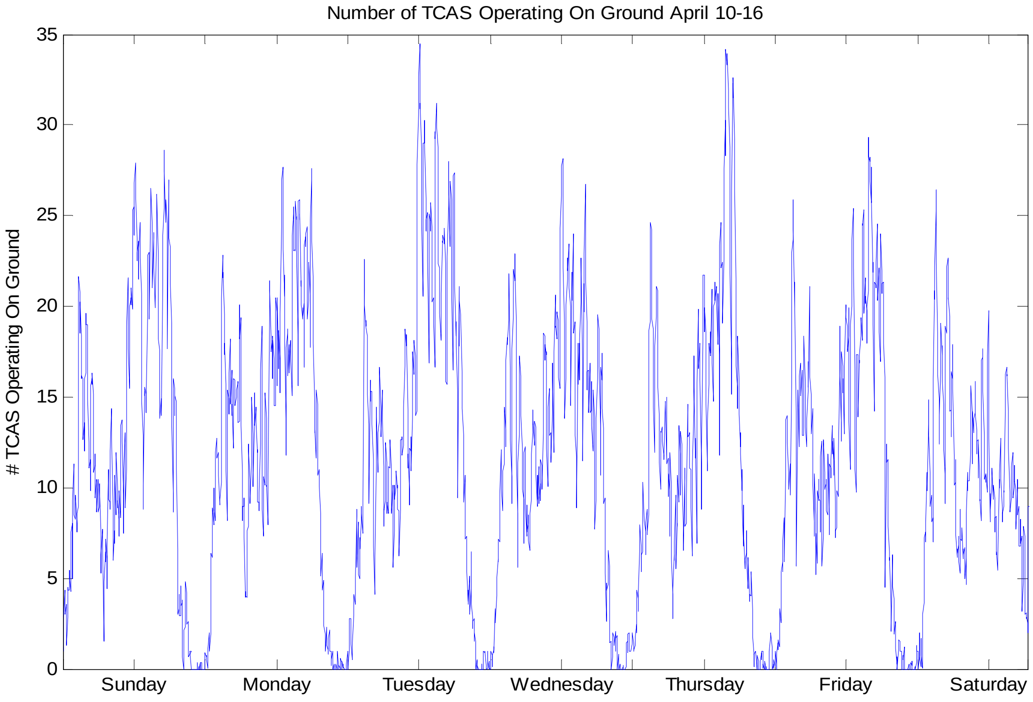

*Figure 34. Number of TCAS operating on-ground, 11–16 April 2011.*

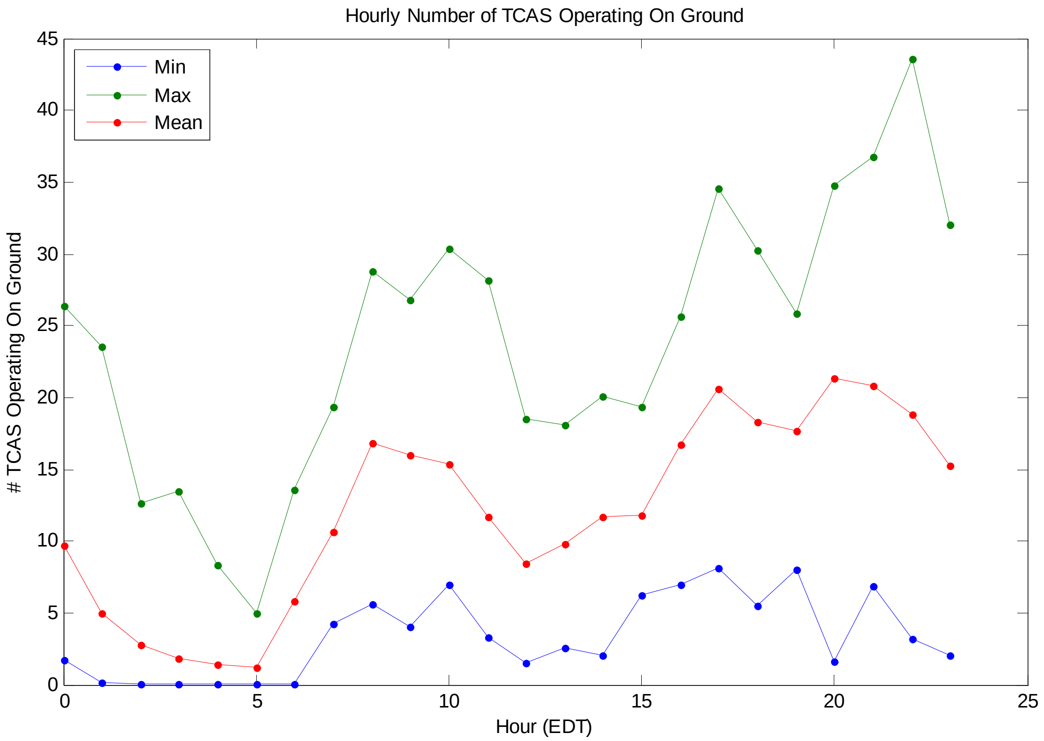

*Figure 35. Hourly number of TCAS operating on-ground, 4–29 April 2011.*

These measurements confirm that there are significant numbers of aircraft operating TCAS on the ground at JFK on a daily basis.

A similar analysis is given in Appendix B, which focuses on the time duration over which landing TCAS aircraft keep their TCAS systems operating after landing, and the similar time duration for departing aircraft. That study also simulated TCAS behavior by including the on-ground operational TCAS units, in order to determine the resulting degradation in the performance of the overall TCAS system.

The analysis and results in Appendix B can be described in more detail as follows. A process was developed to quantify the impact of aircraft operating their TCAS units on the airport surface. One month of 1030 and 1090 MHz recordings from April 2011 was analyzed to monitor the operation of Mode S transponders and TCAS units in the JFK area. Aircraft tracks from TRAMS radar data, recorded from the JFK Mode S sensor, were used to identify aircraft taking off and landing at the JFK airport. The 1030/1090 MHz data was used to create a distribution of Mode S and TCAS behavior for the aircraft identified as taking off or landing by the TRAMS radar data. The distribution of aircraft activity was used to modify a high density aircraft dataset from November 2009 to include an accurate representation of Mode S and TCAS operation on the airport surface of JFK, EWR, and LGA. The revised dataset included an average of 65 additional TCAS aircraft operating on-ground, doubling the instantaneous TCAS count within 30 NM of JFK. A TCAS surveillance simulation was used to compare the effects of the additional aircraft operating on the airport surface (included in the modified dataset) with the original dataset which had minimal TCAS or Mode S activity on the airport surface. The additional aircraft operating on the airport surface increased the average number of TCAS messages received by an airborne aircraft within 30 NM of JFK by approximately 33% on 1030 MHz and 91% on 1090 MHz.

An important next step is to examine the potential safety impact that TCAS operation on the ground has on airborne TCAS units. Results from this study indicate that on average the surveillance range of airborne aircraft within the JFK area was reduced by 17%. While the reduction in surveillance range is allowed by the specifications, it is possible that excessive operation of TCAS units on the airport surface could cause the surveillance range of airborne TCAS units in certain altitude volumes to be decreased to a point that TCAS pilots have insufficient time to fully respond to Resolution Advisories." Analysis will continue to determine the safety impact of the decreased TCAS surveillance range.

# 5. ANALYSIS OF TCAS AIR-TO-AIR COORDINATION

## 5.1 COORDINATION INTRODUCTION

The vertical sense selection of a TCAS Resolution Advisory (RA) is coordinated in TCAS-TCAS encounters to ensure that complementary advisories are issued. This coordination process is performed using a special set of interrogations and replies. Over the past two years, Lincoln Laboratory has developed an automated coordination monitoring program to evaluate the performance of the TCAS coordination process using 1030/1090 MHz monitoring data. In all encounters, the observed coordination processes have properly ensured complementary sense selection. However, the automated program, run both with data recorded previously in Lexington, MA, and with the current JFK data, has revealed a collection of anomalies, some of which have been investigated to ensure that no safety issues exist. Of the anomalies identified and investigated thus far, no specific safety issues exist. For comparison purposes, the following subsections give overall coordination statistics and anomalies for both the baseline dataset (Lexington, MA) and the current JFK data.

The following subsections contain:

5.2: An overview of coordination and the automated coordination monitoring program
5.3: Baseline message formatting anomalies
5.4: Baseline coordination process anomalies
5.5: Baseline coordination statistics
5.6: JFK results, including coordination statistics and coordination process anomalies. Additionally, example JFK encounters are shown demonstrating the level of detail that is attained using 1030/1090 MHz data for event analysis.

## 5.2 OVERVIEW OF COORDINATION AND THE AUTOMATED COORDINATION MONITORING PROGRAM

When a TCAS aircraft issues an RA against a TCAS equipped intruder, a coordination interrogation message will be transmitted once every second to the intruder aircraft. This message includes the aircraft’s Vertical Resolution Advisory Complement subfield (VRC), which is the primary indication of the vertical sense of the RA. In essence, the VRC alerts the intruder aircraft of the intended vertical sense that TCAS has selected so that a complementary RA can be selected. Each coordination interrogation elicits a coordination reply message from the intruder, which acts as a technical acknowledgement that the coordination interrogation has been successfully received.

RA Reports are also downlinked to any Mode S sensor tracking the aircraft once each scan during the RA and for the 18 seconds following the RA. Version 7 TCAS units will also transmit an RA Broadcast interrogation once every 8 seconds and at the conclusion of the RA. These coordination-related messages contain data fields with information about any ongoing RAs. Some of the subfields available include the ARA (Active RA, the RA displayed to the pilot), the RAC (RA Complements, a composite of all vertical complements received from other TCAS aircraft), and the RAT (RA Terminated indicator).

Figure 36 shows coordination between two TCAS equipped aircraft, highlighting the various coordination-related RF messages:

1. TCAS Coordination interrogation (UF16-30)[2]
2. TCAS Coordination reply (DF16-30)
3. RA Broadcast interrogation (UF16-31)
4. RA Report (DF20 or DF21)

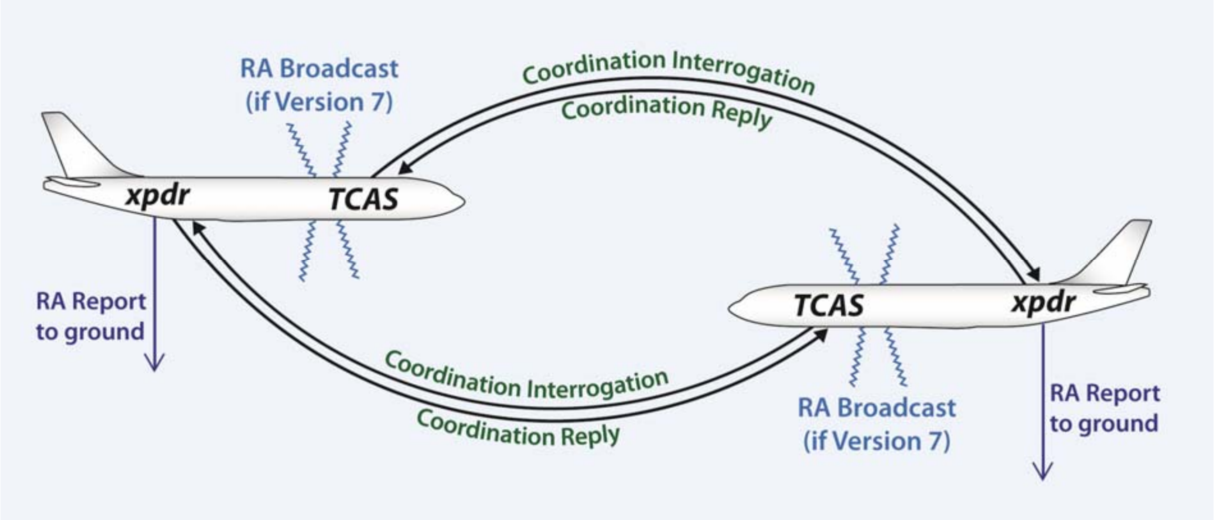

*Figure 36. Coordination-related RF messages.*

If both TCAS aircraft declare RAs against each other, each will carry out its own interrogation/reply sequence and its own set of RA Reports and TCAS RA Broadcasts. While the data contained in each sequence is intrinsically linked, analysis is simplified by separating the messages as if

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[2] The notation 'UF16-30' means Uplink Format 16 (i.e., Mode S long air-to-air special surveillance interrogation) with message type $30_{hex}$ (identifying a coordination message).

they weren’t. Coordination interrogations (and the replies they elicit), RA Reports, and RA Broadcasts from each aircraft are grouped together and can be thought of as that aircraft’s perspective of the coordination process.

Monitoring coordination-related transmissions in the United States airspace was initiated following similar monitoring performed in the European airspace [12]. In the European effort, formatting errors and suspicious addresses were documented. In the first stage of the Lincoln coordination monitoring program, all received messages are examined for the specific formatting errors observed in the European study. While some formatting errors can be detected in this manner, much of the data contained in coordination-related messages can only be analyzed in the context of the ongoing RA and coordination process.

In the second stage of the Lincoln coordination monitoring program, each TCAS-TCAS coordinated RA is analyzed in depth using all available messages. Coordinated RAs are identified using the Mode S addresses contained in various coordination messages. All relevant messages for each encounter are grouped together in chronological order. The automated analysis software steps through the coordinated encounter message by message. Each message is analyzed to ensure that the coordination process occurs as defined in the MOPS, messages are transmitted at the proper rates, and all data contained in each message is consistent with other transmissions and with the overall encounter. Of particular importance is consistency in indicated complementary sense selection. Any unusual information or occurrences detected are flagged and summarized in an output file. Flagged RAs can then be manually analyzed to determine whether the behavior was acceptable or anomalous. Additional information about the automated coordination analysis and outputs provided can be found in [2].

## 5.3 BASELINE MESSAGE FORMATTING ANOMALIES

As previously reported in [2], Lincoln Laboratory has not observed in the US airspace most of the message errors reported in the German monitoring work. Table 1 shows a comparison of reported message errors as observed in the German report and in Lincoln’s monitoring work. While RA Broadcast messages with the incorrect broadcast address have been decoded, it is believed that these are the result of expected parity errors, and not part of a wider problem.

## TABLE 1

## Message Bit Errors

| Message Type | Anomaly | Lincoln Data | German Data |
|---|---|---|---|
| TCAS coordination interrogation | Invalid redundancy check | no | yes |
| TCAS coordination interrogation | Invalid sender address | no | yes |
| RA Broadcast interrogation | Incorrect Mode A code | no | yes |
| RA Broadcast interrogation | Horizontal RA | no | yes |
| RA Broadcast interrogation | All-zero Mode C code | no | yes |
| RA Broadcast interrogation | Metric Mode C code | no | yes |
| RA Broadcast interrogation | Incorrect broadcast address | yes | yes |
| TCAS coordination reply | All zeros except for header | yes | no |

Additional message format anomalies observed by Lincoln:

1. All-zero TCAS coordination reply

   In this anomaly, aircraft are observed transmitting coordination reply messages (DF16-30) on 30 second intervals for extended periods of time. All fields in the messages contain no data. It was determined that the messages are low-level self-test messages used by a manufacturers in an older TCAS implementation. The messages would not be used in any manner by other aircraft.

2. Broadcast Messages with flipped bit

   A large percentage of all coordination interrogation messages were addressed to a small number of Mode S addresses. The Mode S addresses do not correspond to aircraft seen in the area at the time. It was determined that the anomaly was due to specific parity errors in TCAS Broadcast interrogations (UF16-32) which appear as coordination interrogations to specific addresses. As TCAS Broadcast interrogations are transmitted regularly by each TCAS aircraft, and always transmitted using the same broadcast address, specific parity errors would always result in identical decoded addresses. This pattern was also identified in the German monitoring.

## 5.4 BASELINE COORDINATION PROCESS ANOMALIES

The automated analysis detected the following anomalies, which were manually verified and in some cases investigated. A few anomalies remain under inquiry by Lincoln Laboratory and the FAA.

1. No RAC

   In 13% of TCAS-TCAS coordinated encounters, an anomaly is observed when an aircraft is the threat in a coordinated RA but has not issued an RA of its own. The aircraft is required to respond to coordination interrogations with a coordination reply containing an RAC as received in the interrogation. In this case, the aircraft transmits coordination reply messages without an RAC (RAC set to 0) throughout the entire RA. There are two plausible explanations for why the RAC is not included in the coordination reply message:

   a. The TCAS unit never received/held the VRC from the coordination interrogation. This would have safety implications as this would mean that the sense coordination effectively did not occur.

   b. The TCAS unit received/held the VRC; however, the RAC was not passed to the transponder or included in the reply. In this case, coordination would have occurred and there would be no safety concerns. Nonetheless, this information is very valuable in monitoring RAs (using 1030 /1090 MHz receivers).

   After the manufacturer of the involved equipment was identified, the anomaly was investigated and determined to be a result of explanation b. Therefore, the anomaly is not believed to be a safety concern; however it was recommended that the issue be corrected in new equipment. In TCAS-TCAS encounters where only one aircraft issues an RA, the coordination reply is the only source of information on whether the threat has received and stored the VRC.

2. RA stops then continues

   Analysis has shown two encounters where an RA stops and then immediately restarts in the middle of a coordinated encounter. In one case RA termination is indicated by the RAT bit, while in the other case the message fields indicate coordination interrogations are no longer occurring. This issue has been observed by the TCAS Operational Performance Assessment (TOPA) program, with examples stopping and restarting multiple times. The TOPA program is looking into this anomaly.

3. Interrogating self

   In one case, an aircraft was observed issuing and attempting to coordinate an RA against itself for almost three minutes. The aircraft transmits coordination interrogations, coordination replies, RA Broadcasts, and RA Reports. Its own Mode S address is included in all address fields as both transmitting aircraft and recipient. There are multiple mechanisms intended to prevent such an occurrence. A transponder should be suppressed during an interrogation and unable to reply to the coordination interrogation. In addition, the TCAS unit should also examine the threat Mode S address and is prohibited from issuing an RA against its own address. This anomaly is a safety concern given the confusion and maneuvers it could potentially induce. A number of additional examples were found in TOPA data, and this is being pursued as a TOPA issue.

4. RA reports not transmitted during 18 second freeze

   At the conclusion of an RA, TCAS equipped aircraft should continue downlinking RA Reports to Mode S sensors for 18 seconds. These reports contain RA information prior to RA termination and are intended to be used for RA monitoring by Mode S sensors with long scan intervals. In 35% of coordinated RAs, RA Reports are not transmitted during the 18 second freeze. It has been determined that this was not implemented in a manufacturer's older transponder version; the downlinks are implemented properly in current versions.

5. Fields missing in RA Reports and RA Broadcasts

   In 7% of encounters, data fields in the RA Reports are set to 0 despite the expected information having appeared in previous messages. In this anomaly, the RAC and/or the ARA are set to zero in messages sent immediately following termination of the RA when RA Reports continue to be transmitted to Mode S sensors for monitoring purposes.

6. RA Broadcast information not updated in a timely manner

   RA Broadcast interrogations are transmitted once every 8 seconds. An additional RA Broadcast is transmitted immediately after the conclusion of the RA. Each RA Broadcast should include the most recently available information. However, we have observed a case where the final broadcast includes the data retrieved for the previous RA Broadcast rather than the most recent information.

In anomalies 4–6, the unavailable messages and information are only used for monitoring purposes and for the most part do not contribute significant additional information to current monitoring efforts. Nonetheless, it is recommended that future implementations or equipment updates correctly include all intended information.

## 5.5 BASELINE COORDINATION STATISTICS

During eight months of 1030/1090 MHz data collection in Lexington, MA, 185 TCAS-TCAS coordinated encounters were observed. Observations include:

- In 70% of these encounters, only one of the two TCAS equipped aircraft issued an RA.

This can be explained by differences in the geometry determined by each aircraft, and by TCAS logic being biased to not issue an RA to a level aircraft in level-off encounters. For example, according to TOPA analyses [13], only the leveling aircraft received an RA in 97% of coordinated level-off TCAS Encounters with 1000' vertical spacing.

- 87% of the RAs were issued by Version 7 TCAS units.
- 55% of the RAs were issued by aircraft with a Version 7-compatible transponder.
- Two RA reversals were detected. In both of these encounters, the sense changed from up to down, though the RA would not be announced to the pilot as a reversal according to the MOPS. RAs are only announced to the pilot as a reversal if the new command is a climb or descend rather than 'maintain.'
- No coordinated Multiple Threat Encounters (MTEs) were observed.

## 5.6 JFK RESULTS

Automated analysis was performed using the 1030/1090 MHz data collected at JFK. Overall, the results were similar to what was observed in the baseline Lexington, MA, airspace. As expected, more TCAS-TCAS coordinated RAs were observed in the dense NY airspace.

Between 4 April and 29 April 2011, 87 TCAS-TCAS coordinated encounters were detected by the automated analysis. On average, four times as many coordinated encounters were detected per day in the dense NYC airspace as were detected in the Lexington MA airspace. Observations include:

- In 73% of these encounters, only one of the TCAS equipped aircraft issued an RA.
- 76% of the RAs were issued by Version 7 TCAS units.
- 54% of the RAs were issued by aircraft with a Version 7-compatible transponder.
- Two RA reversals were detected. In one of these encounters, the sense changed from up to down, though the RA would not be announced as a reversal according to the MOPS.
- No coordinated multiple threat encounters were observed, though an aircraft was observed receiving two RAs in rapid succession.

The formatting anomalies in Section 5.3 above occurred with similar frequency in JFK as in Lexington. Referring to the coordination process anomalies in Section 5.4, anomalies 1 and 5 were observed in roughly similar frequencies as were observed in Lexington, MA (10% and 6%, respectively, for JFK as compared with 13% and 7% for Lexington). Anomaly 4 was observed more often at JFK than in Lexington (53% versus 35%). This could be explained by more aircraft having older equipment or a specific carrier having a large number of aircraft with older equipment. The other coordination process anomalies were seen with less frequency at JFK than in Lexington; this was likely due to the short duration of monitoring performed at JFK rather than a true difference in frequency. **Overall, no new**

**anomalies were identified in the JFK data. Two encounters were observed where a communication link issue was identified or suspected.**

### 5.6.1 Interesting Example JFK Encounters

This section describes two encounters that were monitored during the data collection at JFK. Their inclusion is intended to demonstrate the need for 1030/1090 MHz monitoring in ongoing system performance evaluation efforts and future systems development. The encounters described show unexpected or unusual system performance; however, in both encounters, separation was achieved and maintained as intended.

In the first RA, an unusual number of re-interrogations are observed during the coordination process. In the second RA, it is shown how the unique detail provided by 1030/1090 MHz monitoring data can be used to understand unusual encounters when radar data is not sufficient. Indeed, the level of detail provided by this data has been used as a valuable tool in other monitoring activities and event analysis. In fact, this monitoring program helped identify and analyze an encounter where coordination stopped following coordinated sense selection due to a known surveillance issue. This third encounter is not described in detail in this report.

Encounter 1

In this TCAS-TCAS coordinated encounter, a large commercial jet on approach to Newark issues a climb RA against a business jet that has just taken off from Teterboro. The business jet does not issue an RA, and no previously mentioned anomalies are observed. Plots of the radar tracks and altitudes of both aircraft can be seen in Figures 37 and 38.

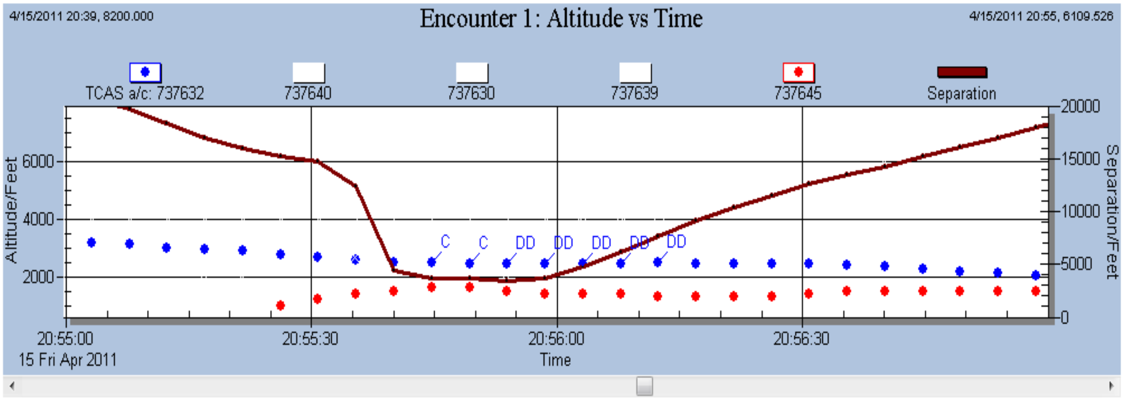

*Figure 37. Encounter 1, altitude versus time.*

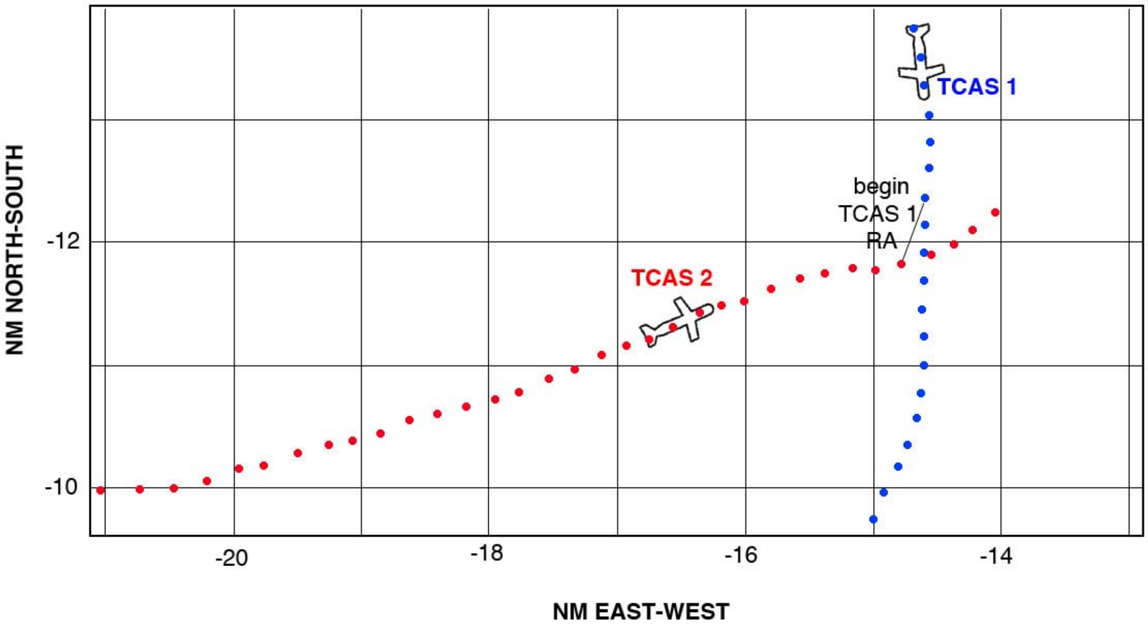

*Figure 38. Encounter 1, x/y plot.*

## TABLE 2

## Encounter 1 Message Exchange

| Msg # | Time (s) | Msg Type | From->to | RAT | VRC/RAC | CVC | ARA | Comments |
|---|---|---|---|---|---|---|---|---|
| 42 | 08.306 | Cord Interr | TCAS1-> TCAS2 |  | DC |  |  |  |
| 43 | 08.306 | Cord Reply | TCAS2-> TCAS1 | 0 | DC |  | UNK |  |
| 44 | 08.320 | Cord Interr | TCAS1-> TCAS2 |  | DC |  |  |  |
| 45 | 08.321 | Cord Reply | TCAS2-> TCAS1 | 0 | DC |  | UNK |  |
| 46 | 08.336 | Cord Interr | TCAS1-> TCAS2 |  | DC |  |  |  |
| 47 | 08.336 | Cord Reply | TCAS2-> TCAS1 | 0 | DC |  | UNK |  |
| 48 | 08.353 | Cord Interr | TCAS1-> TCAS2 |  | DC |  |  |  |
| 49 | 08.369 | Cord Interr | TCAS1-> TCAS2 |  | DC |  |  |  |
| 50 | 08.384 | Cord Interr | TCAS1-> TCAS2 |  | DC |  |  |  |
| 51 | 08.384 | Cord Reply | TCAS2-> TCAS1 | 0 | DC |  | UNK |  |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 52 | 08.401 | Cord Interr | TCAS1-> TCAS2 | | DC | | | |
| 53 | 08.669 | RA Report | TCAS1->ground | 0 | 0 | | Climb | |
| 54 | 09.327 | Cord Interr | TCAS1-> TCAS2 | | DC | | | |
| 55 | 09.342 | Cord Interr | TCAS1-> TCAS2 | | DC | | | |
| 56 | 09.343 | Cord Reply | TCAS2-> TCAS1 | 0 | DC | | UNK | |
| 57 | 09.359 | Cord Reply | TCAS2-> TCAS1 | 0 | DC | | UNK | |
| 58 | 09.376 | Cord Interr | TCAS1-> TCAS2 | | DC | | | |
| 59 | 09.391 | Cord Interr | TCAS1-> TCAS2 | | DC | | | |
| 60 | 09.407 | Cord Interr | TCAS1-> TCAS2 | | DC | | | |
| 61 | 09.407 | Cord Reply | TCAS2-> TCAS1 | 0 | DC | | UNK | |
| 62 | 10.378 | Cord Interr | TCAS1-> TCAS2 | | DC | | | |
| 63 | 10.378 | Cord Reply | TCAS2-> TCAS1 | 0 | DC | | UNK | |
| 64 | 11.147 | Cord Interr | TCAS1-> TCAS2 | | DC | | | |
| 65 | 12.330 | RA Report | TCAS1->ground | 0 | 0 | | DNDesc | => do not descend |
| 68 | 13.336 | Cord Interr | TCAS1-> TCAS2 | | DC | | | |
| 69 | 13.350 | Cord Interr | TCAS1-> TCAS2 | | DC | | | |
| 70 | 13.366 | Cord Interr | TCAS1-> TCAS2 | | DC | | | |
| 71 | 13.383 | Cord Interr | TCAS1-> TCAS2 | | DC | | | |
| 72 | 13.400 | Cord Reply | TCAS2-> TCAS1 | 0 | DC | | UNK | |
| 73 | 13.414 | Cord Reply | TCAS2-> TCAS1 | 0 | DC | | UNK | |
| 74 | 13.431 | Cord Interr | TCAS1-> TCAS2 | | DC | | | |
| 75 | 14.214 | Cord Interr | TCAS1-> TCAS2 | | 0 | CDC | | CVC |
| 76 | 14.228 | Cord Interr | TCAS1-> TCAS2 | | 0 | CDC | | --interr after CRA-- |
| 77 | 14.244 | Cord Interr | TCAS1-> TCAS2 | | 0 | CDC | | --interr after CRA-- |
| 78 | 14.261 | Cord Interr | TCAS1-> TCAS2 | | 0 | CDC | | --interr after CRA-- |
| 79 | 14.278 | Cord Interr | TCAS1-> TCAS2 | | 0 | CDC | | --interr after CRA-- |
| 80 | 14.309 | Cord Interr | TCAS1-> TCAS2 | | 0 | CDC | | --interr after CRA-- |
| 81 | 14.428 | RA Broadcast | TCAS1-> | 1 | 0 | | Corr,Up,Pos, | RA terminated |

T1 = TCAS1, T2 = TCAS2

DD = ‘don’t descend’, DC = ‘don’t climb, CDD = ‘cancel don’t descend’, UNK = unverified format, CVC = cancel vertical code

Though it is not unusual to observe re-transmission of coordination interrogations in the datasets, the majority of interrogations receive an immediate reply, and more than two interrogations are rarely required. Similarly, in most cases, a coordination reply that is elicited is received by the interrogator and rarely requires additional interrogations. However in this example, it appears as if the coordination replies are not being received properly by the interrogating TCAS. Table 2 shows a portion of the coordination interaction between the two aircraft.

While missing some of the directional interrogations, the monitoring receiver shows that coordination replies are being elicited by the intruder aircraft once per second and that additional replies to re-interrogations are observed multiple times per second (3–7 re-interrogations per interval) for the duration of the RA. Coordination re-interrogations are spaced 16 ms apart, so the above table shows replies to re-interrogations spaced 16 ms after the previous reply rather than 1 second.

It is expected that the aircraft should be able to receive and decode most of the coordination reply messages. Coordination interrogations and coordination replies are transmitted at full power, coordination replies are transmitted omnidirectionally, and the aircraft are within 4 NM of each other. Even near the closest point of approach (~1 NM) there are multiple re-interrogations. While transponder availability could explain the communication issue, if so, one would expect to see more examples of encounters with many re-interrogations and missed replies. An alternative explanation could be equipment malfunction or a multi-path induced problem due to proximity to the surface. While initial sense selection coordination was successful, it is impossible to know whether the communication link was adequate enough to respond to changes such as an RA reversal. While no specific anomalies were observed in the message contents, the situation could potentially be a safety concern. Determining the cause of this communication degradation is difficult without access to the involved aircraft. It is recommended that any future monitoring efforts look for similar cases. Alternative explanations or analysis could also be considered using existing data.

### Encounter 2

In this TCAS-TCAS coordinated encounter, two regional jets issue RAs against each other around 12,000 ft in altitude, south of New York City. Both aircraft are climbing and traveling towards each other when the aircraft at slightly higher altitude levels off. This encounter is interesting as the geometry of the encounter and RA selection (and timing) may seem unintuitive. In addition, the RA results in non-compliance by the pilots and an RA reversal. However by analyzing the encounter in detail, it can be confirmed that TCAS did perform as intended and issued commands that would provide adequate separation if followed. The encounter also serves as an important example of the limitations of radar based monitoring and the detail that can be seen using 1030/1090 MHz monitoring for event analysis.

Plots of the radar tracks and altitudes of both aircraft can be seen in Figures 39 and 40. These plots show the horizontal and vertical geometries of the encounter. It should be noted that a large horizontal separation existed when there was low vertical separation, preventing a collision.

Using the RA downlinks collected by the TCAS RA Monitoring System (TRAMS) sensors (Figure 39), it is shown that the climbing aircraft (TCAS1) receives a descend RA; however, the pilot does not comply with the RA. Approximately 10 seconds into the encounter, it is observed that the following happens:

1. A reversal occurs
2. The level aircraft (TCAS2) receives an RA which is indicated to be a reversal
3. Both RAs are altitude crossing
4. TCAS1 and TCAS2 cross altitudes

In this case, the RA was recorded by two TRAMS sensors, with each sensor receiving 23 downlinks (46 total). The downlinks of the two aircraft to the two sensors were separated by about 1 second, leaving 3 to 4 seconds during each scan without new information about the ongoing RA. The granularity of this data makes it difficult to fully understand what occurred during the RA and whether TCAS performed correctly in this instance. Using the 1030/1090 MHz monitoring system, 254 messages were recorded consisting of coordination messages and downlinks to at least four Mode S radars. Messages with new information are received multiple times each second from each aircraft. During the 5 second period when changes in the declared RA occur, about 6 downlinks are received by TRAMS sensors as seen in Table 3.

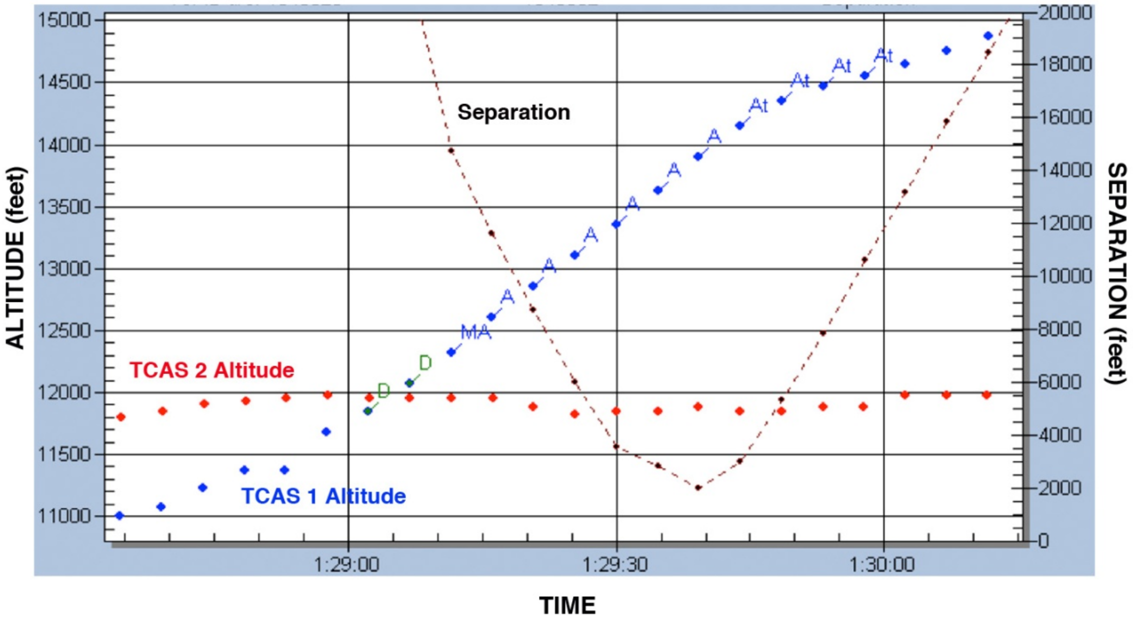

*Figure 39. Encounter 2, altitude and separation versus time.*

Tables 4 and 5 show a selection of the message by message output of the automated analysis software for the same 5-second period. It is important to remember that each TCAS unit operates on one second intervals meaning that changes in the announced RA occur only once per second, and there may be some delay within the interval before information appears in a transmitted message. Using this detailed information, it is possible to understand in detail how TCAS performed in this encounter.

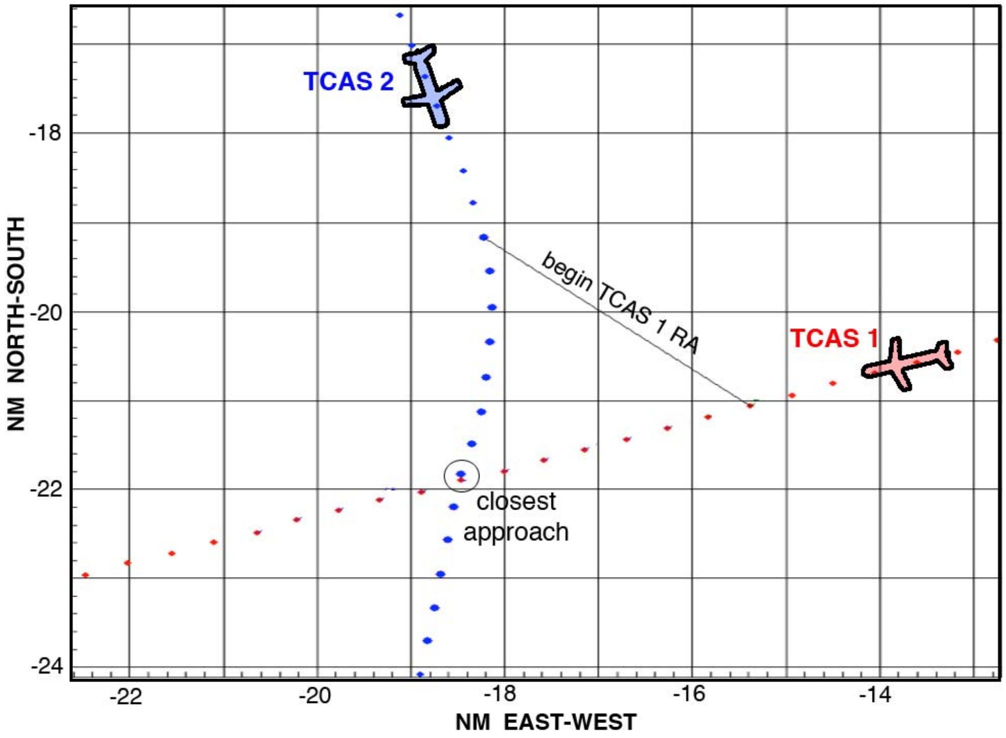

*Figure 40. Encounter 2, x/y plot.*

## TABLE 3

## RA Reports Received with TRAMS Monitoring System

**TCAS 1**

| Local Time | ARA |
|---|---|
| 21:29:07 | Increased Crossing Descend |
| 21:29:11 | Preventative, Up, Positive (Maintain) |
| 21:29:12 | Preventative, Up, Positive (Maintain) |

**TCAS2**

| Local Time | ARA |
|---|---|
| 21:29:07 | Climb |
| 21:29:11 | Descend |
| 21:29:12 | Descend |

## TABLE 4

## Encounter 2, 5-Second Message Exchange from TCAS 1 Perspective

| Msg # | Time | Msg Type | From->to | RAT | VRC/RAC | CVC | ARA | Comments |
|---|---|---|---|---|---|---|---|---|
| 21 | 07.998 | Cord Interr | T1->T2 |  | DD |  |  |  |
| 22 | 07.998 | Cord Reply | T2->T1 | 0 | DD |  |  |  |
| 23 | 08.027 | RA Broadcast | T1-> | 0 | 0 |  | Corr,Dn,Pos, |  |
| 24 | 09.035 | Cord Interr | T1->T2 |  | DD |  |  |  |
| 25 | 09.163 | RA Report | T1->ground | 0 | 0 |  | Corr,Dn,AltCr,Pos, | => AltCr |
| 26 | 09.356 | RA Report | T1->ground | 0 | 0 |  | Corr,Dn,AltCr,Pos, |  |
| 27 | 09.942 | Cord Interr | T1->T2 |  | DD |  |  |  |
| 28 | 09.958 | Cord Interr | T1->T2 |  | DD |  |  |  |
| 29 | 09.958 | Cord Reply | T2->T1 | 0 | DD |  | Clm |  |
| 30 | 09.977 | RA Report | T1->ground | 0 | 0 |  | Corr,Dn,AltCr,Pos, | --Victim RAC Missing(DL)-- |
| 31 | 10.153 | RA Report | T1->ground | 0 | DC |  | Corr,Dn,Incr,AltCr,Pos, | => Incr |
| 32 | 10.154 | RA Report | T1->ground | 0 | DC |  | Corr,Dn,Incr,AltCr,Pos, |  |
| 33 | 10.950 | Cord Interr | T1->T2 |  | DD |  |  |  |
| 34 | 10.950 | Cord Reply | T2->T1 | 0 | DD |  | Clm |  |
| 35 | 11.547 | RA Report | T1->ground | 0 | DC |  | Corr,Dn,Incr,AltCr,Pos, |  |
| 36 | 11.966 | Cord Interr | T1->T2 |  | DC | CDD |  | -Sense Reversal- sense = up |
| 37 | 11.966 | Cord Reply | T2->T1 | 0 | DD |  | Desc | -- threat ARA/VRC: Incompatible Reply ARA- |
| 38 | 12.988 | Cord Interr | T1->T2 |  | DC | CDD |  |  |
| 39 | 12.989 | Cord Reply | T2->T1 | 0 | DC |  | Desc |  |
| 40 | 13.094 | RA Report | T1->ground | 0 | DD |  | Prev,Up,Pos, | => Prev Up notIncr notAltCr |

## TABLE 5

## Encounter 2, 5-Second Message Exchange from TCAS 2 Perspective

| Msg # | Time | Msg Type | From->to | RAT | VRC/RAC | CVC | ARA | Comments |
|---|---|---|---|---|---|---|---|---|
| 12 | 09.873 | Cord Interr | T2->T1 | | DC | | | sense = up |
| 13 | 09.874 | Cord Reply | T1->T2 | 0 | 0 | | Corr,Dn,AltCr,Pos, | |
| 14 | 09.884 | RA Broadcast | T2-> | 0 | DD | | Corr,Up,AltCr,Pos, | Corr AltCr Pos |
| 15 | 09.938 | RA Report | T2->ground | 0 | DD | | Clm | climb |
| 16 | 10.231 | RA Report | T2->ground | 0 | DD | | Clm | |
| 17 | 10.236 | RA Report | T2->ground | 0 | DD | | Clm | |
| 18 | 11.060 | Cord Reply | T1->T2 | 0 | DC | | Corr,Dn,Incr,AltCr,Pos, | |
| 19 | 11.593 | RA Report | T2->ground | 0 | DD | | Clm | |
| 20 | 11.902 | Cord Reply | T1->T2 | 0 | DC | | Corr,Dn,Incr,AltCr,Pos, | |
| 21 | 12.869 | Cord Reply | T1->T2 | 0 | DD | | Prev,Up,Pos, | -Sense Reversal- sense = down |
| 22 | 13.873 | Cord Reply | T1->T2 | 0 | DD | | Prev,Up,Pos, | |
| 23 | 14.052 | RA Report | T2->ground | 0 | DC | | Desc | => descend |

Figure 41 shows a detailed altitude plot of the coordinated RA. Each dot is the altitude reported by the aircraft in TCAS surveillance replies. As previously mentioned, a large horizontal separation existed when there was low vertical separation, preventing a collision.

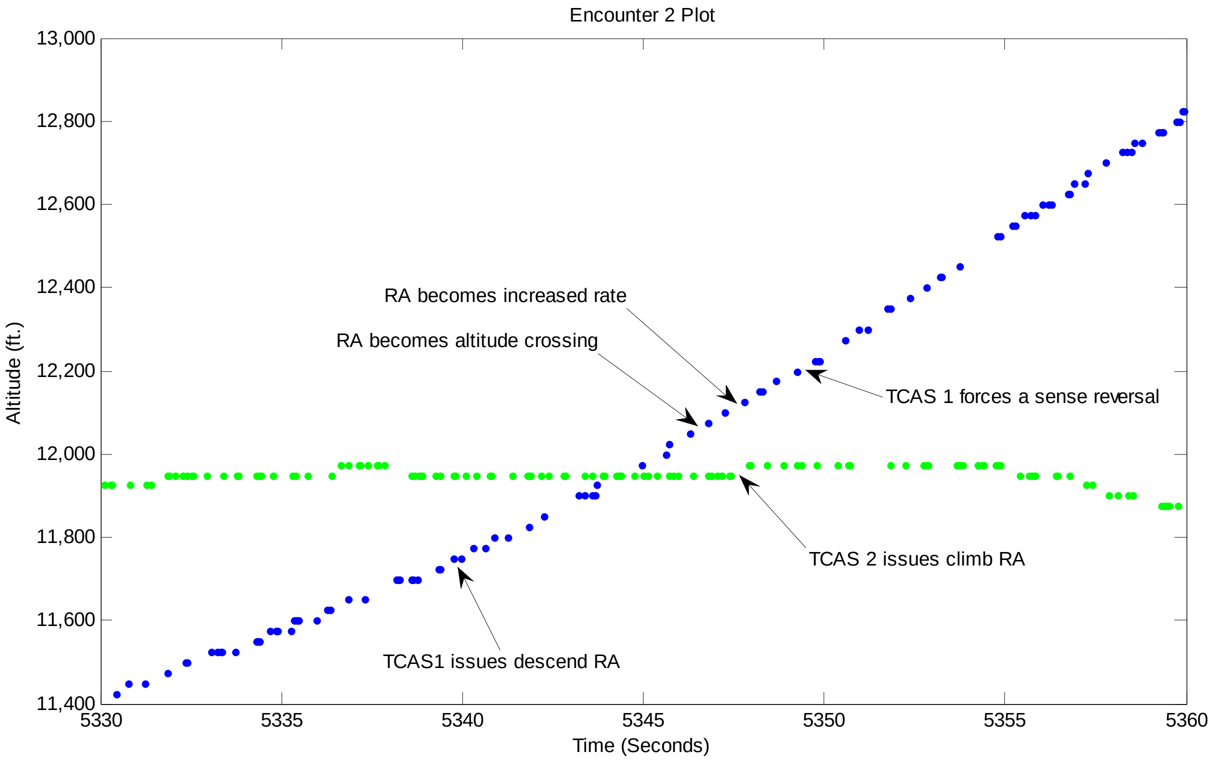

*Figure 41. Encounter 2, altitude versus time, detail.*

The initial RA is issued when TCAS2 (green) is level and TCAS1 (blue) is about 200 feet below TCAS2 and climbing at 2000 feet per minute with at least 4 NM of horizontal separation. It may intuitively make sense that given a climb RA and the horizontal distance, TCAS1 would achieve enough altitude to attain acceptable separation without requiring the pilot to change his trajectory. TCAS1 however selects a descend RA to resolve the encounter.

To understand this selection, we note that TCAS assumes perfect pilot compliance beginning 5 seconds after the RA is issued. Assuming a 2000 feet per minute climb, at 5 seconds into the RA, TCAS 1 would be roughly 50 feet below TCAS2 when the pilot is expected to begin their maneuver. At that point, a 1500 fpm descend RA would give slightly less separation than continuing the 2000 fpm climb RA. However, either RA would likely provide adequate separation as the time until closest approach is over 20 seconds. Furthermore, TCAS is heavily biased to select non-altitude-crossing RAs over crossing RAs, and at that point, TCAS1 is below TCAS2. Therefore TCAS selects the non-crossing descend RA that is expected to provide adequate separation.

It is observed that the TCAS1 pilot does not comply with the RA and continues to climb. It is possible that the pilot has visually acquired the other aircraft and is performing a crossing climb while maintaining visual separation. Alternatively, the pilot may have decided to ignore the RA given that the threat is 4 NM away, and the aircraft is seconds away from crossing altitude.

At 9.16 seconds into the RA, an RA Report is received from TCAS1 indicating that the RA is altitude crossing. We can infer from this that TCAS1 has recognized that the two aircraft have now crossed altitudes (which requires 100 feet separation), and the selected RA maneuver would cause the aircraft to again cross altitudes (TCAS1 has a descend and is now above TCAS2). At this point, the two aircraft still have at least 3 NM of separation, and are at least 15 seconds from closest point of approach. While it is clear that the TCAS1 pilot is not complying with the RA, TCAS Version 7.0 logic operates using expected trajectories and will not take pilot compliance into account. Version 7.1 logic is capable of monitoring pilot compliance in some encounters.

At 9.87 seconds, TCAS2 issues a crossing climb RA. Up until this point, TCAS2 has refrained from issuing an RA as the logic attempts to minimize maneuvers that remove level aircraft from their approved altitude. TCAS2 however is now required to issue an RA since the geometry is crossing. One might expect that TCAS2 would issue a descend RA (given that it is below TCAS1 which is climbing) which would cause TCAS1 to reverse RA sense (giving it an RA matching its vertical speed). However, TCAS1 is the ‘Master’ of the coordination process, forcing TCAS2 to select a complimentary sense and leaving it unable to force a reversal.

At 10.15 seconds, TCAS1 determines that separation is not being achieved as expected. TCAS1 attempts to increase separation by instructing the pilot that the RA is now ‘increased rate.’ This transition to increased rate must occur before a reversal can occur. This is due the fact that the RA is a crossing RA, and for crossing RAs TCAS logic requires there to be two intervals where a reversal is desired by TCAS before the RA can be reversed. During the intervening interval increased rate is selected.

At 11.96 seconds, TCAS1 transmits a coordination interrogation message indicating that it is reversing the sense of the RA. TCAS1 now has a ‘maintain vertical speed’ RA. TCAS2 is observed to reverse its RA to a complementary descend. In all subsequent messages the reversal geometry is maintained. While it is surprising that the reversal occurs 3 seconds after the two aircraft cross altitudes, TCAS assumes that the pilot is following the initial RA, and an increased rate must be attempted prior to a reversal.

This analysis shows that despite the unusual sequence of events, the RA was issued in a timely manner and TCAS did perform as intended in the MOPS. The surprising RA selections are a result of pilot non-compliance and TCAS Version 7.0 assuming compliance when selecting the RA.

# 6. ANALYSIS OF 1090 MHz EXTENDED SQUITTER

## 6.1 OVERVIEW

Monitoring at 1090 MHz allows examination of 1090 MHz ADS-B transmissions that are not recorded by Mode S ground sensors. If ADS-B data is shown to meet certain criteria, this data will likely be used to enhance future collision avoidance systems.

Squitters are Mode S downlink replies that are broadcast by an aircraft's Mode S transponder at specific intervals. There are two types of squitters: short (56-bit) DF11 transmissions or "acquisition squitters" which contain the aircraft address and are transmitted once per second by every Mode S transponder, and long (112-bit) DF17 transmissions or "Extended Squitters" (ES) which contain the same information as short squitters plus an extra 56-bit message field. The content of the ES 56-bit message field determines the transmission rate for the message.

The minimum ADS-B message set, as defined by RTCA DO-260B [7] and FAA TSO C-166b [8], consists of six basic ES messages (see Table 6).

**TABLE 6**

**Basic Six Extended Squitter Messages or Minimum ADS-B Message Set**

| Mode S Transponder Register Number | Register Name | Frequency of Transmission |
|---|---|---|
| 0,5 | Airborne Position | 2/sec |
| 0,6 | Surface Position | 2/sec if moving;<br>every 5 sec if stationary |
| 0,8 | Aircraft Identification and Category | every 5 sec if moving;<br>every 10 sec if stationary |
| 0,9 | Airborne Velocity | 2/sec |
| 6,5 | Aircraft Operational Status | Version 0: every 1.7 sec<br>Version 1: every 2.5 or 0.8 sec |
| 6,1 | Extended Squitter Aircraft Status* | event driven |

*Previously called Emergency / Priority Status

## 6.2 RESULTS

### 6.2.1 Extended Squitter Availability

Extended Squitter availability questions to be answered include: (1) the percentage of Mode S aircraft in the JFK airspace that transmit any of the six basic ES messages, and (2) which of the six basic ES messages are transmitted.

Figures 42 and 43 below show, by country, the number of unique Mode S aircraft observed during the April 2011 JFK data collection that transmitted any of the six basic ES massages. The blue portions of the bars represent aircraft that were reporting both acquisition squitters and Extended Squitters. The green portions of the bars represent aircraft that were reporting only acquisition squitters. Note in Figure 43 most countries have a high percentage of ES reporting. This is expected since an ADS-B mandate in Europe is anticipated, and ES is most often implemented in conjunction with Elementary Surveillance (ELS, mandated 31 March 2008) and / or Enhanced Surveillance (EHS, mandated 31 March 2009). As shown in Figure 42, the US and Canada have a low percentage of ES reporting.* Overall, approximately 25% of the Mode S aircraft within the coverage of the Lincoln 1030 / 1090 receiver at JFK report at least some type of ES message. This is shown in Figure 44.

**Note that this 25% is slightly different from the ADS-B equipage percentages given in Section 3 of this report. The reason for the difference is that the Section 3 computations were based on combined radar/omnidirectional data, with range limited to the 60 NM range of the radar. Figure 44 represents data from the larger coverage area of the omnidirectional receiver, with ranges of up to 300 NM.*

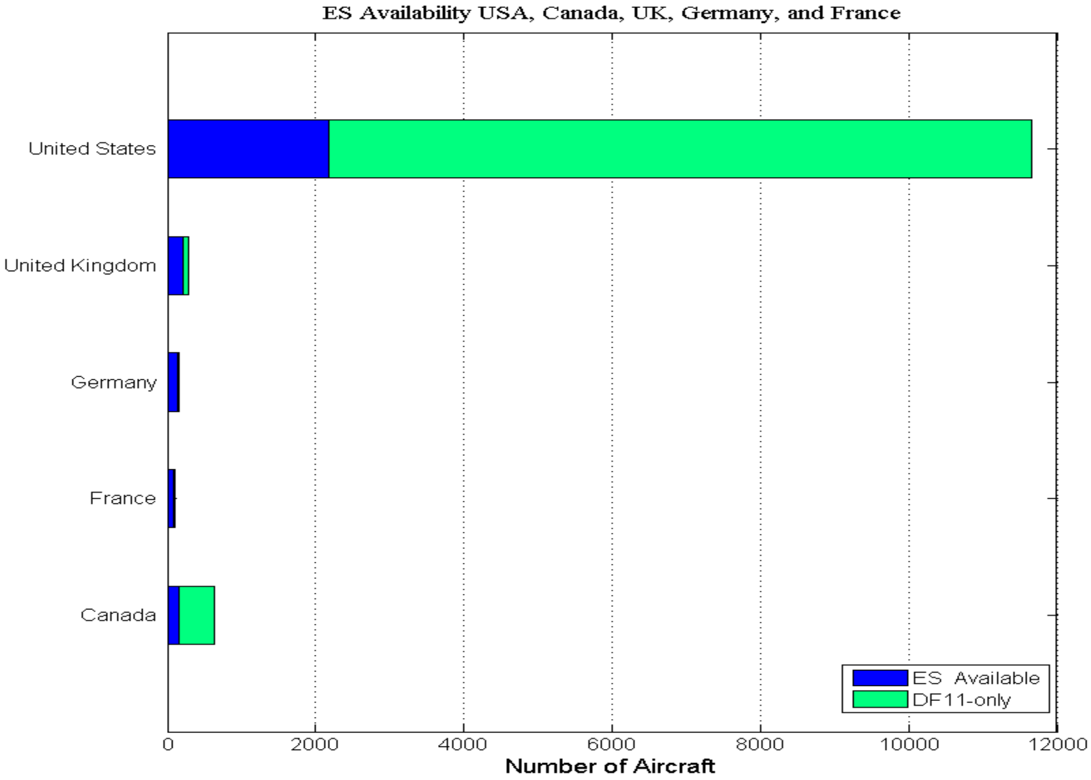

*Figure 42. ES availability by country (US, UK, Germany, France, Canada).*

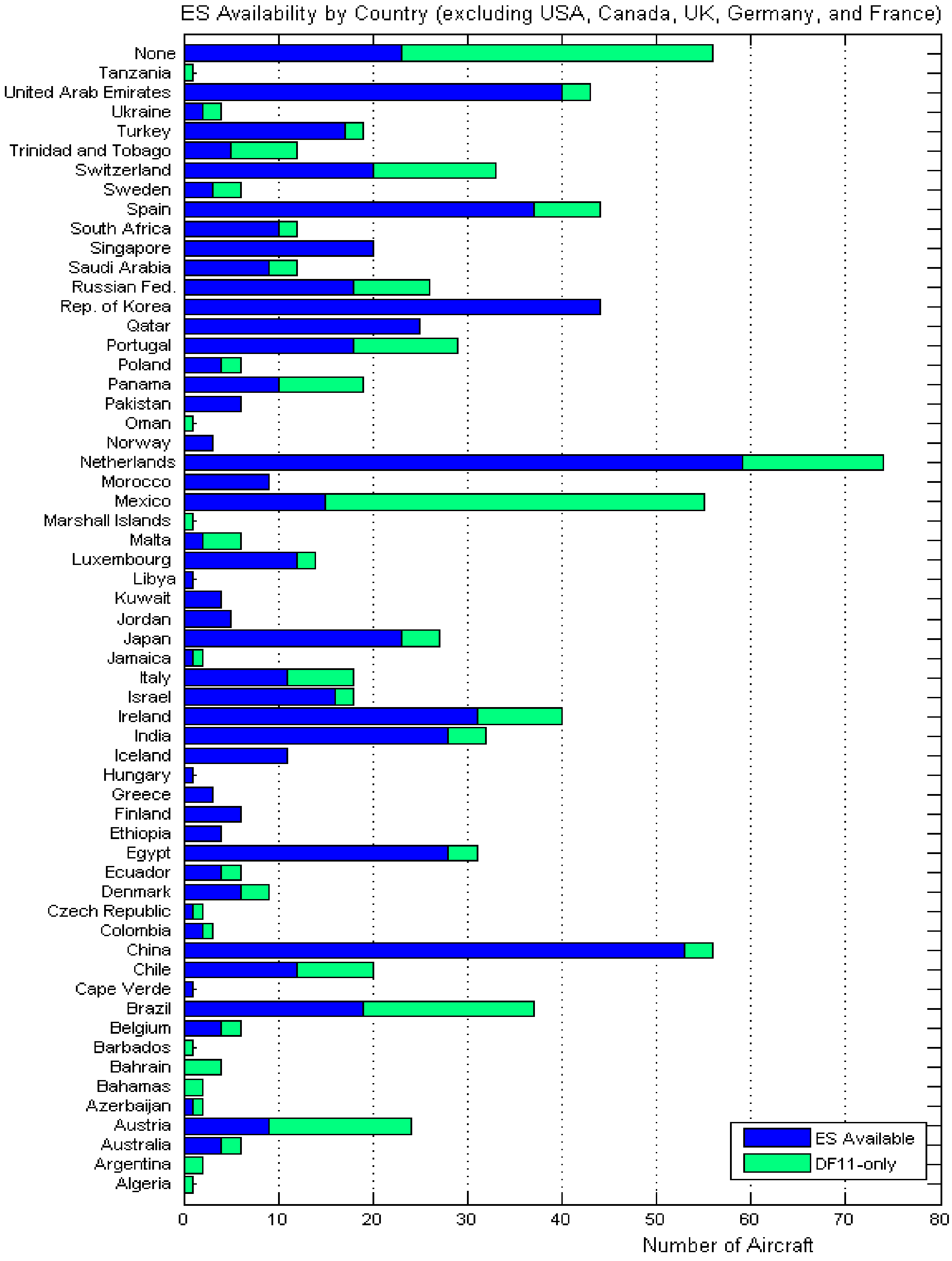

*Figure 43. ES availability by country (excluding US, Canada, UK, Germany, and France).*

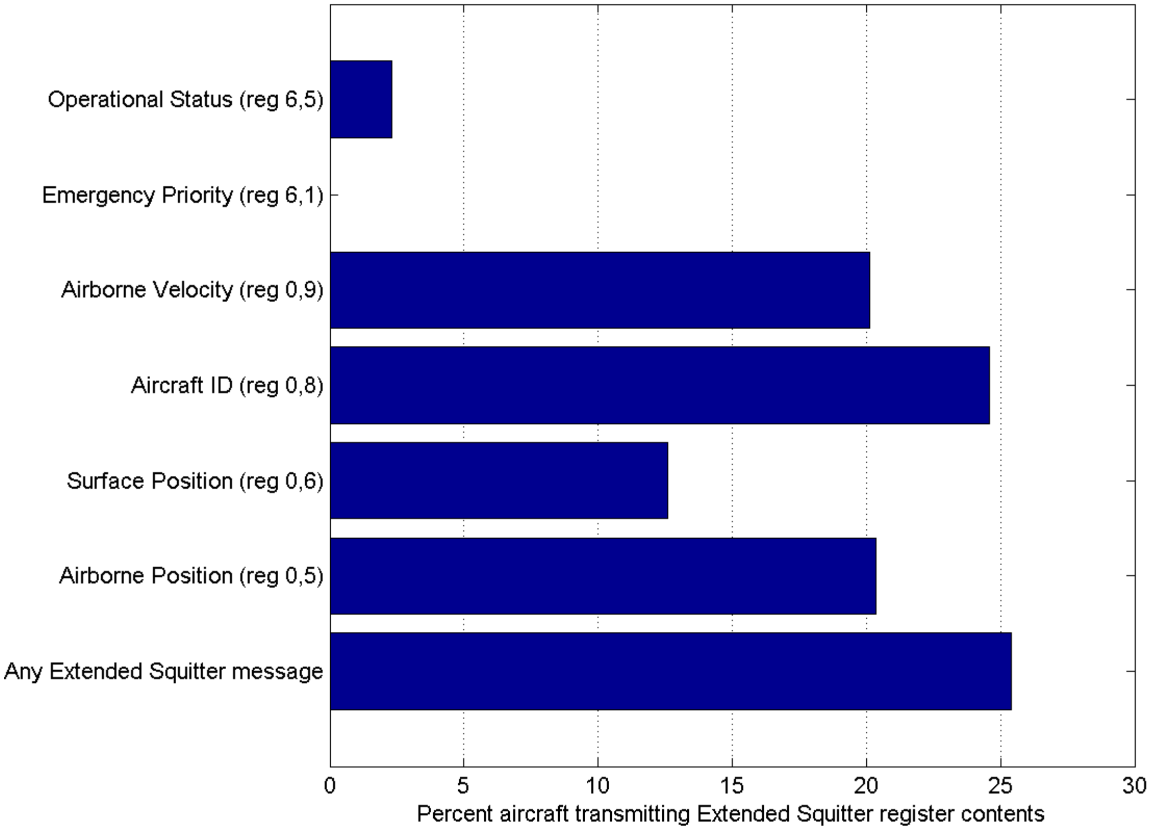

*Figure 44. Extended Squitter statistics (percent of aircraft transmitting specific ES messages).*

### 6.2.2 Aircraft Operational Status Messages

Aircraft Operational Status Messages contain some fields which are of potential interest to TCAS. The transponder version indicates which information may be available from the aircraft. Figure 45 displays the reported Navigation Accuracy Category – position (NAC-p) values reported during 28 April 2011 for US aircraft.

Table 7 provides a summary of the meaning of each NAC-p value. Aircraft reporting “unknown accuracy” are expected to be excluded from certain ADS-B applications.

## TABLE 7

## NAC-p Summary

| NAC-p value | EPU | Meaning |
|---|---|---|
| 0 | Unknown | Unknown accuracy |
| 7 | 0.05 <= EPU < 0.1 nmi | RNP 0.1 accuracy |
| 8 | 30 <= EPU < 92.6 meters | GPS (with SA) |
| 9 | 10 <= EPU < 30 meters | GPS (SA off) |
| 10 | 3 <= EPU < 10 meters | WAAS |

Figures 45 and 46 provide information on NAC-p values reported by aircraft in the JFK airspace on 28 April 2011. Figure 45 contains NAC-p values reported by US aircraft, Figure 46 provides NAC-p values reported by non-US aircraft.

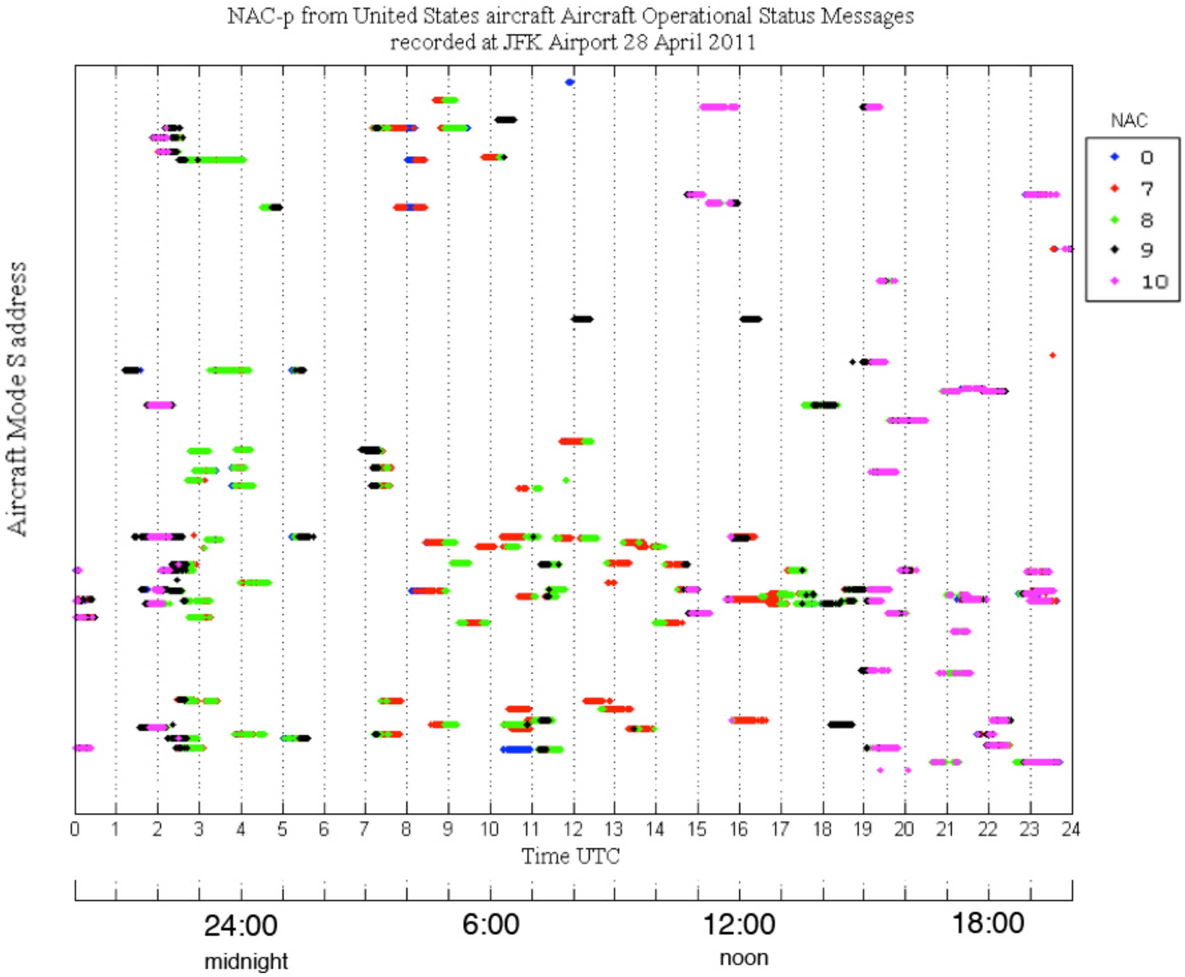

*Figure 45. NAC-p from US aircraft Operational Status Messages recorded at JFK, 28 April 2011.*

The results in Figure 45 indicate certain patterns. There is a preponderance of purple (high accuracy) during the period 15:00 to 21:00 local time and a preponderance of green (less accuracy) between 23:00 and 01:00 local time. This could be explained by one or two particular airlines dominating the air traffic in those time periods.

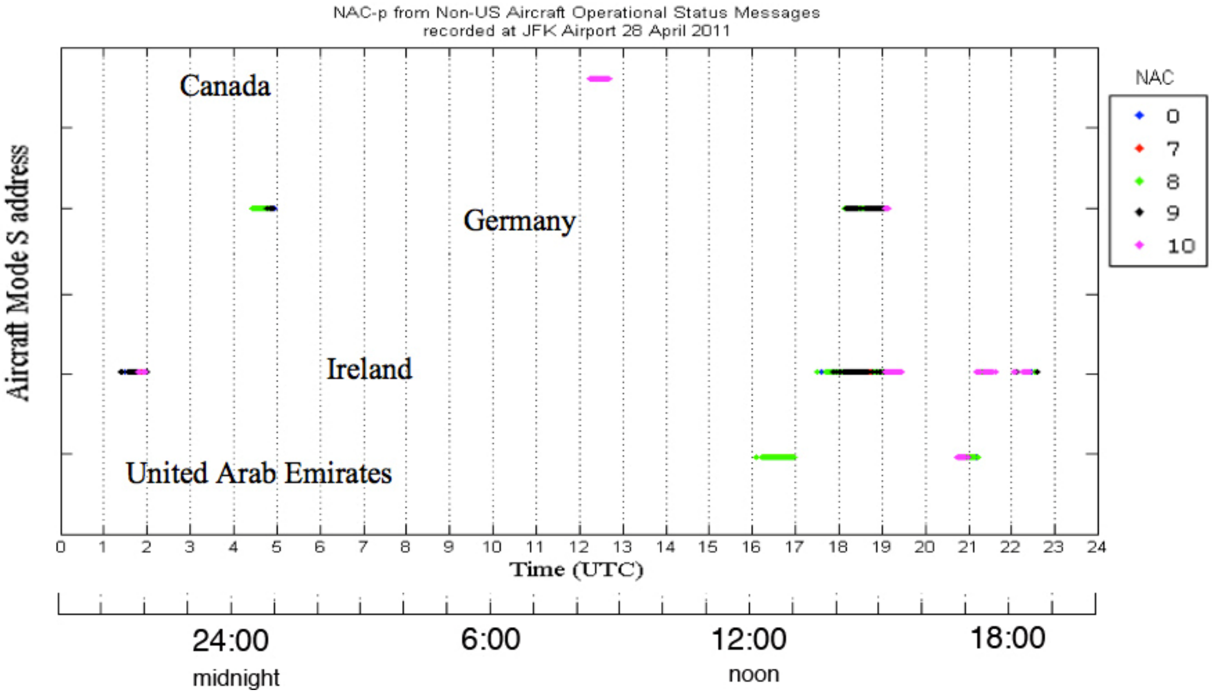

*Figure 46. NAC-p values for non-US aircraft.*

Figure 46 shows the NAC-p values reported by seven non-US aircraft on 28 April 2011. Canada (top) and the United Arab Emirates (bottom) each have a single aircraft. There are two aircraft from Germany. Ireland has one aircraft near 1:00 AM UTC, and two other aircraft that appear concurrently between 17:00 and 19:00 UTC, and again separately between 21:00 and 23:00 UTC.

Another conclusion from this data is that very few aircraft in this airspace had NAC=0, which means accuracy-unknown. In other words, nearly all of the aircraft transmitting position messages with NAC values had some declared accuracy.

# 7. SUMMARY

The direct measurements made at JFK in New York are shown in Figures 13 through 15 (omnidirectional reception rate) and Figures 10 and 11 (number of aircraft). Each of these figures shows the measured rate every hour of every day over the 25 days of measurements. In addition to the direct measurements, analysis using both radar data and omnidirectional data together made it possible to determine several interesting percentages and conclusions.

Mode S equipage. Among all transponder equipped aircraft, 88 percent were equipped with Mode S, and the remaining 12 percent were equipped with ATCRBS. The New York Mode S percentage is much higher than the value measured in the Boston area, where Mode S aircraft made up approximately 50 percent of the total population.

TCAS equipage. Among Mode S aircraft, 86 percent were equipped with TCAS.

ADS-B equipage. Among Mode S aircraft within 60 NM of JFK, 18 percent were equipped with ADS-B transmitting position messages. A slightly higher percentage, 20 percent, were transmitting at least some ADS-B message formats. Among Mode S aircraft in the larger omnidirectional reception area, approximately 25 percent of Mode S aircraft were transmitting some ADS-B message formats. The corresponding percentage in the Boston area is approximately 28 percent. In the New York data, it was also found that for nearly all of the aircraft transmitting position messages, the message included some declared value of position accuracy.

TCAS on the airport surface. It was found that many aircraft were continuing to operate TCAS while on the airport surface at JFK. Continuing TCAS operation on the airport surface is at variance with the spectrum approval of TCAS. Measurements showed that on average, during peak times, 20 to 30 aircraft were operating TCAS on the surface, and a maximum close to 45 was observed. These large numbers help to explain why the Mode S reply rate is high in the JFK area, and also why the TCAS count is often very high when flying in this area in view of the three major metropolitan airports.

Reply types. Different Mode S reply types are determined by the DF code, which is contained in the first 5 bits of the Mode S transmission. Sorting the Mode S receptions by reply type, it was found that replies to TCAS were the most common type. Replies to TCAS were significantly more common than replies to radars, and they constitute about 60 percent of all Mode S reply types. Short squitters (DF11 transmissions with II code = 0) were found to make up approximately 10 percent of all reply types. Extraneous short squitters (squitters transmitted beyond the expected 1 per second) were found to be about 5 percent of all reply types.

Aircraft density. The density of aircraft was found to be highest at JFK, diminishing monotonically as a function of distance away from JFK. Expressed as a function of range, the cumulative number of aircraft grows linearly with range, having a rate of about 3 aircraft per NM of range away from the radar at JFK airport.

<u>ADS-B messages</u>. An examination of ADS-B receptions shows that aircraft from many different countries appeared in the New York airspace. For most of those countries (with the US being a notable exception), the majority of aircraft were equipped with ADS-B. These countries are listed, along with the number of aircraft detected from each country and the percentage that are equipped with ADS-B.

<u>TCAS coordination messages</u>. TCAS coordination messages were received by the omnidirectional receiver, providing an opportunity to study coordination exchanges in TCAS-TCAS encounters. During the 25-day measurement period, 87 TCAS-TCAS encounters were observed, a TCAS-TCAS encounter rate four times greater than in the Boston area. In the most basic sense, TCAS coordination was successful in every case; i.e., the up/down maneuver sense was correctly communicated between the two aircraft, and when both aircraft selected Resolution Advisories, the two RAs were compatible. It was rare but there were cases (2 encounters) in which the up-down sense of the coordination was reversed after the initial coordination. No TCAS-TCAS encounters involved multiple threats. Previously identified coordination anomalies were observed at JFK with similar frequency to observations made in Lexington, MA. In one encounter, a significant degradation in the communication link was observed; this will be investigated.

The results from this report are being used in a number of significant ways:

- Recorded JFK surveillance data is being used to support the work of RTCA SC-147 in developing revisions to TCAS standards documents.
    - JFK data has been used to supplement radar recordings for building a comprehensive aircraft environment for input into the Lincoln Laboratory TCAS surveillance simulation. Simulation findings have led to proposed modifications which can dramatically reduce TCAS 1030/1090 MHz spectrum usage.
    - First-time information about on-ground TCAS operation has led to proposed modifications requiring on-ground TCAS aircraft to limit their active interrogation power and to use passive ADS-B surveillance when possible.
- Data related to TCAS surveillance is being used in the development of surveillance algorithms for ACAS X, the next-generation collision avoidance system under development by the FAA TCAS Program Office.
- Examination of specific 1030 and 1090 transmissions has supported and will continue to support the FAA Certification Office in analysis of equipment anomalies.
- The understanding of the relationship between ground-based and airborne 1030/1090 measurements made possible by this data collection is expected to enable greater future use of

ground-based measurements in place of the more expensive and time-limited airborne flight testing.

- Data recorded at JFK can provide an independent check of fruit models generated from airborne measurements and serves as a resource for FAA spectrum activities underway.

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# GLOSSARY

| | |
|---|---|
| ADS-B | Automatic Dependent Surveillance-Broadcast |
| ARA | Active Resolution Advisory |
| ATCRBS | Air Traffic Control Radar Beacon System |
| ES | Extended Squitter |
| FRUIT | False Replies Uncorrelated in Time |
| MOPS | Minimum Operational Performance Standards |
| NAC-p | Navigational Accuracy Category – position |
| NAS | National Airspace System |
| NIC | Navigational Integrity Category |
| NTA | Number of TCAS Aircraft |
| NUC | Navigational Uncertainty Category |
| PSR | Primary Surveillance Radar |
| RA | Resolution Advisory |
| RAC | Resolution Advisory Complement |
| SSR | Secondary Surveillance Radar |
| TA | Traffic Advisory |
| TCAS | Traffic Alert and Collision Avoidance System |
| TOPA | TCAS Operational Performance Assessment |
| TRAMS | TCAS RA Monitoring System |
| TSO | FAA Technical Standard Order |
| UTC | Coordinated Universal Time |
| VRC | Vertical Resolution Advisory Complement |
| WJHTC | FAA William J. Hughes Technical Center |

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# APPENDIX A
# THALES RECEIVER MODIFICATIONS

## A.1 SIDE BY SIDE COMPARISON

In 2009, under sponsorship of the FAA TCAS Program Office, MIT Lincoln Laboratory began operating a prototype system to monitor 1030/1090 MHz activity in the New England airspace. The system is located at Lincoln Laboratory in Lexington, MA, and uses a Thales omnidirectional 1030/1090 MHz receiver to collect data for subsequent analysis and research pertaining to TCAS operation. Two reports [1,2] have documented 1030/1090 MHz activity to date in the New England area.

The FAA William J. Hughes Technical Center (WJHTC) also operates a 1030/1090 MHz monitoring system, referred to as the Data and Transponder Analysis System (DATAS), recently upgraded to become DATAS II. The WJHTC system can be used for airborne and/or ground monitoring. In addition to TCAS-related activities, it has been used to measure the 1030/1090 MHz interference environment in support of the FAA program for Automatic Dependent Surveillance – Broadcast (ADS-B). A recent WJHTC report [4] documented analysis of 1030/1090 MHz airborne data recorded during a Northeast Corridor flight test in 2007.

It is desirable, for all users of the results, that the 1030/1090 MHz measurements made by the two organizations be generally consistent. To that end, at the request of the TCAS Program Office, Lincoln Laboratory and WJHTC embarked on a side-by-side 1030/1090 MHz measurement program for the purpose of comparing and validating the two measurement systems.

The two measurement systems were installed together at a site near the Philadelphia International Airport Parallel Runway Monitoring (PRM) radar which is well away from the main terminal buildings. Both the Lincoln Laboratory and the WJHTC systems used omnidirectional antennas which were mounted on a van, as illustrated in Figure A-1.

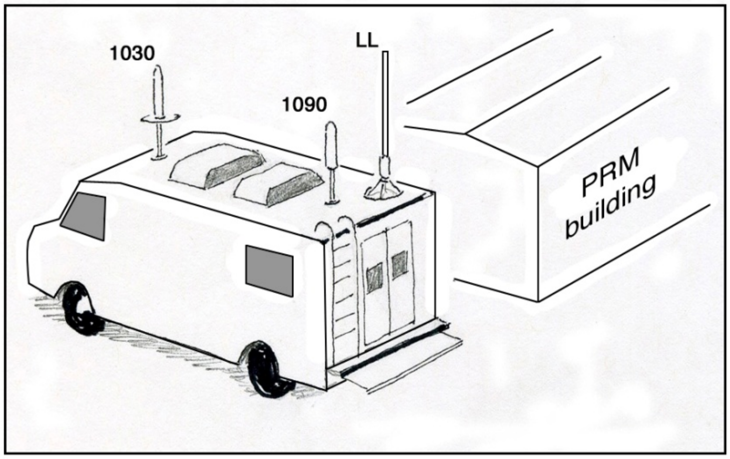

*Figure A-1. Installation of omnidirectional receiving antennas.*

The PRM tower was an obstruction to the omnidirectional receivers, and furthermore the site is not far from a number of trees that are higher than the receiving antennas. These obstructions, however, were inconsequential to the overall objective of the data collection, which was to compare the data recorded by the two systems. Therefore, the site was sufficient for this side-by-side comparison.

## A.2 MEASUREMENTS

An initial comparison of the side-by-side systems which focused on a single aircraft to determine basic system performance was performed. This analysis led to the conclusion that timing is calculated accurately by both systems, latitude CPR decoding is being performed correctly, and received power measurements are being made by the two systems that are reasonably consistent with each other and are in agreement with the theoretical received power levels that would be expected from an aircraft.

Knowing that the two systems agreed in basic measurements, the next step was to compare measurements of the whole environment, meaning receptions from all the aircraft in view. The first of such comparisons was the 1030 MHz and 1090 MHz Mode S reception rates as a function of time over a 90 minute period. Included in the reception rate were all uncorrected Mode S messages with a received power level (at the antenna) greater than –74 dBm on 1030 MHz and –84 dBm on 1090 MHz.

This analysis indicated that the general trends in measured reception rate agreed well. However, there was a very noticeable difference in the magnitude of the reception rate recorded by the two systems. The WJHTC receiver appears to measure more Mode S signals on the uplink and downlink channels by a ratio of roughly 2:1. To better understand this difference seen between the two systems, attention was focused on a single ‘snapshot’ of time. The 1030 MHz and 1090 MHz Mode S reception rate at 17:15:00

UTC was examined as a function of power and is shown in Figures A-2 and A-4 (WJHTC measurements) and Figures A-3 and A-5 (Lincoln Laboratory measurements). Since a moving average filter was applied to the temporal reception rate data, these figures in actuality represent an 11 second average centered at 17:15:00.

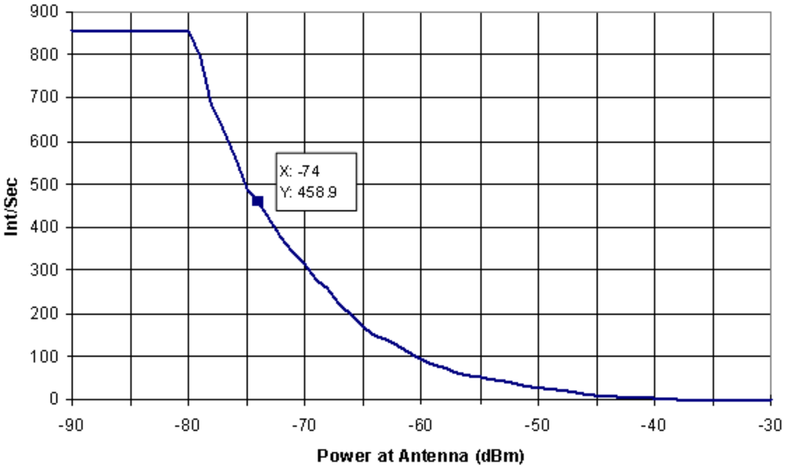

*Figure A-2. Measured power distribution of 1030 MHz Mode S receptions (WJHTC).*

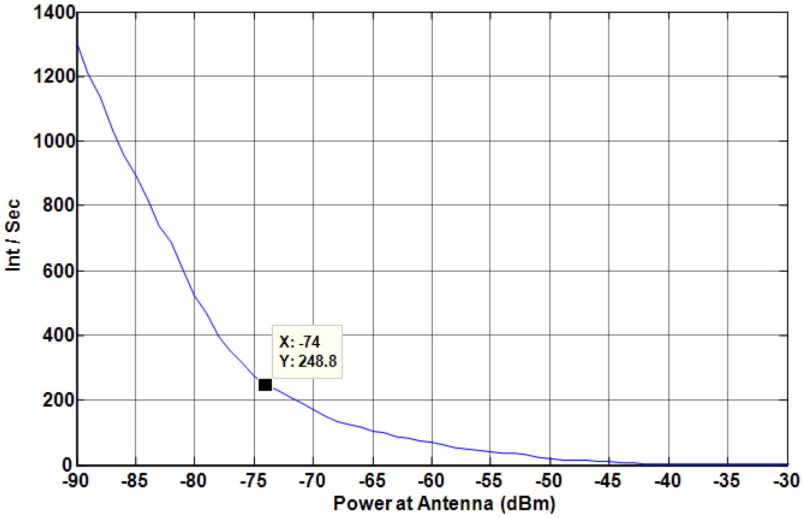

*Figure A-3. Measured power distribution of 1030 MHz Mode S receptions (Lincoln Laboratory).*

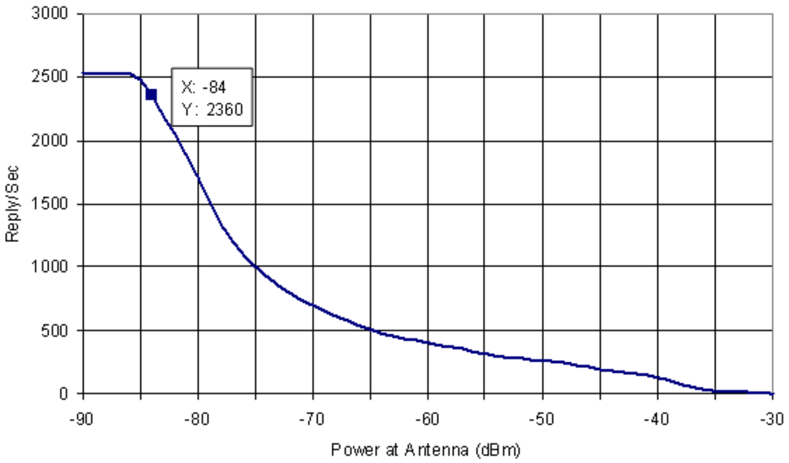

*Figure A-4. Measured power distribution of 1090 MHz Mode S receptions (WJHTC).*

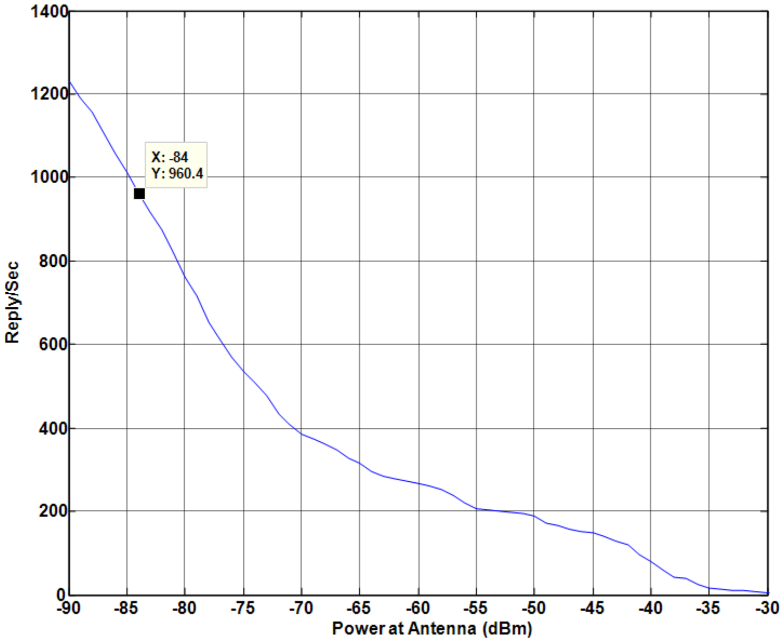

*Figure A-5. Measured power distribution of 1090 MHz Mode S receptions (Lincoln Laboratory).*

An additional observation of interest is that the two measured reception rates appear to diverge as the power level threshold decreases. For example, if a comparison were made using a threshold of –60 dBm on 1030 MHz or –50 dBm on 1090 MHz, the ratio of messages measured by WJHTC to the messages measured by Lincoln Laboratory is closer to 1:1.

This analysis of the data collected during this test showed that a large discrepancy existed in the 1030 and 1090 MHz Mode S reception rates produced by the two systems. Several minor factors were identified as contributing to this difference; however, these factors did not explain the ratio of roughly 2:1 observed in the results. Further in depth investigation of data revealed key insight into the configuration of the two systems that accounted for the majority of this difference.

## A.3 DIFFERENCES

The predominant reason attributed to causing the 2:1 difference in the results was the nature of the Thales receiver to discard messages considered not useful to an end user. This behavior of the receiver reflects upon its intended function, to provide only messages that can be acted upon.

On 1030 MHz, the WJHTC receiver recorded Mode S uplink messages that were not decoded. In other words, the WJHTC reception rate measurements included instances where power was detected on the 1030 MHz carrier frequency, but a Mode S message was not decoded from the signal. The second difference noted in the one minute of 1030 MHz Mode S data was the WJHTC data set included messages that were noted as having a P5 suppression pulse overlaid on the Mode S message. The purpose of the P5 pulse is to prevent a transponder from receiving an interrogation when it is not in the main beam of the interrogation source. The Thales receiver would have discarded many such messages as they would contain no usable data.

On 1090 MHz, the WJHTC receiver recorded Mode S downlink messages with any number of low confidence bits. The Thales receiver was configured to only record messages that contained no low confidence bits. As seen in Figure A-6, messages with low confidence bits accounted for a significant fraction of the total number of 1090 MHz receptions made by the WJHTC receiver.

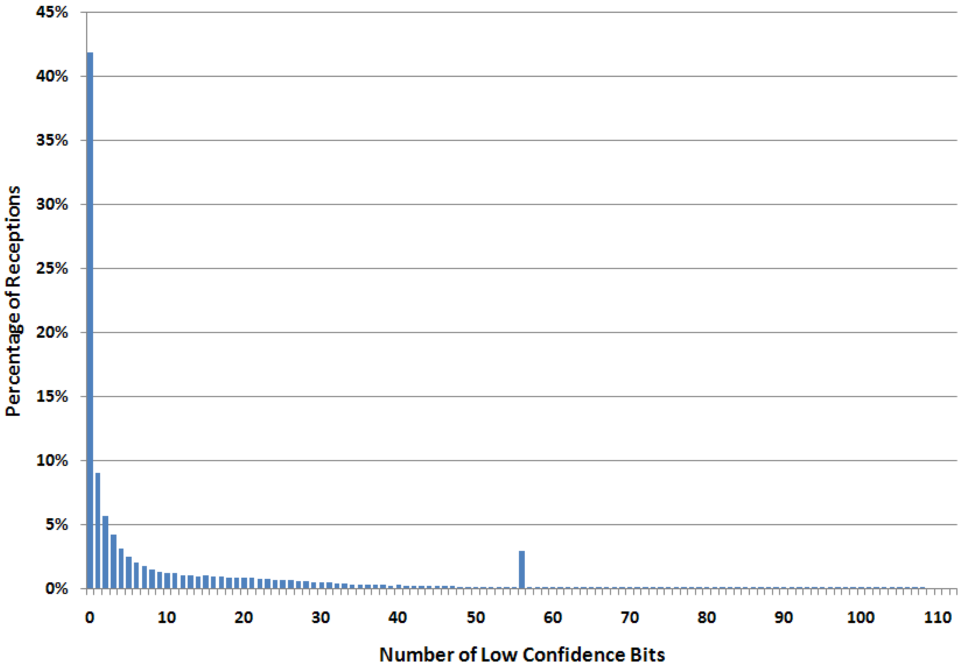

*Figure A-6. Low confidence bits in 1 minute of WJHTC 1090 MHz Mode S receptions.*

A difference noted between the two data sets on both 1030 and 1090 MHz involved the threshold that was used to calculate the reception rate (–74 dBm on 1030 MHz and –84 dBm on 1090 MHz). For example, on 1090 MHz, due to the quantized power levels recorded by the Thales receiver and the correction factor used to remove cable loss, the Lincoln Laboratory reception rate was calculated to only include those messages that were received with a power level greater than or equal to –83.2 dBm. The WJHTC reception rate was calculated by first rounding the received power of each message to the whole integer and then applying the –84 dBm cutoff. This method effectively calculated the 1030 MHz Mode S reception rate with slightly more sensitive threshold of –84.5 dBm. A similar threshold discrepancy occurred on 1030 MHz

Figures A-7 and A-8 are visual representations of these differences seen between the two measurements. The original calculated receptions rates measured by the WJHTC are plotted alongside the Lincoln Laboratory measured rates. A filter was applied to the original WJHTC data set to resolve the differences described above. The figures demonstrate the results of applying this filter to the WJHTC data set. As can be seen, when this filter was applied to the one minute of WJHTC data, the 1030 MHz Mode S reception rate measured by WJHTC and Lincoln Laboratory agree to within approximately 3%. The adjusted 1090 MHz Mode S reception rate measured by WJHTC and Lincoln Laboratory agree to within approximately 5%. This is an encouraging finding that demonstrates the reception capability of the two systems is far more common than initial results suggested.

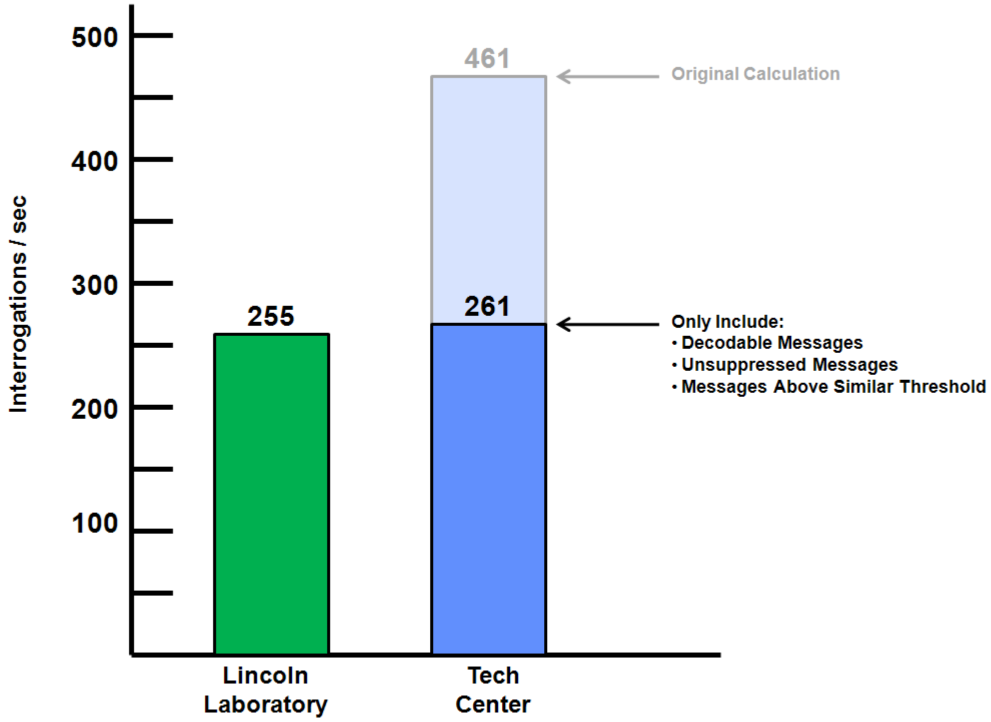

*Figure A-7. Adjusted difference in 1 minute of 1030 MHz Mode S reception rate.*

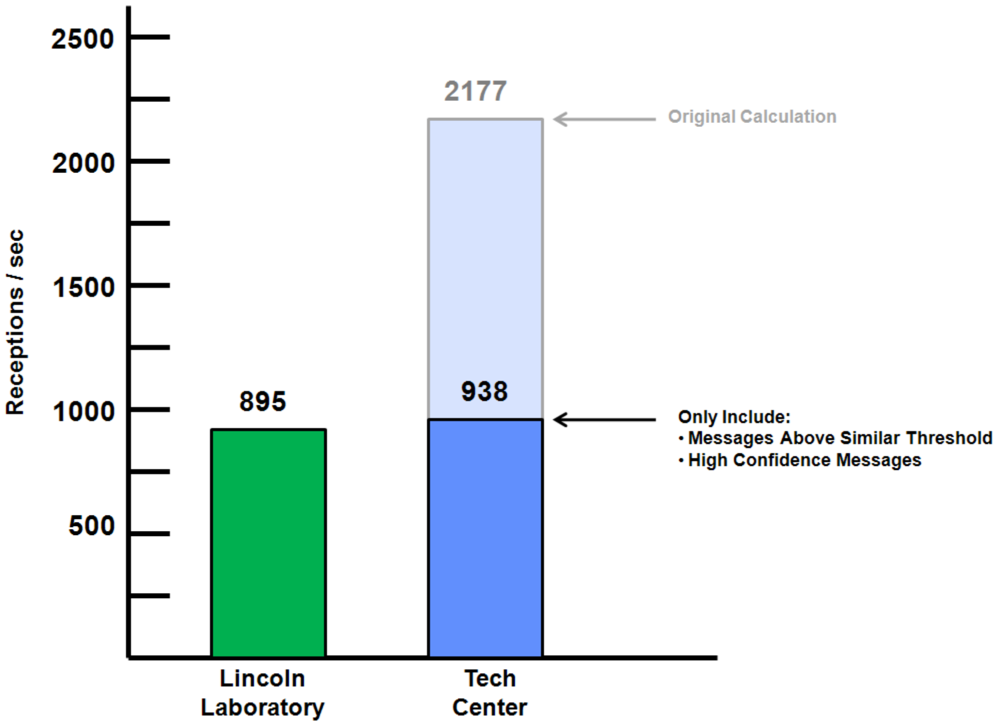

*Figure A-8. Adjusted difference in 1 minute of 1090 MHz Mode S reception rate.*

The difference in the configuration used by the two systems in no way implies that one system was operating incorrectly. While the reception rates recorded by Lincoln Laboratory included only those messages that contained data useful to an end user, the reception rates recorded by the WJHTC receiver are more representative of the Mode S FRUIT (False Replies Uncorrelated In Time) present in the environment. This suggests that the configuration of a receiver is dependent on the intended function of the measurement being taken. Since the intended use of the Thales receiver by Lincoln Laboratory is to analyze the contents of Mode S messages, the receiver had not been configured in such a way as to record all of the additional messages that may constitute the FRUIT environment.

## A.4 MODIFICATIONS TO THE LINCOLN LABORATORY RECEIVER

As a result of this analysis, Lincoln Laboratory has worked closely with Thales to configure the receiver to record 1030 and 1090 MHz Mode S data in a more similar fashion to the WJHTC receiver. By doing so, Lincoln Laboratory will have the capability to measure Mode S reception rates that are more representative of the Mode S FRUIT environment.

The configuration change made to the Thales receiver was achieved through two different mechanisms. The first mechanism required a modification to user settings provided by a computer program that interfaces directly with the 1030 and 1090 MHz receiver cards. As this program was not specifically designed to accomplish the task at hand, the available settings were limited and did not allow Lincoln Laboratory to make all of the necessary changes to the receiver. For this reason, Thales provided Lincoln Laboratory with the means to control the system at a much more detailed level.

To quantify the difference made by the configuration updates, data was collected at the normal installation for the Thales receiver atop Kathadin Hill in Lexington, MA. More information pertaining to this installation is provided in [2]. This data collection showed approximately a 15% increase in 1030 MHz Mode S message receptions. It was expected that this relative increase in receptions will be more substantial in an environment with greater interference, such as Philadelphia International Airport or JFK, as interference induced low confidence bits are the primary reason messages had been discarded.

The data collection exhibited a similar increase in 1090 MHz Mode S receptions. Figures A-9 and A-10 demonstrate the effects of operating the receiver with and without the configuration changes.

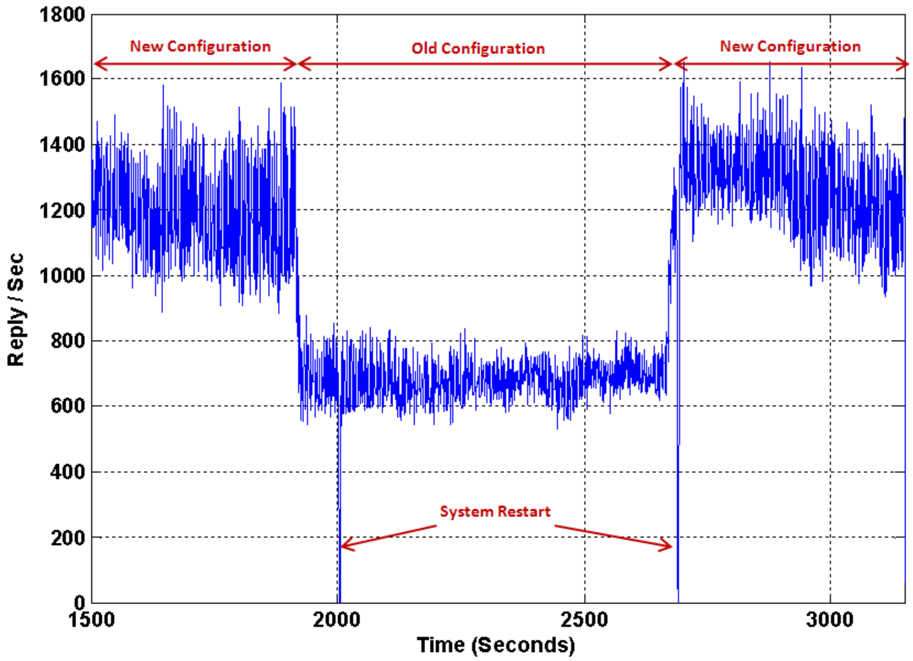

*Figure A-9. 1090 MHz Mode S reception resulting from configuration modification.*

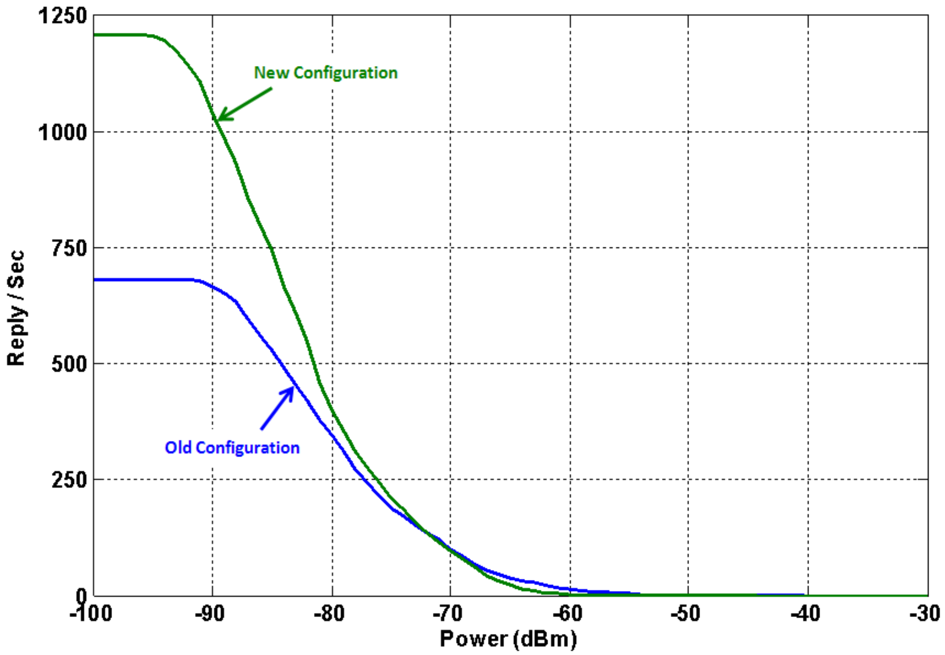

*Figure A-10. 1090 MHz Mode S power distribution resulting from configuration modification.*

Figure A-9 provides the 1090 MHz Mode S reception rate as a function of time. The horizontal axis is given as seconds elapsed since the beginning of the experiment. No power level threshold was applied to the reception rate calculation shown in Figure A-9. At the beginning of the experiment, the Thales receiver was operating with the new modified configuration. At approximately 1900 seconds into the experiment, the receiver was reverted to the old configuration. Finally, at approximately 2700 seconds, the receiver was modified once again to the new modified configuration. The vast change in reception rate seen at the transition points represents the relative increase in 1090 MHz Mode S reception rate using the modified receiver configuration.

Figure A-10 is the cumulative 1090 MHz Mode S power distribution with and without the configuration changes to the Thales receiver. As the figure shows, the receiver clearly records more receptions due to the modifications to the configuration. The observation should be made that the relative difference in receptions between the two configurations increases as the power threshold decreases. This divergence can be attributed to the fact that low power messages are more likely to be interfered with and thus more likely to have low confidence bits and be discarded by the Thales receiver when it is configured with the old settings.

Two additional important observations should be made regarding the 1090 MHz Mode S data. First is that the data shown in Figures A-9 and A-10 is not comparable to the data recorded in Philadelphia as the two measurements were taken in very different aircraft environments. Second, if this experiment were performed at the Philadelphia International Airport or JFK, the divergence described above would be more substantial and would begin at a lower power level since the interference environment in that location is more significant. Therefore, the relative increase in receptions shown in Figure A-9 does not correspond directly to the relative increase that would be expected in Philadelphia or JFK.

# APPENDIX B
# TCAS OPERATION ON THE AIRPORT SURFACE

## B.1 INTRODUCTION

In the spring of 2010, RTCA Special Committee 147 (SC-147) reconvened after an extended hiatus. The new terms of reference (TOR) that were drafted for the committee included the following deliverable:

> *Changes to the Hybrid Surveillance and/or TCAS II MOPS as necessary so as to prohibit the increase in TCAS interrogation power when interrogation rates have been decreased during operation of passive surveillance.*

MIT Lincoln Laboratory has worked closely with the RTCA SC-147 Surveillance Working Group (SWG) over the past year to perform the analysis necessary to satisfy this deliverable. The scope of our work has encompassed two main areas:

1. To develop a modification to the TCAS surveillance algorithms that addresses the deliverable defined by the TOR. The product of this effort is known as the Channel Optimization and Limiting for TCAS (COLT) algorithm.
2. To understand the impact associated with implementing a modification to the TCAS surveillance algorithms.

Also included within the scope of the SC-147 TOR is to provide recommendations that would:

> *Reduce the radio frequency congestion at 1090 MHz.*

Several surveillance modifications to TCAS version 7/7.1[3] (DO-185B [9]) and TCAS Hybrid Surveillance (DO-300 [10]) to satisfy the SC-147 TOR have been explored and documented within the committee.

A major part of the surveillance modification analysis is accomplished through the use of a high fidelity TCAS surveillance simulation. The simulation models TCAS surveillance activity onboard aircraft. As changes are made to the surveillance algorithms, the TCAS activity on aircraft is analyzed to determine the impact of the modifications. Traditionally, the simulation uses an input of aircraft tracks fused from recordings from multiple radars; however it is recognized that the radar recordings do not

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[3] The surveillance requirements for TCAS II version 7 and version 7.1 are identical.

include comprehensive data from aircraft that are operating on the airport surface. Recently MIT Lincoln Laboratory performed a month long data recording exercise of the 1030 and 1090 MHz channels at JFK airport in New York, NY during April 2011. This data was leveraged to supplement the radar datasets with information about Mode S transponder and TCAS operation on the airport surface. This report describes the process of extending a radar dataset to include operation of aircraft on the airport surface using the information gathered from the Lincoln Laboratory 1030/1090 MHz recordings.

Section B.2 provides an overview on how the 1030/1090 MHz recordings were analyzed along with radar datasets to find distributions of Mode S and TCAS activity on the airport surface. Section B.3 shows the method and results of supplementing a specific radar dataset. Section B.4 gives an update on the TCAS surveillance simulation results with the new dataset. Section B.5 provides a summary.

## B.2 DATA RECORDING AT JFK

### B.2.1 Process

The following process was developed to characterize the operation of Mode S transponders and TCAS units on the airport surface. First, messages are identified from the 1030/1090 MHz recordings that can determine either Mode S or TCAS operation. Those message types are detailed in Table B-1. DF messages are on the 1090 MHz channel and UF messages are on the 1030 MHz channel. If one of the specified messages exists for a particular Mode S address, then it can be determined that the given aircraft is operating either its Mode S transponder or TCAS unit depending on the message.

**TABLE B-1**

**Messages Used to Determine Operation**

| **Mode S Messages** |
|---|
| DF0 Special Surveillance Reply (transponder reply to TCAS surveillance interrogation) |
| DF4 Altitude Surveillance Reply (transponder reply to Mode S ground radar) |
| DF5 Identity Surveillance Reply (transponder reply to Mode S ground radar) |
| DF11 Squitter (spontaneous once-per-second identification transmission from Mode S transponders) |
| **TCAS Messages** |
| DF0 Special Surveillance Reply (RI=2 or 3 indicates operational TCAS) |
| UF16 TCAS Broadcast Interrogation (identification transmission every 8–10 s by an operational TCAS) |

The next step is to create a timeline of activity for each aircraft. If messages are reliably received from an aircraft over a period of time, then the aircraft is determined to be operating during that time.

Once messages from the aircraft are no longer received reliably, the aircraft is determined to be powered off. This process is repeated for both Mode S and TCAS so that time periods for operation of each unit, for each aircraft, are constructed.

Once operation timelines have been established from the 1030/1090 MHz recordings, radar recordings of aircraft from the same time and location are used to identify aircraft taking off and landing at the airport. The 1030/1090 MHz recordings took place at JFK airport; therefore, recordings from the Mode S radar at JFK were used to gather aircraft positions. The radar data from the TCAS Resolution Advisory Monitoring System (TRAMS) at JFK was used as this dataset includes aircraft position data as well as the aircrafts' unique Mode S addresses. Aircraft takeoffs are identified by searching for aircraft that originate near the airport; range and altitude filters are used to make this distinction. Also it was verified that the aircraft have increasing range rate on average from the airport over the length of the track. Landing aircraft were detected in a similar manner, ending the track at the airport surface and decreasing range rate on average.

The aircraft tracks that have been identified as taking off or landing at the airport of interest are then matched up with the timelines of operation from the 1030/1090 MHz recordings using Mode S addresses. Length of operation of the radar track is compared with the 1030/1090 timeline. The additional time of operation present in the 1030/1090 data that is not included in the radar track is the information of interest. An example of a landing aircraft is seen in Figure B-1. In order to ensure that there is ample time considered to find the additional time of operation, at least one extra hour of 1030/1090 data after the TRAMS track ends is available. For example, TRAMS tracks in Figure B-1would end between hours 1 and 2, with 1030/1090 data continuing until hour 3.

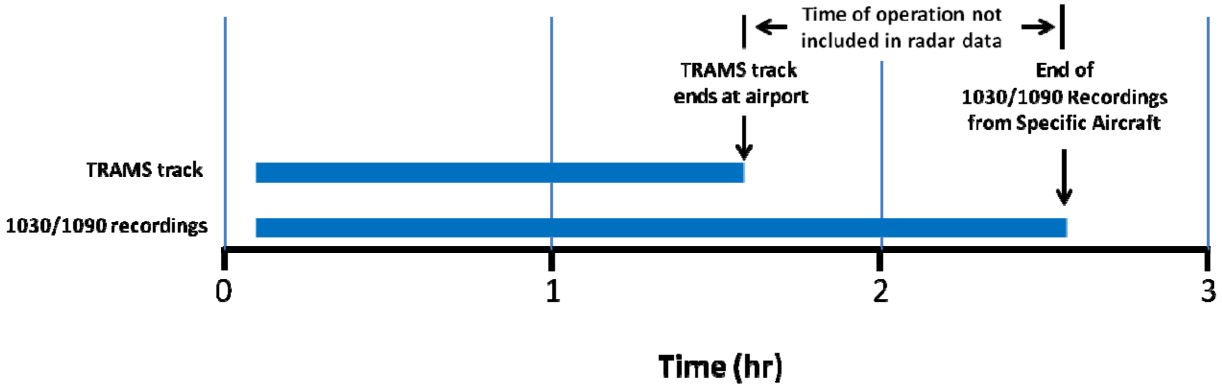

*Figure B-1. Example of determining on-ground operation of a landing aircraft.*

Since there is not a consistent amount of time after landing until the TRAMS radar track ends, the end of the 1030/1090 timeline is compared with the time in the TRAMS track when the aircraft transitions through 1000 feet in altitude during its decent to the airport runway. This way there will be a consistent point of reference to measure the time of operation. The "modified time of operation not included in radar data," as labeled in Figure B-2, is recorded for each landing aircraft and compiled into an empirical distribution. The distribution is created separately for each Mode S and TCAS operation. A similar procedure is repeated for aircraft taking off and also compiled into separate distributions.

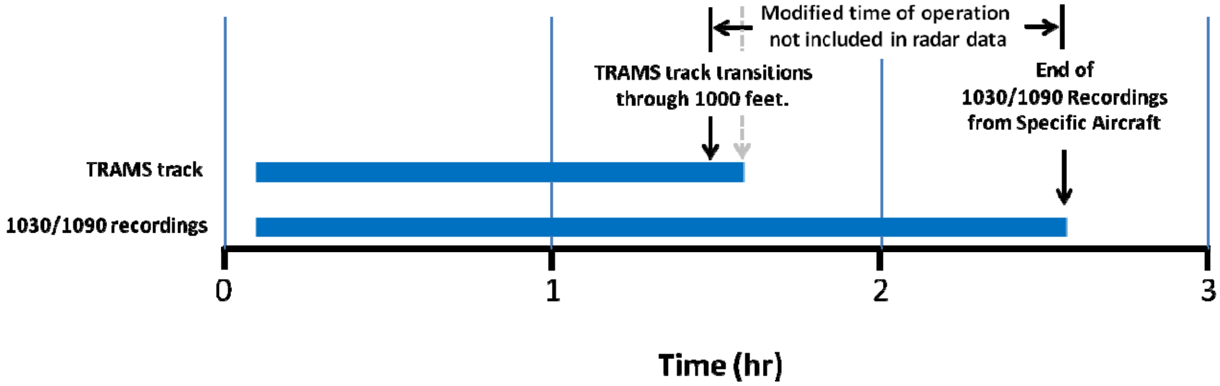

*Figure B-2. Example of determining on-ground operation of a landing aircraft.*

### B.2.2 Results

The 1030/1090 MHz recordings were performed for 24 days in April 2011. For this study the hours of 12:00 to 18:00 local time (EDT) were used as those times are consistently high traffic. The procedure for creating Mode S and TCAS empirical distributions of airport surface operation was performed for both taking off and landing aircraft. The TCAS distributions were compiled as the fraction of time the Mode S transponder was operating, as TCAS operation is dependent on Mode S operation. An example is if the Mode S transponder operated for 100 seconds after landing and the TCAS operated for 75 seconds after landing, then the TCAS result would be recorded as 0.75 or 75%. The empirical cumulative distribution functions (CDF) are shown in Figures B-3 through B-6.

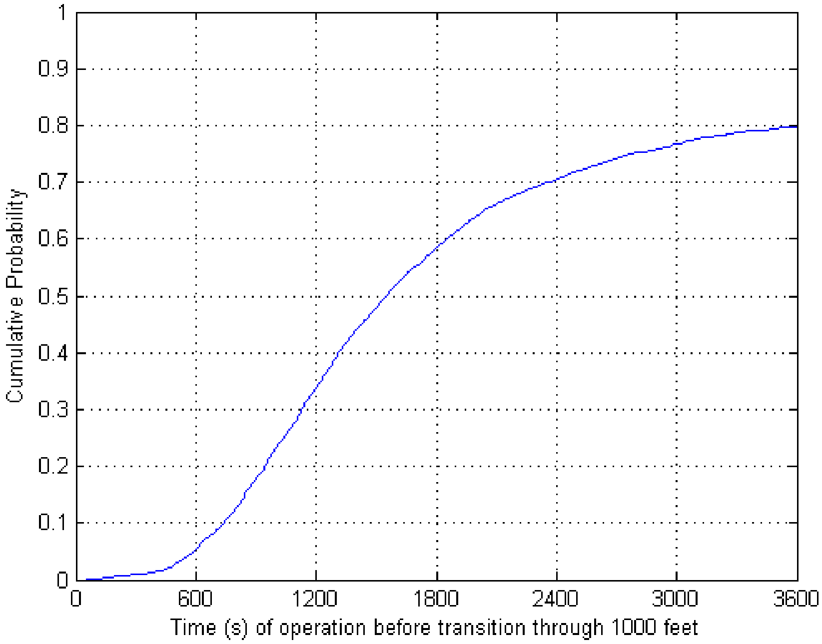

*Figure B-3. Mode S on-ground operation time, takeoff, empirical CDF.*

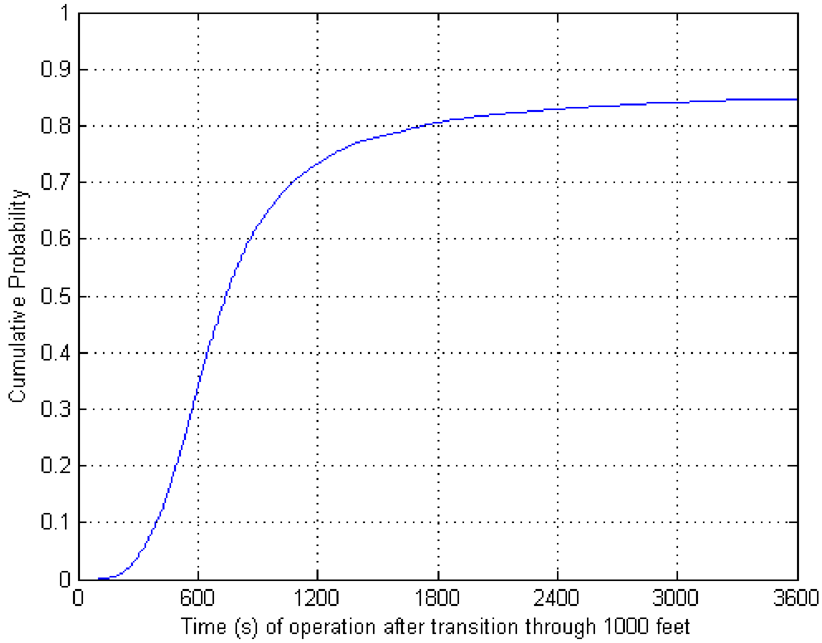

*Figure B-4. Mode S on-ground operation time, landing, empirical CDF.*

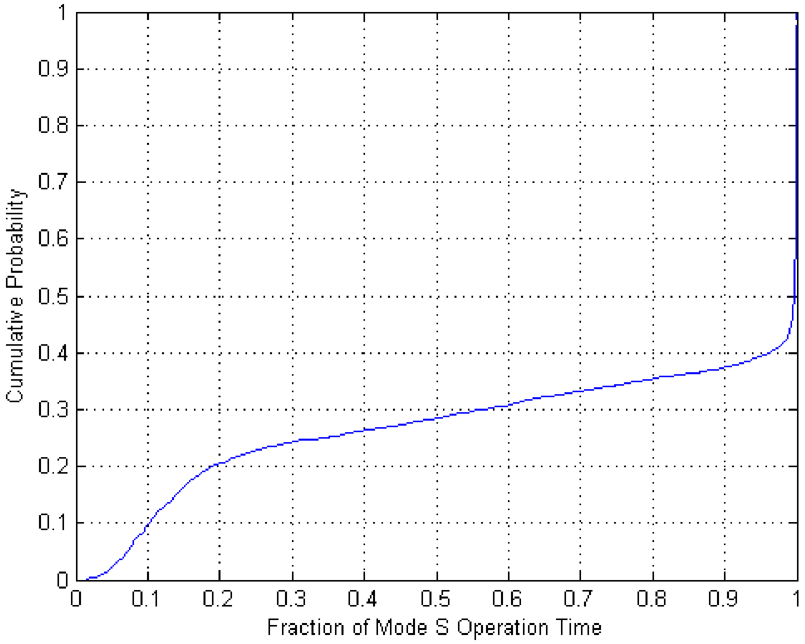

*Figure B-5. TCAS on-ground operation time, takeoff, empirical CDF.*

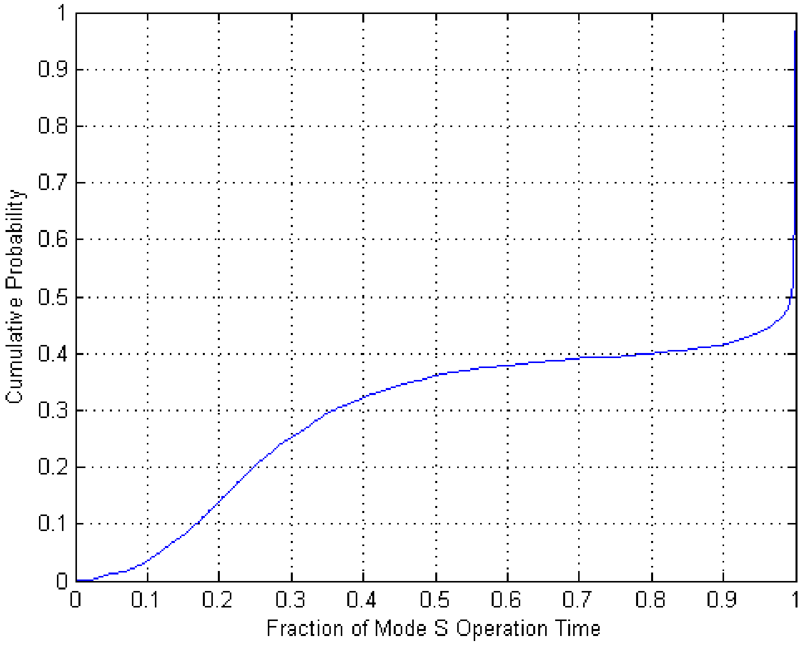

*Figure B-6. TCAS on-ground operation time, landing, empirical CDF.*

The Mode S cumulative distribution functions show the distribution up to 3600 seconds or one hour. As described in the previous section, due to the method of processing, the distribution can only be guaranteed to be accurate for times of operation of one hour or less. The fraction of aircraft that operate on the surface for greater than a period of one hour is defined by one minus the fraction that operate for less than one hour. Before takeoff approximately 20% of aircraft operate their Mode S transponder for a period of time greater than one hour, and after landing approximately 15% of aircraft operate their Mode S transponder for a period of time greater than one hour. On landing aircraft nearly 70% of aircraft operate their Mode S transponders for a period of less than 20 minutes, while before takeoff aircraft are likely to operate Mode S transponders for a longer period of time. Analysis of the TCAS distributions shows that for both before takeoff and after landing the TCAS unit is operated in unison with the Mode S transponder by approximately half of aircraft.

## B.3 DATASET MODIFICATIONS

This section describes the method of modifying the radar dataset previously used for TCAS analysis of a high aircraft density environment (JFK area from 17:00 to 18:00 EST November 29, 2009 [11]) to include a more accurate representation of Mode S and TCAS operation on the airport surfaces.

### B.3.1 Method

The procedure to modify the dataset involves sampling from the cumulative distribution functions (CDF) that were developed in the previous section. The first step is to identify aircraft taking off and landing at airports of interest within the dataset. For this dataset the major airports chosen were John F. Kennedy International Airport (JFK), Newark Liberty International Airport (EWR), and LaGuardia Airport (LGA). The assumption is made that aircraft on the airport surfaces at JFK, EWR, and LGA in November 2009 will operate their Mode S transponders and TCAS units similarly to the data gathered at JFK in April 2011. The aircraft taking off and landing were identified with the same methods as those described in Section B.2.1. For each aircraft the proper, either takeoff or landing, Mode S CDF is sampled to determine the time of operation to add to the beginning or end of the track, depending on takeoff or landing. The proper TCAS CDF is then sampled and multiplied by the previously chosen Mode S sample to determine the time of additional operation for the TCAS unit. The aircraft track is extended using either its first or last known position for takeoffs and landings respectively. The aircraft is assumed to be stationary in that position for the entire time of operation while on the airport surface.

In order to account for aircraft that have landed before the hour of study, 17:00 to 18:00, or took off after, and would be operating on the airport surface within the hour of study, the radar dataset was initially created to be three hours in duration, 16:00 to 19:00. All taking off and landing aircraft tracks in that time period were extended according to the rules above. The data set was then truncated to the proper time period of 17:00 to 18:00.

### B.3.2 Results

Table B-2 shows the average number of aircraft operating TCAS on the airport surface over the hour of study before and after the modification of the dataset. The updated dataset agrees well with analysis of the number of TCAS operating on the airport surface at JFK calculated from the 1030/1090 MHz recordings from April 2011. [See Section B.4 of this report.] Figure B-7 shows one minute averages of the number of aircraft operating TCAS on the airport surface for each airport.

**TABLE B-2**

**Average Number of Aircraft Operating TCAS on the Airport Surface**

| Airport | Before Modification | After Modification |
|---|---|---|
| John F. Kennedy (JFK) | 1.2 | 27.1 |
| Newark (EWR) | 0.8 | 19.5 |
| LaGuardia (LGA) | 0.1 | 18.9 |

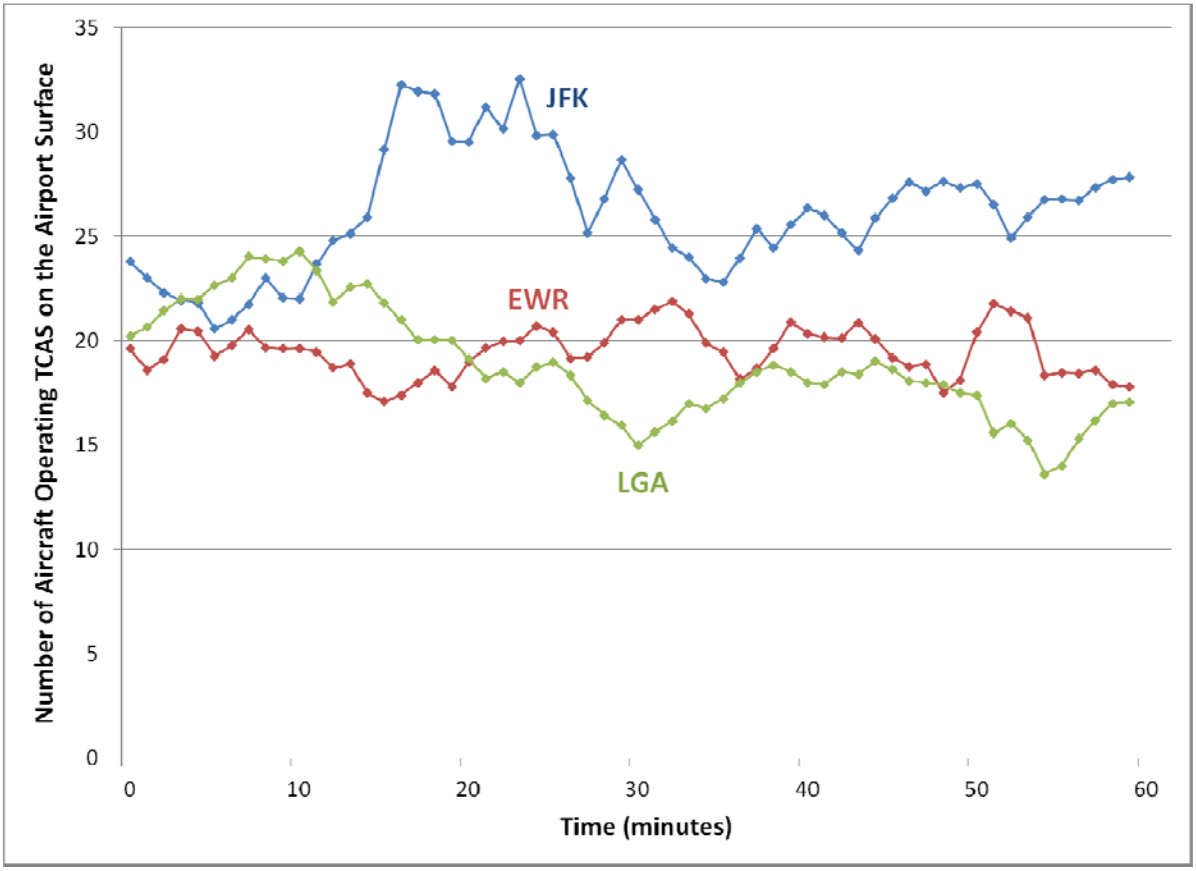

*Figure B-7. Number of aircraft in the modified dataset operating TCAS on the airport surface.*

## B.4 SIMULATION RESULTS

This section describes the changes in the TCAS simulation output with the new dataset. An overview of the simulation, the old dataset, a description of the metrics used for results, and previous results are available in the paper "TCAS Surveillance Algorithm Modification for Reduced Channel Utilization" [11]. A comparison is made with the old dataset and new dataset; the results are shown in Table B-3. In simulations using the new dataset, there is a 33% increase in 1030 MHz (UF0) messages received on average by a TCAS aircraft within 30 NM of the JFK airport. On 1090 MHz (DF0), there is a 91% increase in messages received (note that the 1090 MHz messages received are counted before being passed through a receiver model; this metric can be thought of as the number of messages that are present at the receiving antenna). The increases are due to the addition of around 65 aircraft operating TCAS on the airport surface. All of the airports considered, JFK, EWR, and LGA, are within 20 NM of JFK; including the extra on-ground aircraft doubles the number of TCAS aircraft within 30 NM of JFK.

### TABLE B-3

### Comparison of Baseline Simulation Results

### 1 Hour Averages of Airborne TCAS Aircraft within 30 NM of JFK

| **Metric** | **Old Dataset** | **New Dataset** |
|---|---|---|
| UF0 Transmit/s | 28 | 31 |
| UF0 Receive/s | 616 | 821 |
| DF0 Transmit/s | 10 | 16 |
| DF0 Receive/s | 1023 | 1958 |

Table B-4 gives the relative reductions in 1030 and 1090 MHz metrics for two TCAS on-ground surveillance improvements for the new dataset compared with their relative reductions with the old dataset. The focus for the study was the change in relative 1090 MHz receiver occupancy due to the revised on ground surveillance. The new dataset shows increased reductions in 1090 MHz due to the improvements, approximately 10% compared to the previous 4% reduction with the old dataset.

### TABLE B-4

### Relative Modification Reduction Comparison

| | **Old Dataset** | | **New Dataset** | |
|---|---|---|---|---|
| | 1030 MHz Transponder Utilization | 1090 MHz TCAS Receiver Occupancy | 1030 MHz Transponder Utilization | 1090 MHz TCAS Receiver Occupancy |
| Baseline (TCAS II v7.0/7.1) | 100% | 100% | 100% | 100% |
| TCAS II v7.0/7.1 with Revised On-Ground Surveillance | 86% | 96% | 87% | 90% |

## B.5 SUMMARY

A process was developed to quantify the impact of aircraft operating their TCAS units on the airport surface. One month of 1030 and 1090 MHz recordings from April 2011 was analyzed to monitor the operation of Mode S transponders and TCAS units in the JFK area. Aircraft tracks from TRAMS radar data, recorded from the JFK Mode S sensor, were used to identify aircraft taking off and landing at the JFK airport. The 1030/1090 MHz data was used to create a distribution of Mode S and TCAS behavior for the aircraft identified as taking off or landing by the TRAMS radar data. The distribution of aircraft activity was used to modify a high density aircraft dataset from November 2009 to include an accurate representation of Mode S and TCAS operation on the airport surface of JFK, EWR, and LGA. The revised dataset included an average of 65 additional TCAS aircraft operating on-ground, doubling the instantaneous TCAS count within 30 NM of JFK. A TCAS surveillance simulation was used to compare the effects of the additional aircraft operating on the airport surface (included in the modified dataset) with the original dataset which had minimal TCAS or Mode S activity on the airport surface. The additional aircraft operating on the airport surface increased the average number of TCAS messages received by an airborne aircraft within 30 NM of JFK by approximately 33% on 1030 MHz and 91% on 1090 MHz. A modification to TCAS to decrease surveillance of aircraft operating on the airport surface was also simulated and compared with results from the original dataset. The modification was shown to be more effective with the new dataset, which includes the aircraft operating on the surface. The results show that the modification will provide a 10% decrease in TCAS activity on 1090 MHz, compared with the 4% reduction simulated previously.

An important next step is to examine the potential safety impact that TCAS operation on the ground has on airborne TCAS units. Results from this study indicate that on average the surveillance range of airborne aircraft within the JFK area was reduced by 17%. While the reduction in surveillance range is allowed by the specifications, it is possible that excessive operation of TCAS units on the airport surface could cause the surveillance range of airborne TCAS units in certain altitude volumes to be insufficient for TCAS to provide the maximum warning time for a potential threat with a high closure rate. Therefore, it is necessary to investigate this area.

Other future work on the subject includes further analysis with the 1030 and 1090 MHz recordings of TCAS operation on the airport surface. The distributions of TCAS activity should be studied to see if there are correlations that exist between TCAS activity and a number of potential factors such as: time of day, weather, day of week, TCAS manufacturer, and airline. Also further investigation could be performed into the differences between radar tracks recorded from a Mode S sensor and the Mode S and TCAS operation observed in the 1030 and 1090 MHz recordings.