technical note technical

Final Report on the Analysis of Data Collected During Flight Tests in the Northeast Corridor of the United States In January 2006 at 1030 MHz and 1090 MHz

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16. Abstract

This report details a testing activity that was conducted to measure the 1030 Megahertz (MHz) and 1030 MHz interference environment in the Northeast corridor of the United States. Planned implementation of Automatic Dependent Surveillance – Broadcast (ADS-B) on 1090 MHz Extended Squitter (ES) requires proper operation in future high density airspace. Since ADS-B will be sharing the 1090 MHz frequency with existing Secondary Surveillance Radars (SSRs), Traffic Alert and Collision Avoidance Systems (TCAS) and other systems, understanding the current interference environment will provide confidence in the predictions of future interference environments in which the system will need to operate. The 1030 MHz measurements were collected to help identify the source of 1090 MHz interference signals since interrogations on the 1030 MHz frequency produce Air Traffic Control Radar Beacon System (ATCRBS) and Mode S replies on the 1090 MHz frequency. Measurements were performed during a flight test in January 2006.

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LIST OF ABBREVIATIONS AND ACRONYMS

1090ES	1090 MHz Extended squitter
ACY	Atlantic City NJ International Airport
ADS-B	Automatic dependent surveillance – Broadcast
Alt.	Altitude
ASR-9	Airport surveillance radar Mode 9
ATCRBS	Air traffic control radar beacon system
Avg MS	Average Mode S
Avg Ws	Average Whisper/Shout interrogations
Avg._MC5	Mode C (five- second averages)
BWI	Baltimore-Washington International Airport, Baltimore, MD
DATAS	Data and transponder analysis system
DF	Downlink format
Dist FBC	Distance of first broadcast
Dist LBC	Distance of last broadcast
Dist Min	Minimum distance of TCAS aircraft
ES	1090 MHz Extended squitter
FPS	Primary military radar
FRUIT	False replies unsynchronized with interrogation transmissions
IIS	Interrogator identifier subfield
Int./Sec.	Interrogations per second
JFK	John F. Kennedy International Airport, New York, NY
Kft	Thousands of feet
MBHits	Main beam hits
MHz	Megahertz
Mode S	Mode select
NMi	Nautical miles (1.15 statute miles)
Pd	Probability of detection
PHL	International Airport at Philadelphia, PA
PRF	Pulse repetition frequency
PRT	Pulse repetition time
PRT1	Initial pulse repetition time
RF	Radio frequency
RMF	Radio frequency measurement facility
ScanT	Scan time
SLS	Side-lobe suppression
SSR	Secondary surveillance radar
TC	Technical center
TCAS	Traffic alert and collision avoidance system
UAT	Universal access transceiver
UF	Uplink format
UTC	Coordinated universal time
W/S	Whisper/shout interrogations
WJHTC	The FAA William J. Hughes Technical Center

EXECUTIVE SUMMARY

This report details a testing activity that was conducted to measure the 1030 Megahertz (MHz) and 1090 MHz interference environment in the Northeast corridor of the United States. Planned implementation of Automatic Dependent Surveillance–Broadcast (ADS-B) on 1090 MHz Extended Squitter (ES) requires proper operation in future high density airspace. Since ADS-B will be sharing the 1090 MHz frequency with existing Secondary Surveillance Radars (SSRs), Traffic Alert and Collision Avoidance Systems (TCAS), and other systems, understanding the current interference environment will provide confidence in the predictions of future interference environments in which the system will need to operate. The 1030 MHz measurements were collected to help identify the source of 1090 MHz interference signals since interrogations on the 1030 MHz frequency produce Air traffic control radar beacon system (ATCRBS) and Mode S (Select) replies on the 1090 MHz frequency.

Measurements were performed during a flight test in January 2006. Interference measurements on 1090 MHz included both ATCRBS and Mode S rates along with associated power levels to characterize the signal distributions received by instrumentation on the flight test aircraft. Analysis of the flight test data indicates that a high interference environment exists in this area.

ATCRBS reply rates on 1090 MHz varied greatly over time and location. On average, when the flight test aircraft was at an altitude of 23000 feet, the ATCRBS reply rate above -84 dBm (decibel milliwatts) was measured at about 23000 per second, and the rate varied from 17000 to 32000 per second. The Mode S FRUIT (False Replies Unsynchronized with Interrogation Transmissions) rate above -84 dBm was on average 2500 per second, with a variation from 1800 to 3300 per second. About half of the Mode S 1090 MHz activity is due to TCAS interrogations, and the other half is from Ground-based Mode S SSR interrogations. TCAS Mode S interrogations far outnumber Ground-based Mode S interrogations, but since each TCAS interrogation is addressed to a single aircraft, the impact is not as great as Ground-based All-Call interrogations. Mode S All-Call replies represent about 40% of the FRUIT, but All-Calls comprise only about 3% of the interrogations. Normally, Ground-based Mode S interrogators track Mode S-equipped aircraft and keep them locked out, which prevents excessive replies to All-Calls. Aircraft beyond tracking range of the Ground-based SSRs are not locked out and reply to all the All-Calls in the antenna main beam.

Measured 1030 MHz interrogation rates at 23000 feet were an average of 290 per second for ATCRBS Mode A and C interrogations (combined), and Mode S interrogations averaged 500 per second with per second variations from 190 to 650. The data collected on 1090 MHz Mode S replies from individual aircraft uncovered a DF (Download Format)=11 with an IIS (Interrogator Identifier Subfield)=0 transmit rate of more than one per second. The DF=11 with IIS =0 rate is expected at one per second per aircraft, which is the Acquisition Squitter rate required by Mode S transponders. A DF=11 with IIS=0 can occur if All-Call Mode S interrogations are using UF=11 with IIS=0, or if an ATCRBS/Mode S All-Call (intermode) interrogation is used. Neither of these types of interrogation is supposedly in use at this time. Another possibility to explore is TCAS Whisper/Shout interrogations that may be misinterpreted as intermode transmissions, depending on the detected pulse width of the last interrogation pulse. Future data collections will focus on investigating this phenomenon.

INTRODUCTION

A flight test was conducted by the FAA William J Hughes Technical Center (WJHTC) on January 26, 2006 in the Northeast corridor of the United States for the purpose of measuring and assessing 1030/1090 MHz activity.

The ADS-B Program of the FAA is in the process of implementing the Ground infrastructure to support ADS-B applications, including Air Traffic Control use of ADS-B, encompassing both 1090 MHz Extended Squitter (1090ES) and the Universal Access Transceiver (UAT) data links. As air traffic grows in the future, and as the implementation of 1090ES equipage on aircraft increases, activity on 1090 MHz will significantly increase as well.

Since the performance of 1090ES ADS-B is highly dependent on the interference rates, there is interest in measuring current rates to better predict the future environment as the ADS-B system evolves. Previous 1030 MHz and 1090 MHz rates have been measured in other geographic areas and are presented on page 42 for comparative analysis. In 1999, a flight test was conducted in the Los Angeles basin area. The Los Angeles terminal area was considered a high interference area due to its high traffic density and numerous Ground interrogators. In 2000, a flight test was conducted in the Frankfurt, Germany area as this was deemed one of the heaviest interference areas of the world. Since the Northeast corridor of the US contains a high traffic density and a high air transport category aircraft population (creating a greater TCAS environment) and has a relatively flat terrain, it was deemed appropriate to conduct a flight test in this region to assess the activity levels. Also, previous measurements were conducted prior to the FAA rollout of Mode S SSRs to replace existing ATCRBS interrogators. Since interference rates on 1090 MHz include both ATCRBS and Mode S activity, the impact of this change in the Ground systems was expected to be reflected in the data.

The aircraft measurement systems included both 1030 MHz and 1090 MHz data collection systems. The 1030 MHz measurement system used was the Data Link and Transponder Analysis System (DATAS). This equipment has been used in the past for numerous flight test measurements. The 1030 MHz measurements were performed to enable a more thorough assessment of 1090 MHz activity. The 1090 MHz interference environment is highly dependent on many factors, including number, type and proximity of Ground Secondary Surveillance Radar (SSR) interrogators, local air traffic density and the number of TCAS-equipped aircraft within signal range. The 1030 MHz interrogation frequency was measured to assess the sources of 1090 MHz response activity. Interrogation rates were measured and the types of interrogations identified by the 1030 MHz measurement system. Additionally, radar data was recorded from most of the SSRs covering the area of the flight test, and air traffic counts were produced from the radar data.

1030 MHZ ENVIRONMENT CHARACTERIZATION FLIGHT OF 01/26/06

Data was collected via DATAS aboard the FAA aircraft N-40 on January 26, 2006. The flight path is shown in figure 1 as a function of altitude. The flight departed the FAA WJH Technical Center at the Atlantic City NJ International Airport (ACY) at approximately 13:30 (UTC) enroute to the Baltimore-Washington International (BWI) area. The first leg of the data

collection segment of the flight was at an altitude of 35,000 feet while northbound from BWI toward JFK International Airport (JFK). The blue trace on figure 1 depicts that leg of the flight (29000 to 98700 on the legend). The primary region of interest, called the Geographical Test Area, was to be a specific area between Philadelphia International Airport (PHL) and JFK (between 14:45 and 14:47 on figure 1) and all interrogation and reply data was to be analyzed for this area of the flight at altitudes of 35000, 23000 and 11000 feet. This data was then to be compared to the rates at other areas of level flight as the analysis evolved.

Unfortunately, data collection problems occurred during the initial leg of this flight at 35000 feet, and no usable 1090 MHz data was recorded until the southbound leg at 23000 feet. One recorder was not working at all, and the other was dropping significant amounts of data, so it could not be counted as a reliable representation of the 1090 MHz environment at that time. As the aircraft approached JFK at 35000 feet, both RMF tapes (recording data from top and bottom 1090 MHz antennas) were replaced, but by the time both units were up and running again, the aircraft was past Philadelphia on the southbound leg at 23000 feet (see red trace in figure 3).

As a result there are two distinct Geographical Test Areas (described in the following graphs as PlotTime) covered in this analysis, as indicated by the red (southbound at 23000 feet) and black (northbound at 11000 feet) traces in figure 3. The yellow trace in figure 3 and the corresponding PlotTimes in subsequent graphs represents the initial northbound leg at 35000 feet, for which no 1090 MHz data was collected, rendering the corresponding1030 MHz data irrelevant to the analysis of the 1090 MHz environment at 35000 feet.

After reaching the JFK area at 35000 feet, the aircraft turned around and descended to 23000 feet for a southbound pass through the same area (white trace on figure 1). Upon reaching the Baltimore area, the aircraft descended to 11000 feet for the return to the JFK area at that altitude (red trace on figure 1), and then returned back to ACY from the north.

The DATAS receiver/preprocessor was a modified Mode S transponder, so the 1030 MHz signals described in this report are similar to those seen by a standard transponder. The N-40 aircraft was equipped with both top and bottom antennas, so the interrogation data that is reported is the output of the diversity logic of the transponder: only the stronger of the two signals was selected if seen on both antennas.

Figure 3 shows the northbound positions of N-40 in the intended Geographical test area indicated by the points 14:45 to 14:47 at 35000 (yellow trace) and 11000 feet (black trace), and the southbound Geographical test area at 23000 feet (red trace). The data collected in these areas was analyzed to compare the interrogation rates as a function of altitude.

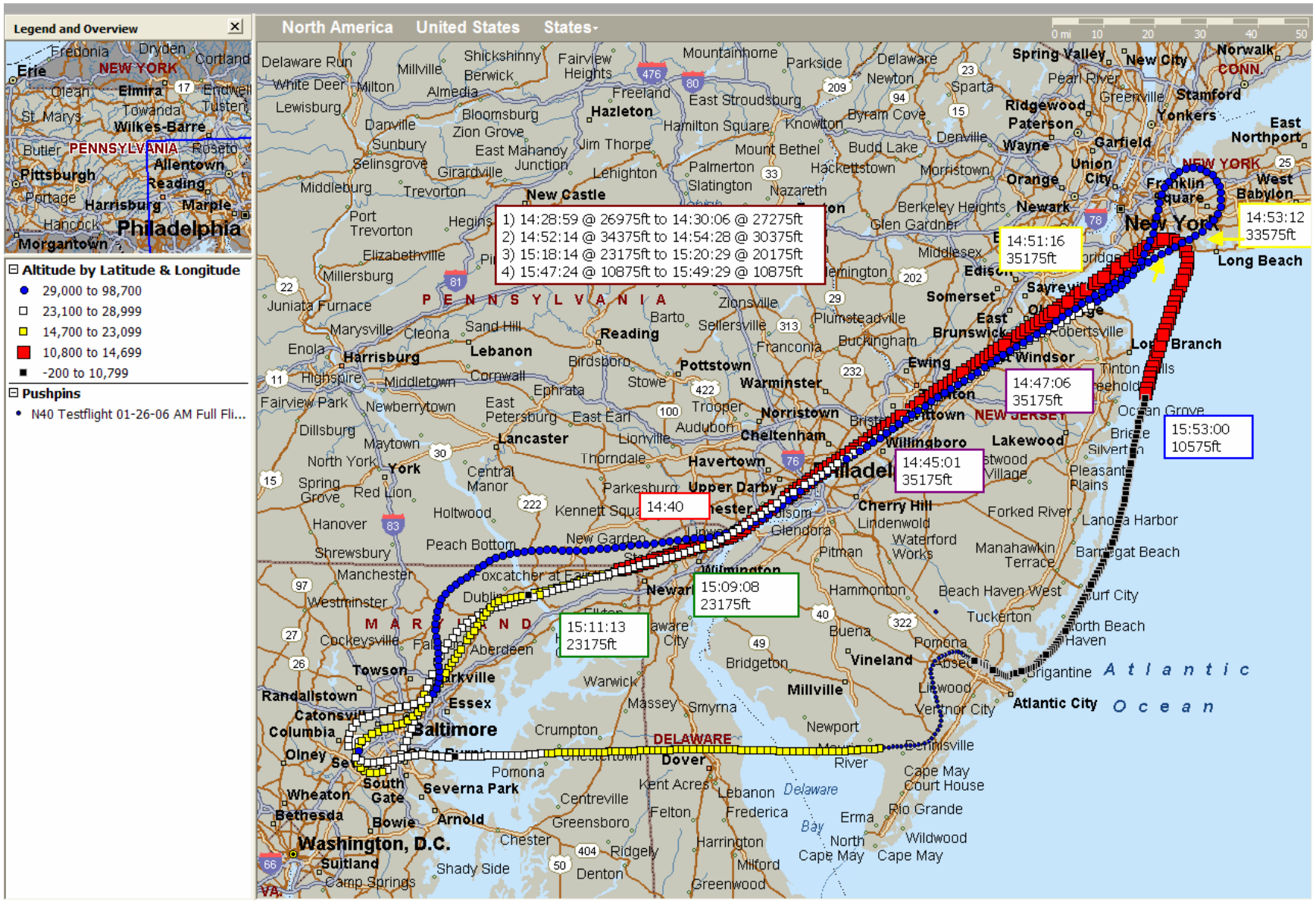

Figure 1: Flight Path of Test Flight as a Function of Altitude

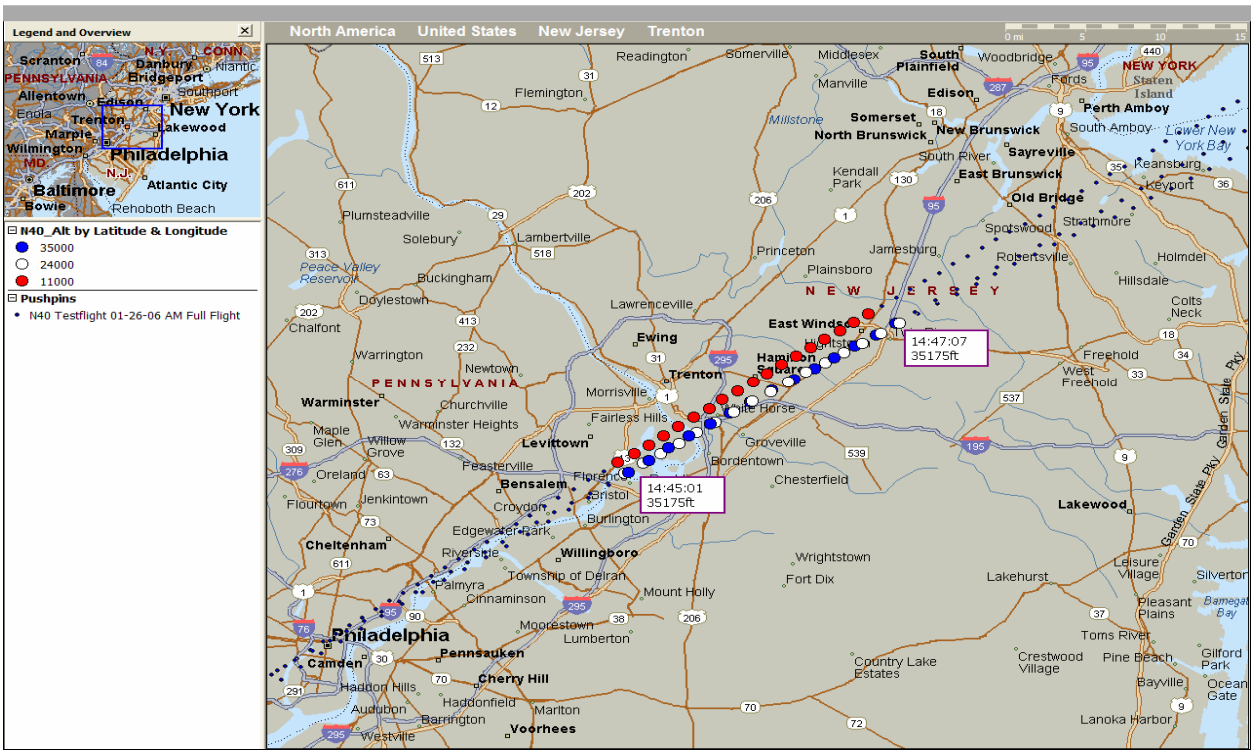

Figure 2: Intended Geographical Test Area between PHL and JFK

Figure 3: Actual Geographical Test Areas at 23000 feet and 11000 feet

Figure 4 shows the unsuppressed Mode A interrogation rate for the flight, displayed (as in subsequent charts of this nature) as averages of measurements taken over five-second intervals. The unsuppressed rates represent interrogations that would require the onboard transponder to reply. The short red lines indicated by PlotTime correspond to the times when the N-40 aircraft was in one of the two Geographical test areas indicated by the black and red traces in figure 3.

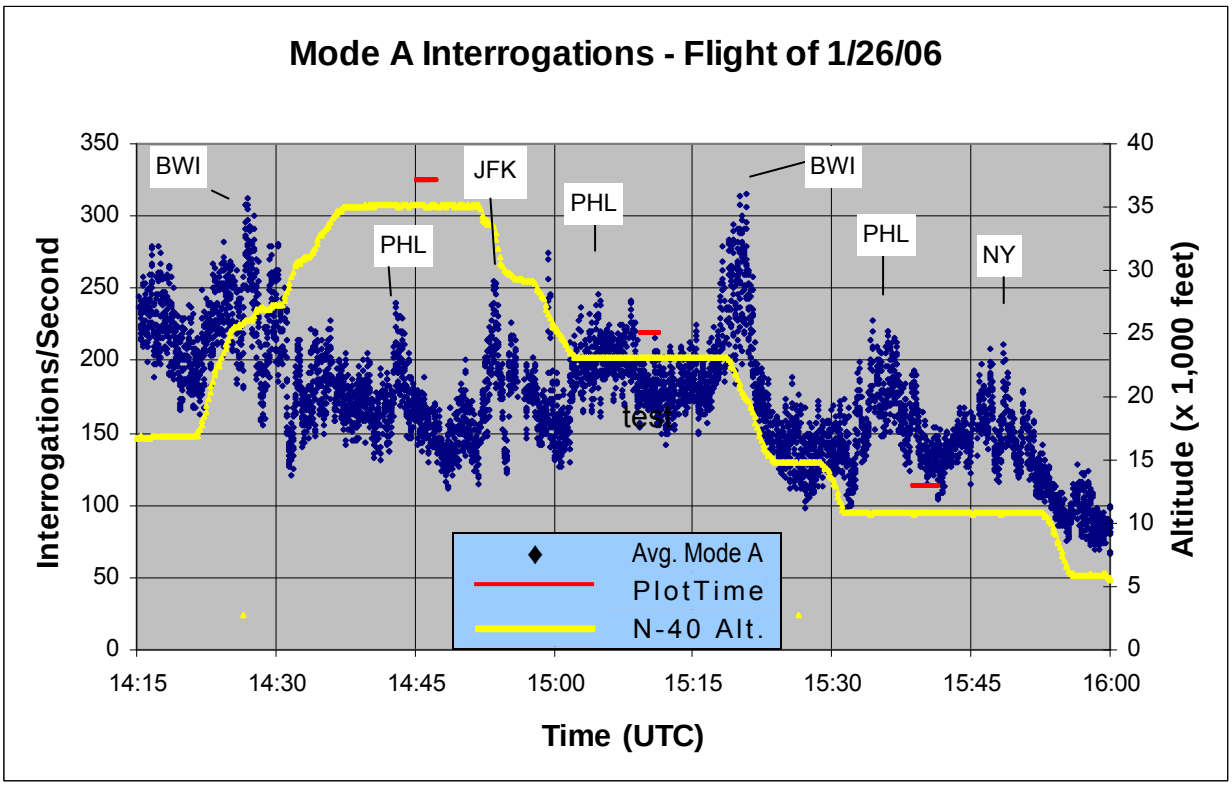

Figure 4: Mode A Interrogation Rates

The rates change significantly depending on aircraft altitude. The Mode A interrogation rates are definitely higher at 23000 feet than at 35000 or 11000 feet. This was unexpected, as normally the interrogation rates are higher at higher altitudes.

Table 1 shows the average interrogation rates per second for the entire time the aircraft is level at the indicated altitude and for the time when in the area indicated by PlotTime on the rate plot.

Table 1: Average Mode A Interrogation Rates/Second

Altitude	Entire time At Altitude	PlotTime	Difference
35k	162.0	158.8	–3.2
23k	191.1	187.6	–3.5
11k	152.4	146.5	–5.9
Average	168.5	164.3	–4.2

Surprisingly, altitude did not make much difference in the observed rates. PlotTime at an altitude of 35000 feet is between the two peaks caused by proximity to PHL and JFK while northbound. PlotTime at 11000 feet is during the same two increases when going northbound again. The interrogation rate going southbound at 23000 feet is more consistent. The highest Mode A interrogation rate occurred about 15:20 when the aircraft was turning around near BWI to return north. Only a little of this information is included in this data, because only data recorded when the N-40 was level was used. The average rate when using the At Altitude data is 168.5. The average when using PlotTime data is 164.3. Thus, even though the interrogation rate changes significantly for the short term, the overall rate is not that much different.

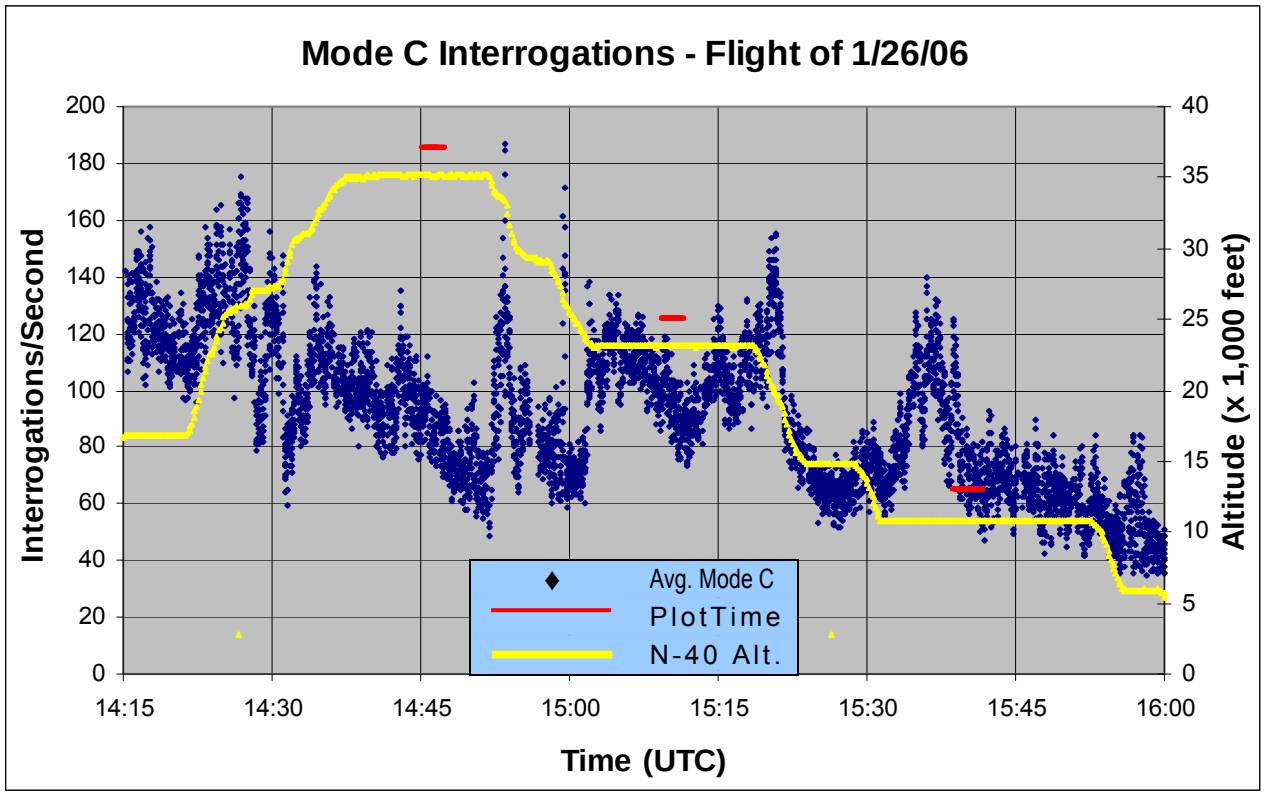

Figure 5: Mode C Interrogation Rates

The Unsuppressed Mode C interrogation rates for the flight are shown on figure 5. The same analysis was performed as that for Mode A. Table 2 shows the Mode C interrogation rates when At Altitude and when in the areas defined by PlotTime. As was the case for Mode A, there is not much difference.

Table 2: Average Mode C Interrogation Rates/Second

Altitude	Entire time At Altitude	PlotTime	Difference
35k	87.9	88.3	0.4
23k	104.2	106.3	2.1
11k	76.0	78.9	2.9
Averages	89.4	91.2	1.8

The Mode C rate decreases on the northbound 35000-foot leg of the flight, with an average rate of 87.9 interrogations per second. Sharp increases occurred at the beginning and end of the transition to 23000 feet (the turn in the New York area to head south). The rate then decreases until about 15:07 when the aircraft is passing PHL. The next two peaks occur at 15:15 and 15:20 when the aircraft is approaching BWI, descending and making the turn to go back north at 11000 feet. The final peak of 140 interrogations/Sec. occurs over the PHL area northbound at 11000 feet. As with the Mode A interrogation rate, there is not much difference if using the rate at level flight for the entire leg or only when in the area of interest (PlotTime). The difference is less than three interrogations per second. For short periods of time, however (e.g., 15:37), the rate can change by 50 interrogations per second for several minutes.

The observed TCAS Whisper/Shout interrogation rates are shown in figure 6. The TCAS activity is obvious on this plot. Refer to these rates and the corresponding aircraft positions shown on figure 7.

The three short red lines in figure 6 that are labeled PlotTime are the times when the aircraft was in the two areas indicated on figure 3. The aircraft, however, is at different altitudes and going in opposite directions, so any effects caused by this are uncontrolled.

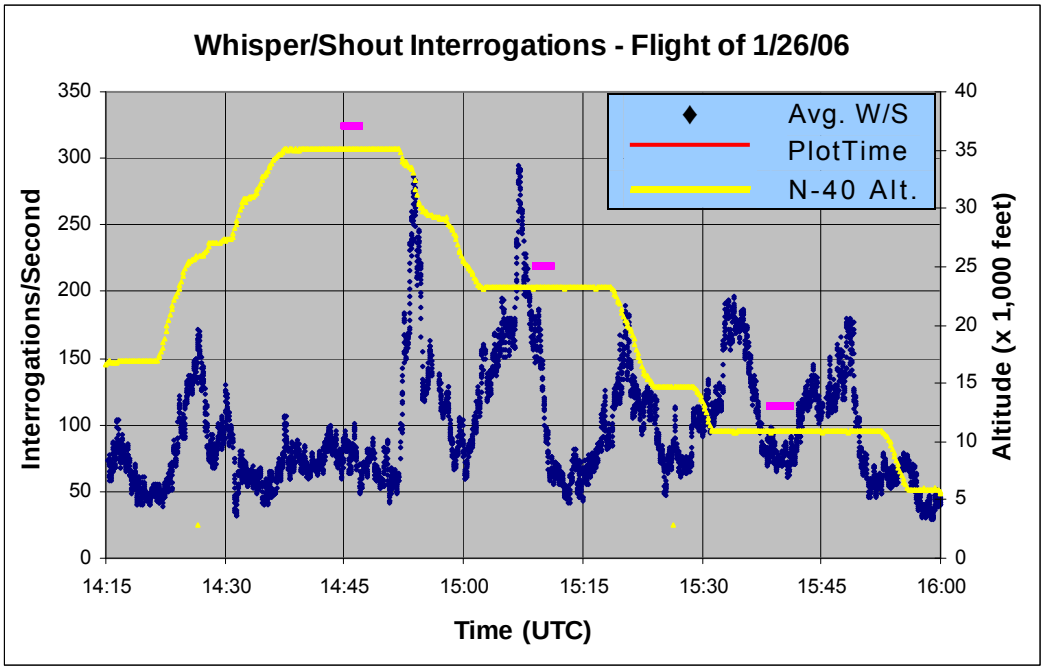

Figure 6: TCAS Whisper/Shout Interrogation Rates

Table 3 shows the TCAS Whisper/Shout interrogation rates when at altitude, and when in the areas defined by PlotTime. As was the case for Mode A and C, there is not much difference except for the run at 11000 feet. There is a difference of more than 35 interrogations per second when measured at the areas of interest (PlotTime). This is midway between the two peaks caused by PHL (15:35) and the approach to JFK (15:45). Note the lack of TCAS characteristics

at 35000 feet. Note also that the rate of Whisper/Shout interrogations changed by more than 200 interrogations per second twice during this flight. These peaks occurred at 14:54 when N-40 was turning around and descending in the JFK area and at 15:07 when it was leaving the PHL area.

Table 3: TCAS Interrogation Rates/Second

Altitude	Entire Time At Altitude	Plot Time	Difference
35k	72.3	77.1	4.9
23k	120.3	127.4	7.1
11k	112.7	77.0	–35.7
Averages	101.8	93.8	-7.9

Figure 7 on the following page shows the number of TCAS aircraft detected from N-40 and identifies the most significant peaks of TCAS Whisper/Shout interrogations. The number of TCAS aircraft was derived by counting the number of different TCAS Broadcast interrogations seen within the prior 20 seconds. TCAS-equipped aircraft broadcast on 1030 MHz using UF=16, which allows TCAS-equipped aircraft to monitor other-TCAS-equipped aircraft. The range at which the broadcasts from these aircraft would be detected by the 1030 MHz data collection system is typical of a Mode S transponder since the receiver sensitivity of the data collection system is within the specified range of a compliant transponder.

The first TCAS Whisper/Shout interrogation peak (166 interrogations per second) occurred at 14:26:45 when there were 73 aircraft within view and N-40 was headed toward the BWI area. The next peak occurred when the aircraft headed north at 14:30:10. There were 125 interrogations per second with 69 aircraft present. The aircraft was at 27000 feet, climbing toward 35000 feet for the first leg of the flight, toward JFK.

The highest W/S rates occurred on the second leg of the flight. The first peak (286 interrogations per second) occurred at 14:54:10 with 105 TCAS aircraft. N-40 was turning around and descending (in the JFK area) toward 23000 feet for the return to BWI. The highest peak (296 interrogations per second) occurred at 15:07:05 with 86 aircraft present while at 23000 feet when the aircraft was leaving the PHL area southbound.

It must be remembered that the RF environment is dynamic. The number of aircraft within sight of our test aircraft was constantly changing. The average number of TCAS aircraft seen at the same geographical area (denoted by PlotTime on the rate plots) was 79 at 35000 feet, 97 at 23000 feet, and 71 at 11000 feet.

Figure 8 shows the number of TCAS aircraft and W/S interrogation rate in a little different manner. The negative spikes on the TCAS Aircraft trace are a byproduct of the mechanism that counts TCAS aircraft. It counts the number of the TCAS Broadcast interrogations from different aircraft and uses the standard TCAS method of calculating the number by monitoring the total of different addresses within the prior 20 seconds. The spikes represent DATAS file boundaries. The program restarts at the beginning of each file without keeping the history from the last file.

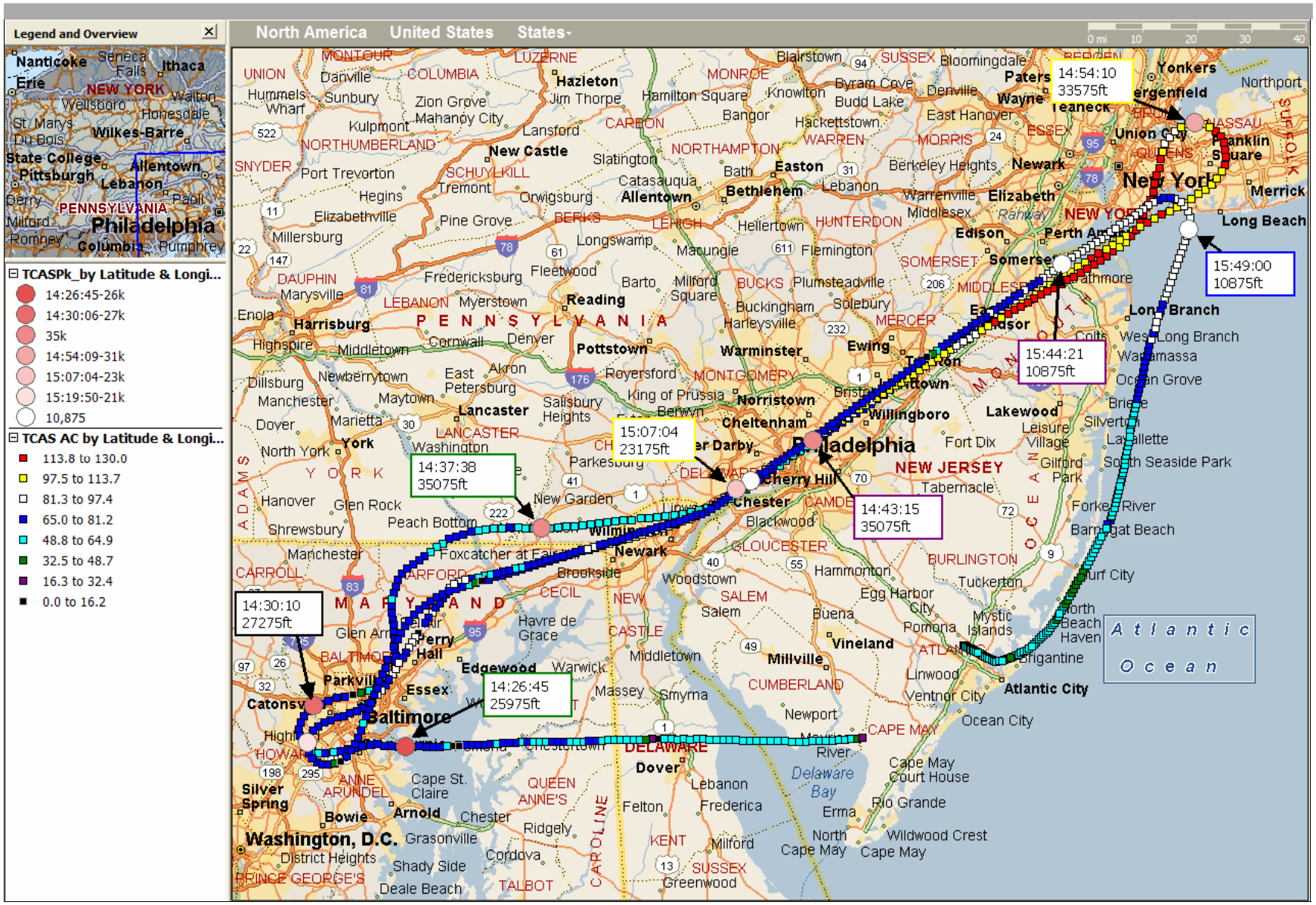

Figure 7: Number of TCAS Aircraft and W/S Interrogation Peaks

As indicated, when N-40 approached New York the first time, there were approximately 120 aircraft within the TCAS listening area. The second time, the number was below 100.

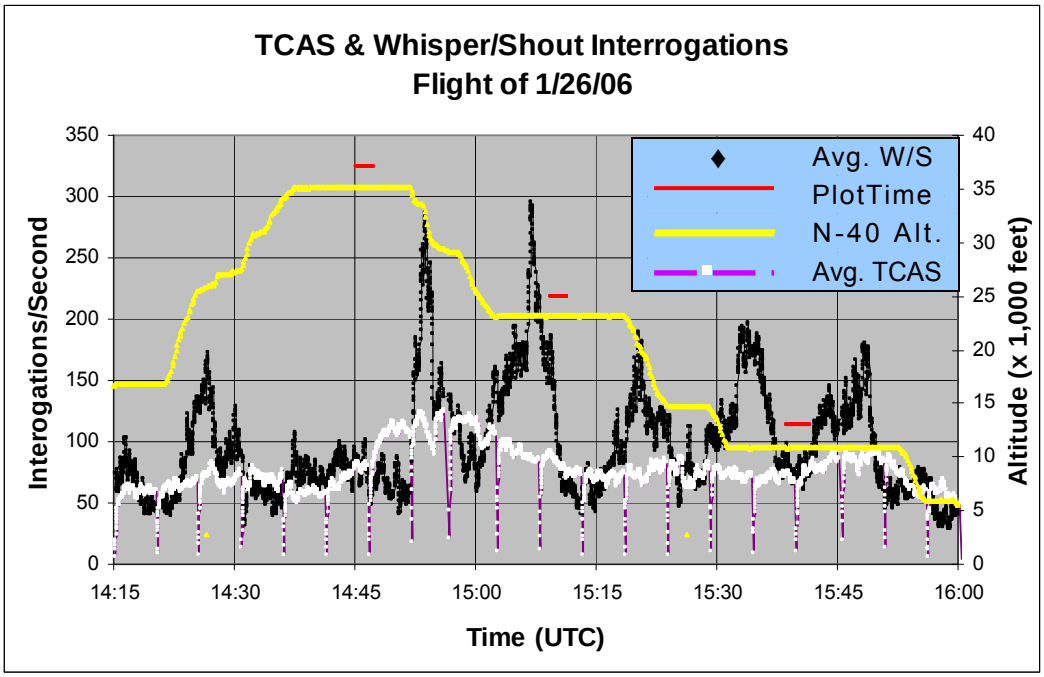

Figure 8: Number of TCAS Aircraft and W/S Interrogation Rates

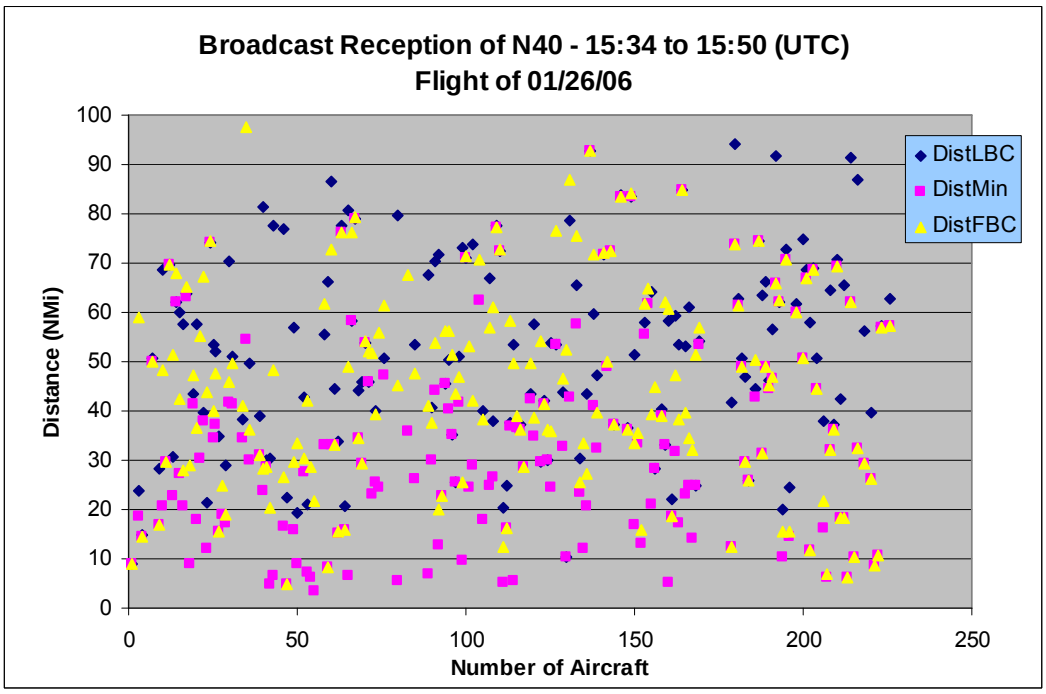

Figure 9: Scatterplot of First, Last and Minimum Range TCAS Broadcasts

TCAS BROADCAST ANALYSIS.

An analysis of TCAS Broadcast interrogations was conducted for a sixteen-minute portion of the flight from 15:34 to 15:50. The distance of the TCAS aircraft from N-40 was calculated when each broadcast interrogation was received. Figure 9 shows the minimum and maximum distance from each aircraft when the first and last broadcasts were detected from that aircraft.

Broadcasts were seen from 225 different TCAS aircraft during this period and table 4 summarizes the data collected. The highest number of broadcasts from any single aircraft was 296. The average number received from a single aircraft was 46.8.

Table 4: Summary of Broadcast Sample

Summary of Broadcast Data Sample 15:34 to 15:50			
	Number of Broadcasts	**Distance First Broadcast (NMi)**	**Distance Last Broadcast (NMi)**
Average	46.8	44.4	52.2
Minimum	1	4.9	8.9
Maximum	296	97.7	94.1

The average distance of TCAS aircraft from N-40 for the receipt of either the first or last broadcast, depending on the direction of flight from N-40, was approximately 47 NMi. There is some bias in this data (towards decreasing the distance) because the aircraft may still be present when the file ends, so the last broadcast is the last one from the data file instead of the actual last detected broadcast.

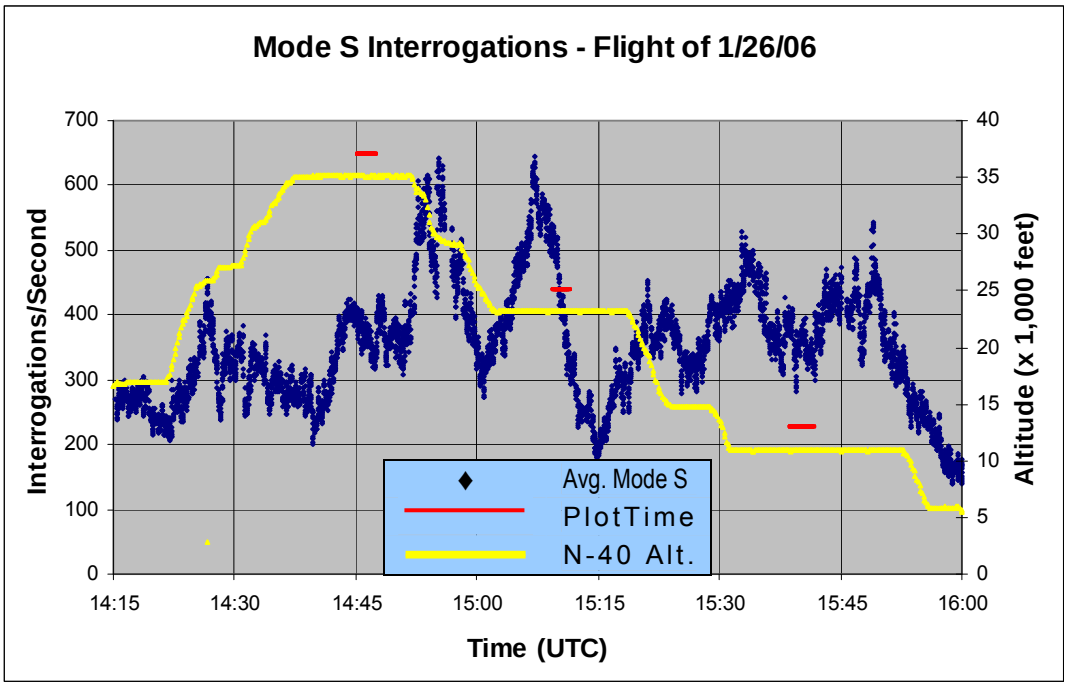

Figure 10: Mode S Interrogation Rates

Figure 10 shows the Mode S interrogation rates detected during the flight. As expected, the Mode S interrogation rate variations are very similar to the TCAS Whisper/Shout interrogations (see figure 8) because the interrogations are primarily TCAS-related, UF=0 formats. The two major peaks occurred at 14:55 and 15:07. These two times were when the aircraft was turning around in New York and descending from 35000 feet to 23000 feet, and when the aircraft was in the area of the PHL airport. The rates in both cases reached about 650 interrogations per second.

Table 5 shows a sample of the UF code distribution from the flight. For this sample, 93% of the interrogations were TCAS related: 89% UF=0 and 4.1% TCAS broadcast interrogations. The row denoted "Peak" indicates the highest number of that interrogation type received in a single second of this sample.

Table 5: UF Code Distribution Sample

	UF=0	**UF=4**	**UF=5**	**UF=11**	**UF=16**	**UF=20/21**
Avg. # Int.	424	18	1	14	20	0.4
Pct.	89.0	3.8	0.2	2.9	4.1	0.1
Peak	62.4	84	9	49	43	2

Figure 11 shows the Mode 2 interrogation rate for the flight. The rate appears to be between 60 and 80 per second except for the time before 14:30 when N-40 was in the BWI area preparing for the first leg of the flight, and between 15:20 and 15:25 when it was turning around near BWI for the last leg of the flight at 11000 feet.

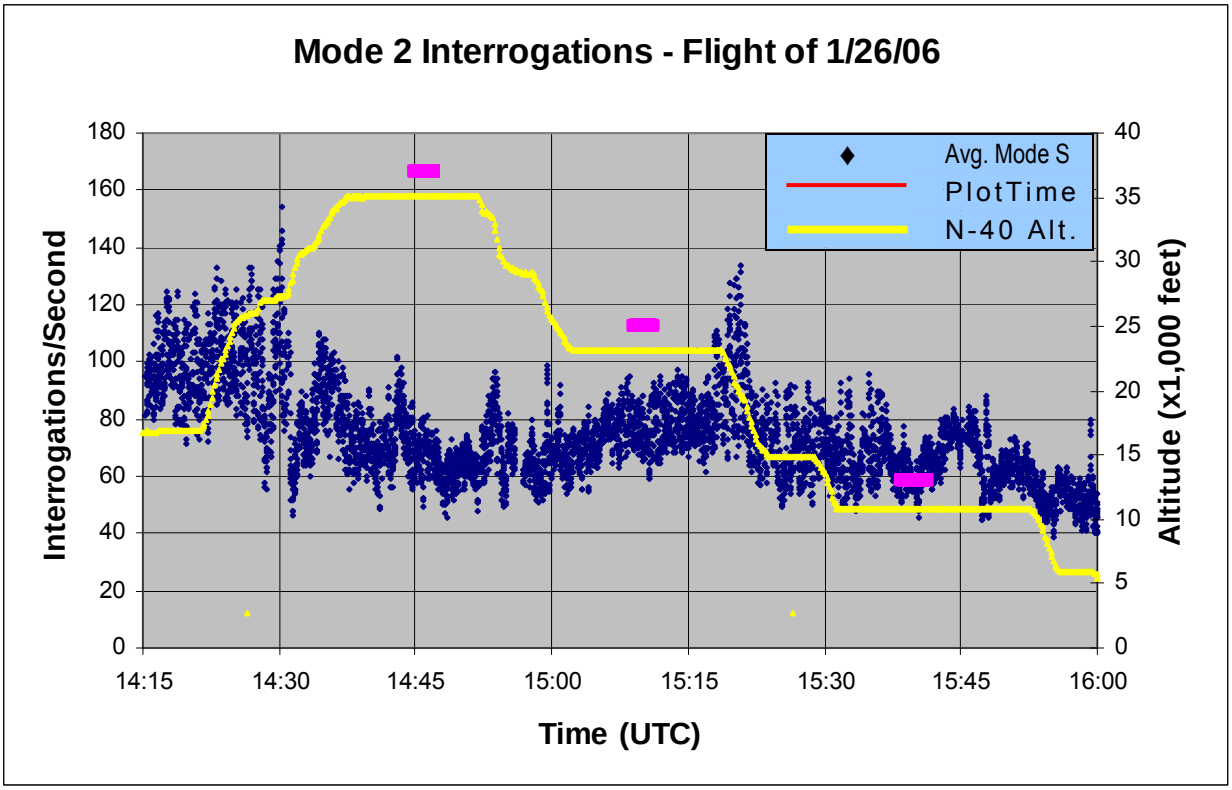

Figure 11: Mode 2 Interrogation Rates

During these two periods, the average rate appears to increase to about 100 interrogations per second. There is a higher concentration of military radars in these areas.

Figure 12 shows the ATCRBS suppression interrogation rate for the flight. This data is consistent with the TCAS interrogation data (see figure 8), as the TCAS Whisper/Shout interrogations are a large contributor to this interrogation type.

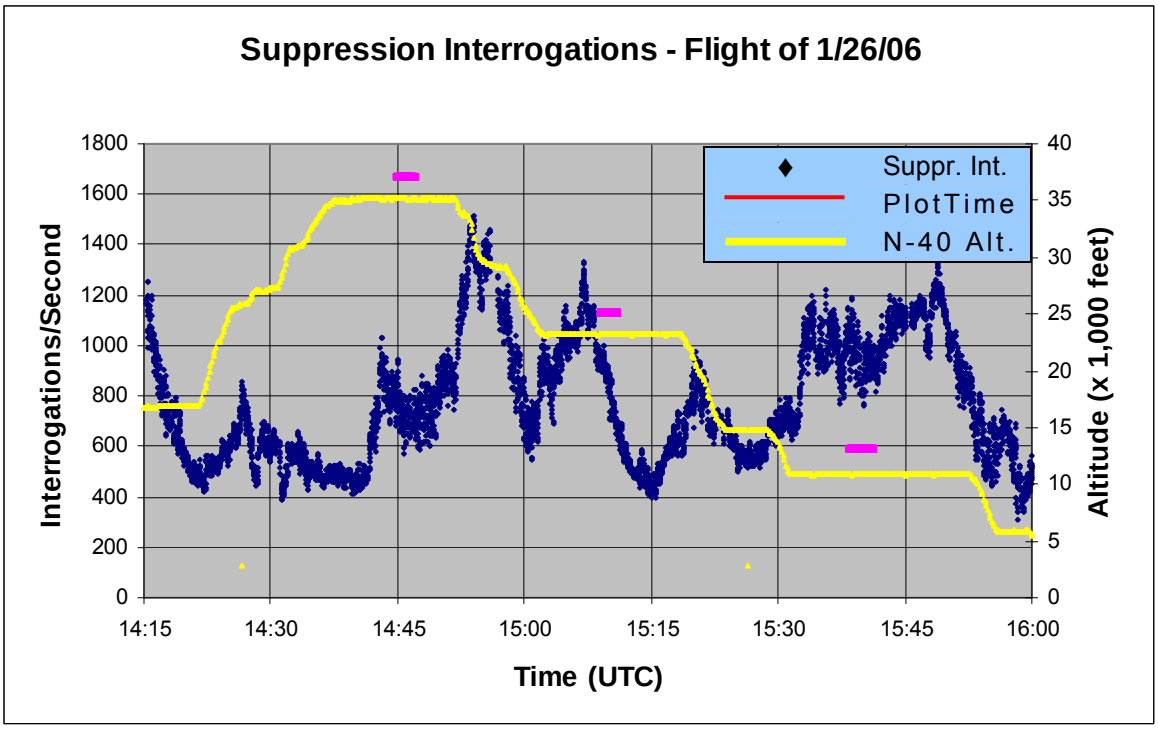

Figure 12: Suppression Interrogation Rates

Two areas of this data, however, show some interesting characteristics (the area before 14:30 and that between 15:35 and 15:50). The suppression rate when the aircraft was approaching BWI at 14:15 was about 1200 per second. By 14:21, the rate had dropped to about 500 suppressions per second. The aircraft was past BWI and making its turn toward the north at this time. This probably indicates interrogators with SLS problems in the area, and this is likely the cause of the increase from 15:35 to 15:50 as well. The aircraft is at an altitude of 11000 feet from 15:35 to 15:50, enabling it to see the side lobes of the ground radars more easily. This can be verified by PRT analysis.

INVESTIGATION OF MODE A AND MODE C INTERROGATION RATES.

When measurements indicated that the interrogation rates (both Mode A and Mode C) were higher at 23000 feet than they were at 35000 feet, some additional analysis was performed to attempt to explain these results.

Figure 13, on the following page, shows that the interrogation rates varied between 50 and 320 Mode A interrogations per second for the flight. The highest rates occurred when the aircraft was approaching BWI from ACY at the beginning of the flight. The rates in this area varied from 180 to 320 interrogations per second. The highest interrogation rate at any other area of the flight was a single spot slightly north of PHL where the rate reached 220 interrogations per second. The Mode C rates show the same characteristic.

The 1030 MHz data was analyzed by searching for the pulse repetition times (PRTs) and the interrogation mode Interlace patterns of the interrogators. The DATAS data contained only the interrogation type and time of arrival, so only the time could be correlated to detect the PRT patterns. This effort concentrated on data from the initial approach to BWI from ACY and its comparison to that collected when in the Geographical Test Area described by figure 2. The goal was to come up with an explanation for the high Mode A and C rates on the approach to BWI from ACY.

The first group of radars identified in the data from the flight are labeled "Group A" in table 6, which follows figure 12. These radar signals displayed very well-defined stagger patterns. These patterns varied from one (no stagger) to fifteen PRTs before the sequence repeated. The PRT column in tables 6 and 7 is in 100 nanosecond clock units (29105 for R1SEQ is 2910.5 μs). Macros were developed to search the data for these patterns and produce statistics such as the mode Interlace pattern, antenna Scan time and the number of interrogations in each detected beamwidth (MBHits). The Hits/second columns include main beam interrogations per second for each radar. The columns are further denoted with a number and letter to indicate reduction file number. Files 9, 10 and 13 were used for this analysis. Files 9 and 10 were collected while enroute from ACY to BWI on the initial approach. File 13 covers the time the aircraft was in the northern Geographical test area. The letter a, b or c denotes the portion of the file that was used to produce the statistics. Table 6 provides a summary of the processing of the group of radars with well-defined characteristics.

Group A consists of 29 radars. Eleven of them can be removed from consideration as they are included in the Mode S group, leaving 18 radars. As indicated, most of these radars produce an average of two to four interrogations per second. Some of them, however, produce significantly more than that (e.g., R23SEQ and R25SEQ, highlighted in yellow and beige, respectively). Radar 25 alone produces more than 20 interrogations per second during files 9 and 10. This is the area where the unsuppressed ATCRBS rates are much higher than anywhere else. Radar 25 is most likely a military radar as it contains Mode 2 interrogations and another unidentified mode (probably Mode 1 or 4) in its pattern. The data collection system did not detect all possible interrogations, including Mode 1 and Mode 4 interrogations, so these unidentified interrogations are labeled "X" in the Interlace pattern column in table 6 to denote unknown. The rate for radar 25 is down to about five interrogations per second at the end of file 13 when N-40 is located midway between PHL and JFK.

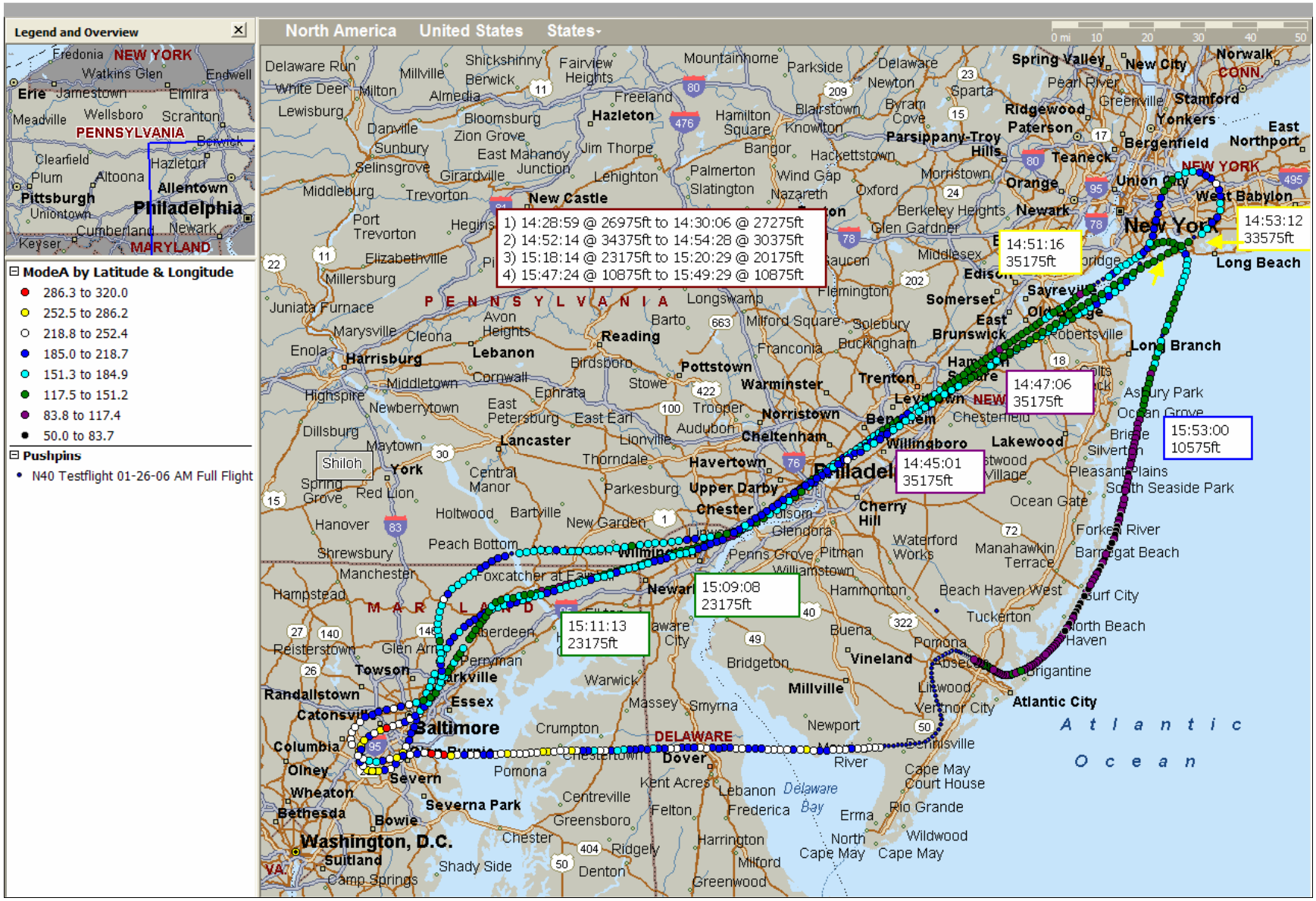

Figure 13: Mode A Interrogation Rates Vs. Aircraft Position

Table 6: PRT Summary of Group A Radars

RADAR #	PRT1	# Stag	Avg. PRF	Interlace	ScanT (Sec.)	Avg. MBHits	Comments	14:13:00 Hits/Sec. 9a	14:15:36 Hits/Sec. 9c	14:20:24 Hits/Sec. 10b	14:22:56 Hits/Sec. 10c	14:34:05 Hits/Sec. 13a	14:39:24 Hits/Sec. 14a	14:43:12 Hits/Sec. 14b
R1SEQ	29105	1	343.6	ACACAC	4.71	15		2.82	4.00	3.74	2.17	2.39	2.88	2.59
R2SEQ	24701	7	397.6	AACAAC	4.64	16		6.14	5.61	4.37	5.53	5.89	5.49	4.66
R3SEQ	76546	6	129.2				Mode S	1.65	1.56	1.68	1.94	1.58	1.77	1.82
R4SEQ	77165	8	129.5				Mode S	2.05	2.54	2.34	2.40	2.02	2.19	2.27
R5SEQ	80842	8	129.5				Mode S	2.21	2.00	2.49	2.47	1.97	1.86	1.83
R6SEQ	34342	15	291.5	2AC2AC	12.20	12.4		3.82	4.63	3.65	4.48	3.25	2.55	2.31
R7SEQ	30112	1	332.1	AACAAC	4.69	17.8		0.65	4.63	3.11	2.89	4.40	4.14	3.78
R8SEQ	30128	1	331.9	2AC2AC	4.70	11.5		1.73	3.41	2.88	1.66	1.55	1.20	1.07
R9SEQ	30865	1	324.0	ACACAC	4.72	19.9		2.77	4.78	4.37	1.96	2.65	1.65	1.13
R10SEQ	29577	1	338.1	ACACAC	4.69	21.1		2.56	4.19	3.75	1.63	3.20	2.87	2.81
R11SEQ	25235	1	396.3	AACAAC	4.70	13.9		0.42	0.29	0.38	0.35	2.26	2.88	2.84
R12SEQ	28838	1	346.8	AACAAC	4.70	12.5		1.72	5.51	4.46	2.61	2.24	2.10	2.22
R13SEQ	81475	8	129.5	ACACAC	4.63	5.3	Mode S IIS=2	3.01	2.24	3.41	3.83	2.35	3.53	3.20
R14SEQ	81525	8	129.6	ACACAC		5.0	Mode S IIS=5	3.11	2.83	3.80	3.50	2.52	3.45	3.88
R15SEQ	81405	8	129.6	ACACAC	4.63	5.2	Mode S IIS=10	2.83	2.63	3.58	3.48	2.80	3.69	3.65
R16SEQ	81586	8	129.5	ACACAC	4.63	5.8	Mode S IIS=3	3.40	2.78	4.89	5.11	2.63	3.45	3.40
R17SEQ	19236	7	382.0	AACAAC	4.70	15.9		5.85	5.56	4.98	3.76	5.32	4.65	4.30
R18SEQ	41323	3	242.0	2AC2AC	12.00	15.9		2.10	2.05	1.80	2.31	1.79	0.26	0.43
R19SEQ	81623	8	129.5	ACACAC	4.62	5.9	Mode S IIS=3	3.39	3.27	3.75	4.43	3.27	3.84	3.75
R20SEQ	81165	8	129.6	ACACAC	4.62	5.7	Mode S IIS=9	3.08	3.17	3.28	2.47	3.17	3.74	3.43
R21SEQ	80917	8	129.6	ACACAC	4.62	5.0	Mode S IIS=4	3.05	3.07	3.22	3.40	2.33	1.94	1.83
R22SEQ	26664	1	375.0					0.31	0.59	0.48	0.51	0.27	0.17	0.14
R23SEQ	33196	1	301.2	ACACAC	6.18	35.0		10.69	8.05	7.73	11.59	5.11	0.13	0.26
R24SEQ	40315	5	247.6	2AC2AC	12.00	12.1		1.66	2.39	1.59	2.08	1.66	1.39	1.31
R25SEQ	36734	15	185.9	2AX2AX	11.20	8.6	X is unknown	13.90	21.85	20.14	28.90	7.12	5.26	3.99
R26SEQ	38320	3	261.0	2AC2AC	120	12.5		0.65	1.12	0.44	0.79	1.67	1.39	1.47
R27SEQ	22353	8	445.5	AACAAC	4.71	26.9		8.34	8.39	7.31	8.12	7.34	6.54	6.01
R28SEQ	80445	8	129.5		4.62	5.5	Mode S IIS=2	3.07	2.44	3.39	3.05	2.63	2.76	2.60
R29SEQ	29998	1	333.4	2AC2AC	3.87	19.1		2.48	1.32	2.02	4.41	1.24	0.27	0.36

There is another group of radars labeled "Group C" that is summarized in table 7 on the following page. These radars are not as well-defined as those in Group A. They consist of a "fixed PRT" that staggers by a random variable amount and have unknown Interlace patterns. There appear to be multiple radars using a very similar PRT in this group. When a well-defined Interlace pattern was detected, it was used to separate this radar from the others in the group. When the data appeared to be from two separate sources with the same characteristics, the radars were labeled "a" and "b" of that group (e.g., R71a and R71b).

As shown in the Interlace column of table 7, most of these radars contain Mode 2 interrogations, indicating they are probably military radars. There are also a couple of radars that appear to issue all Mode A interrogations. Another characteristic of this group is the very high number of main beam interrogations. This may be because of side lobes, or the use of an E-scan type antenna, as there are many groups of interrogations between the apparent main beam groups of interrogations. These could be other radars using the same interrogation criteria, or the same ones with the ability to direct the beam in certain directions at random. Some of the radars (e.g., R83 and R84) are not present for very much of the files, leading to the low number of hits per second contributed to the overall environment.

R90 is another special radar. It is using an Interlace pattern consisting of consective Modes repeated (22AACC, etc.). This radar has a very high PRF (almost 400 interrogations per second) and averages 11.1 hits per main beam, and apparently is using an E-scan antenna.

The characteristics of a number of radars in this group are not well defined from analysis conducted thus far. Additional analysis could provide further insight as to the characteristics of these radars.

Table 7: PRT Summary of Group C Radars

					14:13:00	14:15:30	14:15:36	14:20:24	14:22:56	14:34:05	14:39:24	14:43:12
	PRT	**Interlace**	**ScanT (Sec.)**	**Avg. MBHits**	**Hits/Sec. 9a**	**Hits/Sec. 9b**	**Hits/Sec. 9c**	**Hits/Sec. 10a**	**Hits/Sec. 10b**	**Hits/Sec. 10c**	**Hits/Sec. 13a**	**Hits/Sec. 13b**
R70	26043	AAAAAA	3.82	5.40	5.10	8.50	8.00	11.10	12.07	10.87	5.50	0.05
R71a R71b	35106	ACACAC	4.87 11.1	10.4	10.33	11.73	11.85	11.08	11.48	13.21	10.03	4.37
R72	26149	AAAAAA	Escan	8.0	13.21	19.31	20.83	24.96	21.62	22.21	12.19	2.71
R73	40390	2AC2AC	12.00	15.1	0.53	1.60	1.07	0.24	0.07	0.16	1.05	1.39
R74	30438	2AC2AC	9.50	13.6	8.65	11.13	4.19	4.14	3.69	6.02	4.34	6.71
R75	30865	ACACAC	4.73	19.2	4.26	4.34	4.34	4.13	3.87	4.71	4.22	3.78
R76a R76b	46301	2AC2AC	Escan	19.5	21.66	21.44	14.63	30.40	14.84	16.98	9.26	6.08
R77	36346	2AC2AC	7.87	7.8	0.45	0.38	0.49	0.44	10.05	11.20	8.26	7.94
R78a R78b	28769	2AC2AC	4.69 3.7	12.1	6.94	6.98	6.83	8.59	5.97	6.49	4.51	8.08
R79a R79b	30318	ACACAC	3.75?? 10??	16.7	24.15	26.20	28.09	25.08	22.58	22.25	19.53	17.69
R80	30128	2AC2AC	4.70	11.4	3.60	4.09	2.63	3.28	2.85	3.48	2.95	2.88
R81a R81b	46371	AAAAAA	Escan	10.4	20.25	22.04	21.95	25.11	17.82	19.38	13.65	2.70
R82a R82b	46371	2AC2AC	Escan	11.8	9.64	32.07	37.31	15.26	14.34	30.16	14.55	8.46
R83	26149	2AC2AC	Escan	3.9	0.02	0.58	1.17	0.10	0.20	1.66	0.54	0.00
R84	26149	ACACAC	Escan	4.1	0.33	0.75	0.39	1.08	1.39	1.79	0.24	0.00
R85	36473	2AC2AC	10??	12.9	9.92	14.19	0.93	0.35	13.59	16.42	5.92	6.64
R86	30469	ACACAC	9.51	21.4	6.98	7.80	8.34	7.36	6.69	6.67	7.33	5.47
R87	30469	AACAAC	Escan	16.3	12.18	12.21	9.56	10.30	8.29	11.27	8.28	5.96
R90	25084	22AACC	Escan	11.1	6.20	11.17	9.51	16.55	11.60	8.44	7.28	5.66

Figure 14 shows the contribution of ATCRBS interrogations from the radars of Group A for the files in the southern area (Files 8 to 10), and the northern Geographical test area (Files 13 and 14) between PHL and JFK.

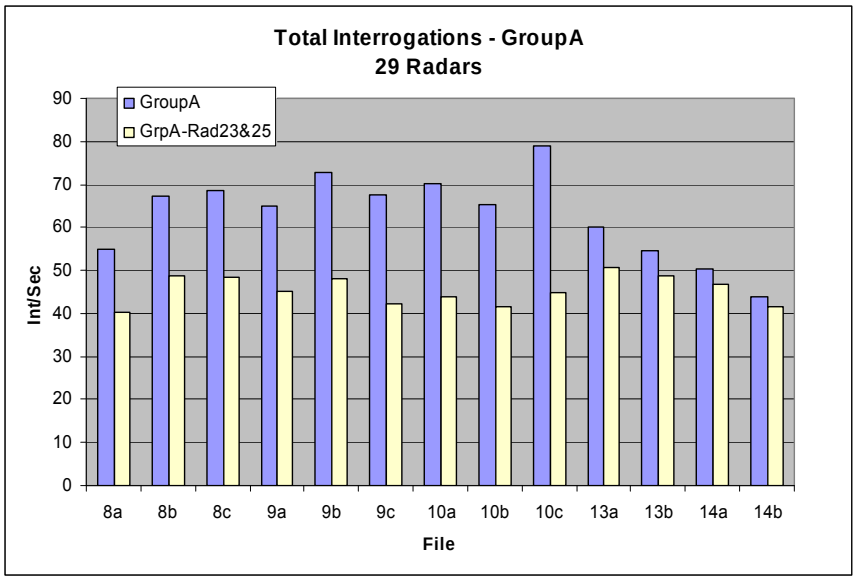

Figure 14: ATCRBS Interrogation Contribution – Group A

As indicated, these radars contribute from about 40 to 80 interrogations per second. When R23 and R25 are removed from the group, the contribution is relatively constant at 40 to 50 interrogations per second.

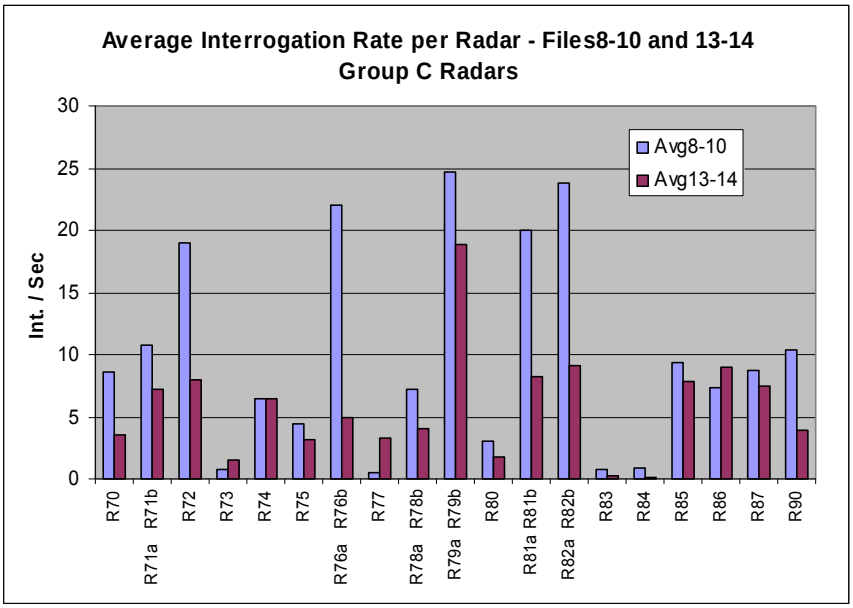

Figure 15: ATCRBS Interrogation Contribution – Group C

Figure 15 shows the average interrogation contribution for each radar in Group C for Files 8 to 10, and 13 to 14 for the flight. In most cases, the average is greater for Files 8 through 10. The greatest difference was for Radar 76 (17 interrogations per second). Overall, the interrogation rate from Group C was 80 interrogations per second greater when in the area of Files 8 to 10 than when in the area of Files 13 and 14. Radars 23 and 25 from Group A had a difference of 16.85 interrogations per second for the same times.

This accounts for 97 interrogations per second of the difference in ATCRBS interrogation rates. It must be noted that these rates are Mode A and C combined. The unsuppressed interrogation data discussed earlier showed a difference of about 100 interrogations per second for each mode. This data was gathered from the PRTs identified. There are obviously more than that in the data. Certainly, however, a case can be made that the radars of Group C (primarily military) are the cause of the increased ATCRBS interrogation rate in the southern area of the data collection flight.

Many of the interrogators, especially in Group C, apparently are using E-scan antenna systems. Many of these are probably airborne interrogators as well. This may contribute to the phenomenon of higher interrogation rates at an altitude of 23000 feet than at 35000 feet.

MODE S PULSE REPETITION TIME DATA.

A summary of the Mode S PRTs found in the data from about 14:15 to 14:52 of the flight is shown in table 8. The Mode S interrogator identity, the IIS code, can be identified from the Mode S interrogation data.

Table 8: Mode S PRT Summary

	Mode S PRT Summary 14:15:16 to 14:51:55								
	Terminal Radars			**Enroute Radars**					
	First Radar			**First Radar**			**Second Radar**		
Radar	**Scan Rate (Sec.)**	**Interlace**	**Avg. Hits /Beam**	**Scan Rate (Sec.)**	**Interlace**	**Avg. Hits /Beam**	**Scan Rate (Sec.)**	**Interlace**	**Avg. Hits /Beam**
IIS=1				11.92	SACSAC	10.0			
IIS=2	4.62	SASC	12.8						
IIS=3	4.61	SASC	13.5	10.1	SACSAC	8.1			
IIS=4	4.63	SASC	13.8	10.1	SACSAC	8.2			
IIS=5	4.62	SASC	10.8						
IIS=6	4.63	SASC	13.5						
IIS=7				4.62	S2ACS2AC	9.4	4.62	SACSAC	9.7
IIS=8	4.62	SASC	7.9	11.96	SACSAC	13.0			
IIS=9	4.63	SASC	13.5						
IIS=10	4.62	SASC	13.8						
IIS=11									
IIS=12				11.99	SACSAC	15.6			
IIS=13									
IIS=14				11.99	SACSAC	11.4			
IIS=15				11.96	SACSAC	16.0			

All IIS codes except 11 and 13 were seen during this period. There were two radars using IIS=7 (later identified as Elwood and FAA Technical Center Building 270, which were engaged in experimentation during our test flight). Elwood was using Supermode 2. There were also two radars per IIS code for IIS=3, 4, and 8 as well. In all of these cases, one was a terminal radar and the other an enroute. All terminal radars were using an Interlace pattern of S4S3, while the enroutes were all using S43S43 except Elwood, which used Supermode 2 (S243S243). The average hits per beam for each radar were taken from the average when the reception was the best for that particular radar. The aircraft traveled at 35000 feet from a position south of Baltimore to about midway between PHL and New York during this period of time.

1090 MHZ ENVIRONMENT CHARACTERIZATION FLIGHT OF 01/26/06

Along with the 1030 MHz data recording and analysis, data was also collected to analyze 1090 MHz activity. Data was collected and recorded via DATAS on 1030 MHz and via the RF Measurement Facility (RMF) on 1090 MHz. The 1090 MHz data was collected via independent receivers connected to top and bottom L-Band omni-antennas independent of the 1030 MHz data collection configuration. Both inputs had an RF preamplifier installed at the antenna.

The test plan was to compare data from the same locations in space on both 1030 MHz and 1090 MHz to fully characterize the RF environment. Figure 16 shows the position of N-40 at various altitudes when it was in the Geographical Test Area as indicated by the large red, white and blue dots. The data collected in this area was to be compared to get the various rates as a function of altitude.

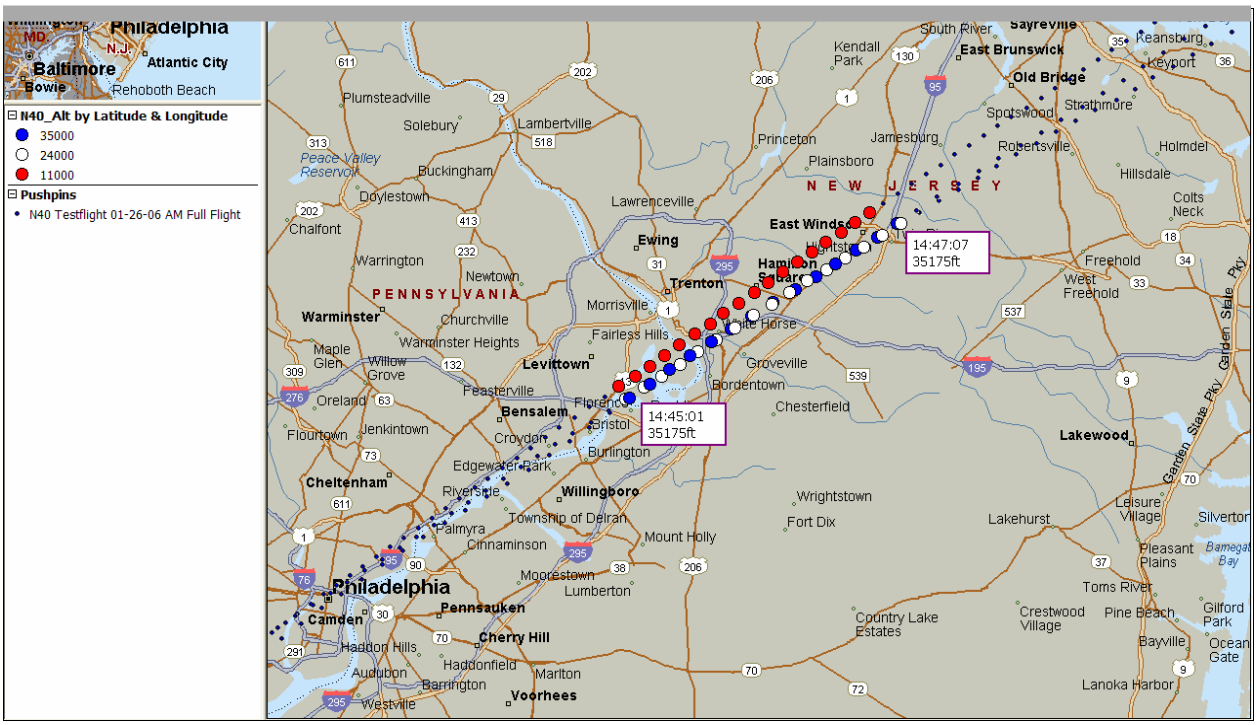

Figure 16: Geographical Test Area between PHL and JFK

As previously indicated, problems occurred during data collection during the initial leg of this flight at 35000 feet, and no usable 1090 MHz data was recorded until the southbound leg at 23000 feet. The red trace in figure 17 shows the area at 23000 feet when both 1030 and 1090 MHz data were collected, from 15:09 to 15:11. Data from both frequencies was successfully captured at 11000 feet in the northern Geographical test area (black trace).

Figure 17: Actual Geographical Test Areas at 23000 feet and 11000 feet

The ATCRBS and Mode S FRUIT rates both vary significantly as a function of relative aircraft position as well as time. The Mode S data of the observed aircraft was analyzed to get information about those aircraft. This data was correlated with Elwood Radar data to produce the population as a function of range with respect to the position of N-40 as it was flying the test patterns. The aircraft range data relative to N-40 was put into bins to produce the plot shown in figure 18. Figure 18 is a plot of the number of Mode S aircraft within the various ranges of N-40 regardless of its position. The three areas selected for analysis were times when the aircraft was at level flight at 35000, 23000, and 11000 feet. As indicated, there were approximately 350 aircraft within range of the Elwood radar detected by N-40 when the aircraft was at 35000 feet. This number increased to almost 400 when the aircraft was level at 23000 feet and descending to 11000 feet. The number decreased throughout the 11000-foot leg until it was about 330 at the end of the flight.

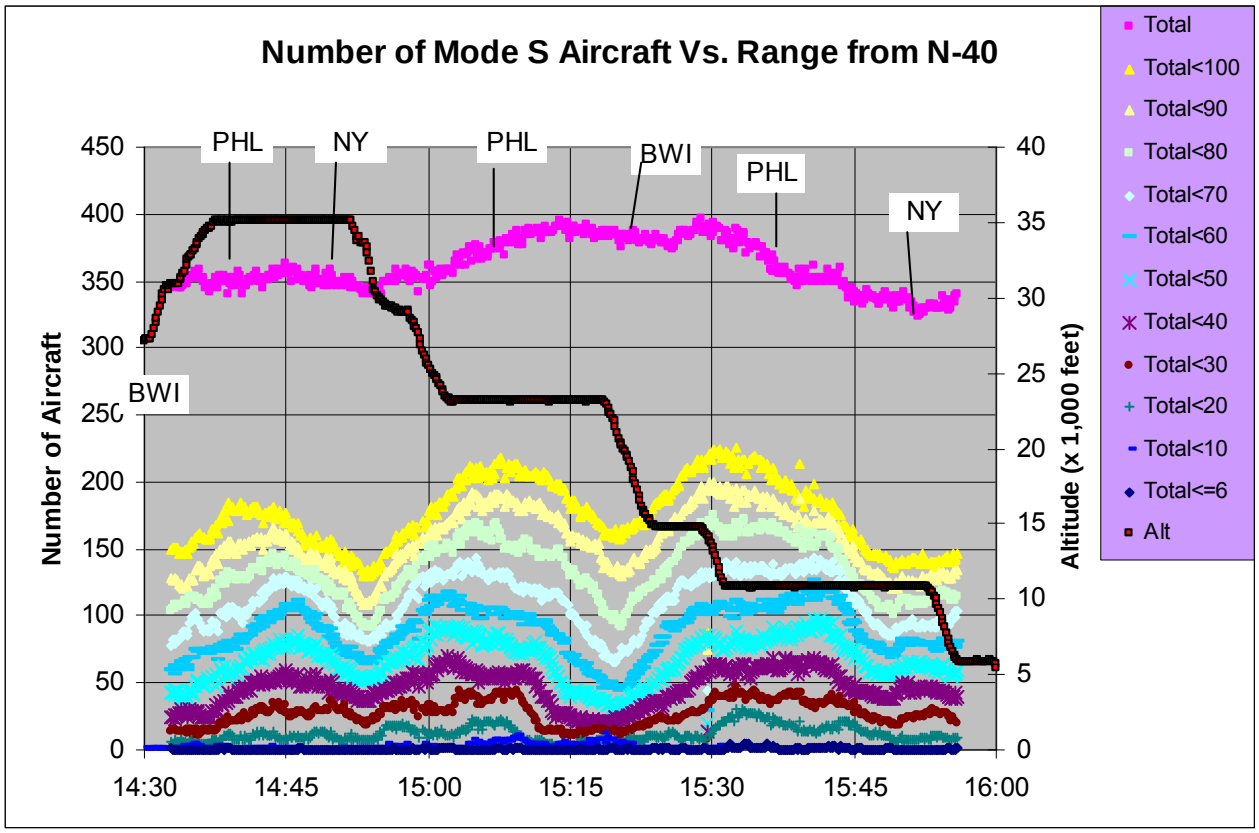

Figure 18: Mode S Aircraft Vs. Range From N-40

The number of aircraft at 100 NMi or less is very important, because that is the range of an aircraft whose FRUIT replies will produce a signal of approximately –84 dBm at the victim antenna with nominal transponder power output. Hence, when the FRUIT rate at –84 dBm is quoted, this can be related to the number of aircraft within 100 NMi. This number increased throughout the flight. At 35000 feet, it was about 180 aircraft, at 23000 feet, it was about 210, and at the beginning of the 11000-foot leg, it was about 220.

The Mode S and ATCRBS FRUIT rates are presented in figures 19 and 20, respectively, for the geographical test area in which the N-40 was at 23000 feet, southwest of Philadelphia.

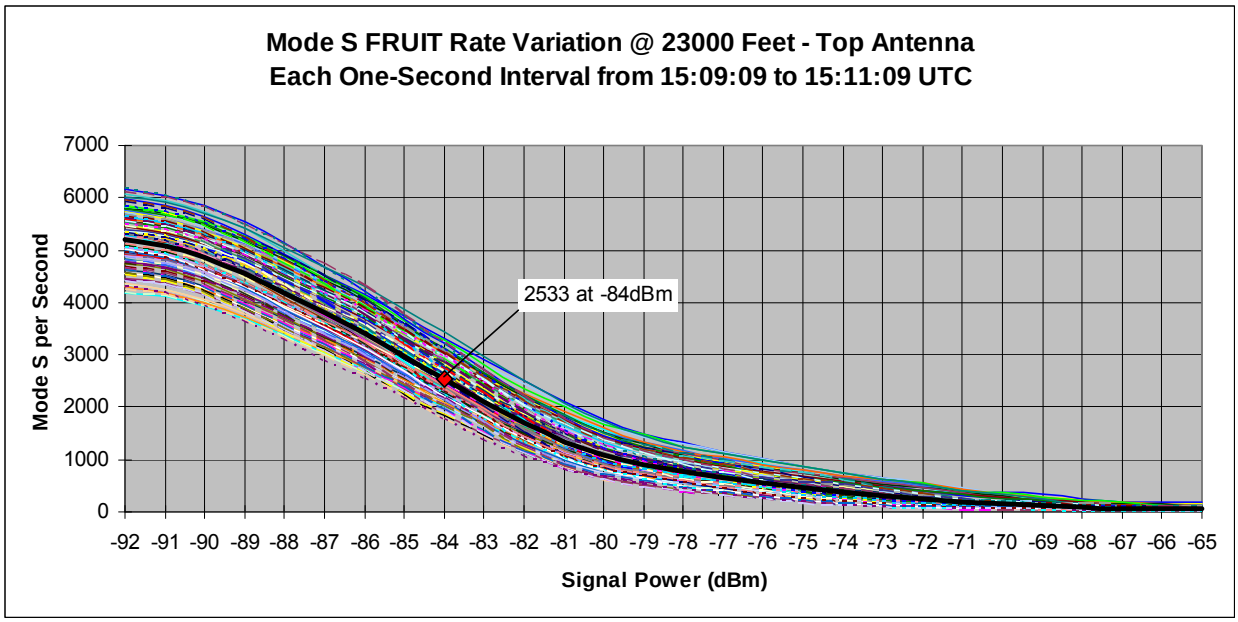

Figure 19: Mode S FRUIT Rate at 23000 feet – 15:09:09 to 15:11:09

The variations are shown in the Mode S FRUIT rate when measured for a one-second interval as indicated on figure 19. The FRUIT rate at –84 dBm varied from 1800 per second to 3300 per second during this two-minute interval. The average rate for the two minutes is shown by the solid black line (2533 at –84 dBm).

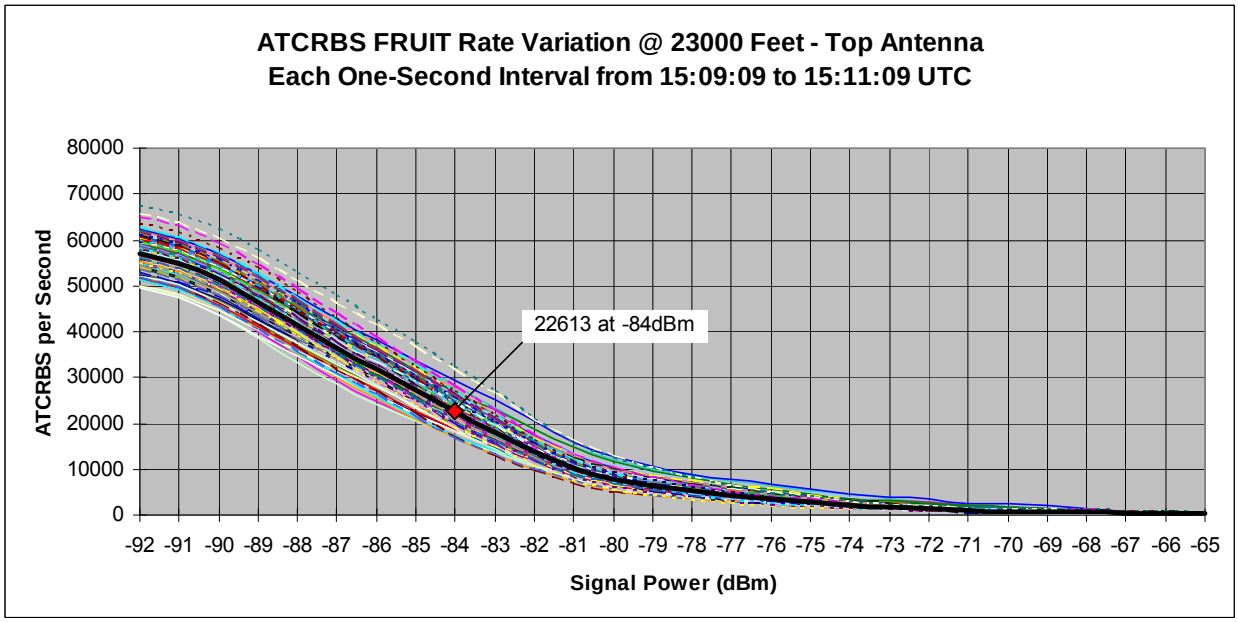

Figure 20: ATCRBS Rate at 23000 feet – 15:09:09 to 15:11:09

The average ATCRBS FRUIT rate was 22613/Sec. at –84 dBm. The rate varied from 17000 to 32000 per second when using the one-second intervals for the same data. The Mode S and

ATCRBS FRUIT rates are shown in figures 21 and 22, respectively, for the geographical test area when the aircraft was at 11000 feet, northeast of Philadelphia.

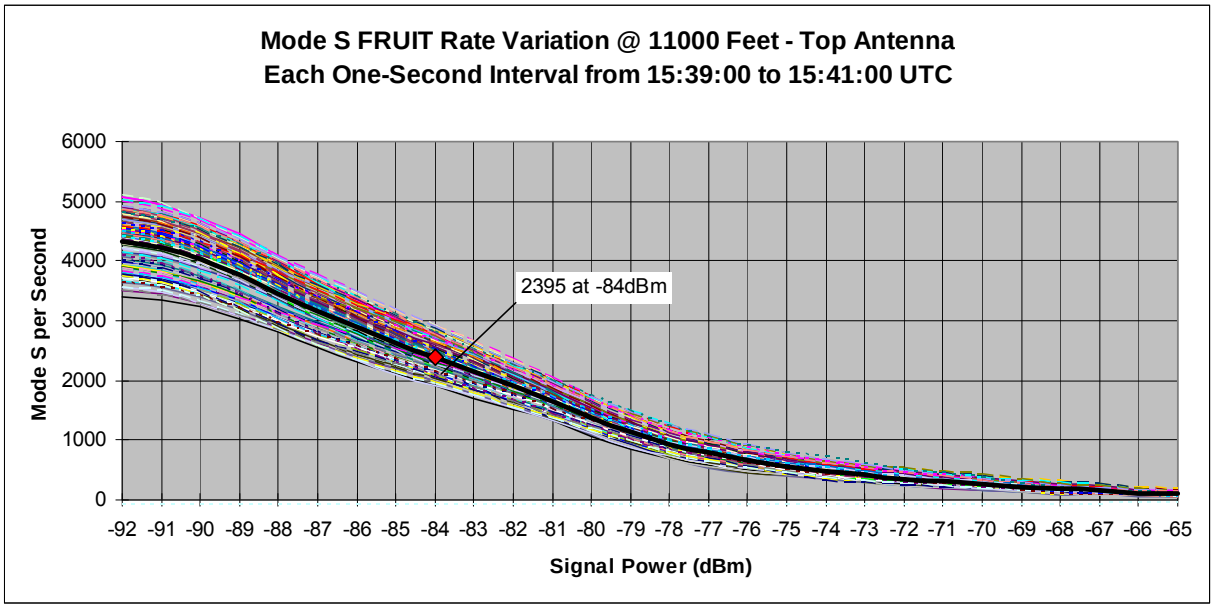

Figure 21: Mode S FRUIT Rate at 11000 feet – 15:39:00 to 15:41:00

The variations are shown in the Mode S FRUIT rate when measured for a one-second interval as in figure 19. The FRUIT rate at –84 dBm varied from 1900/second to 2950/second during this two-minute interval. The average rate for the two minutes is shown by the solid black line (2395 at –84 dBm).

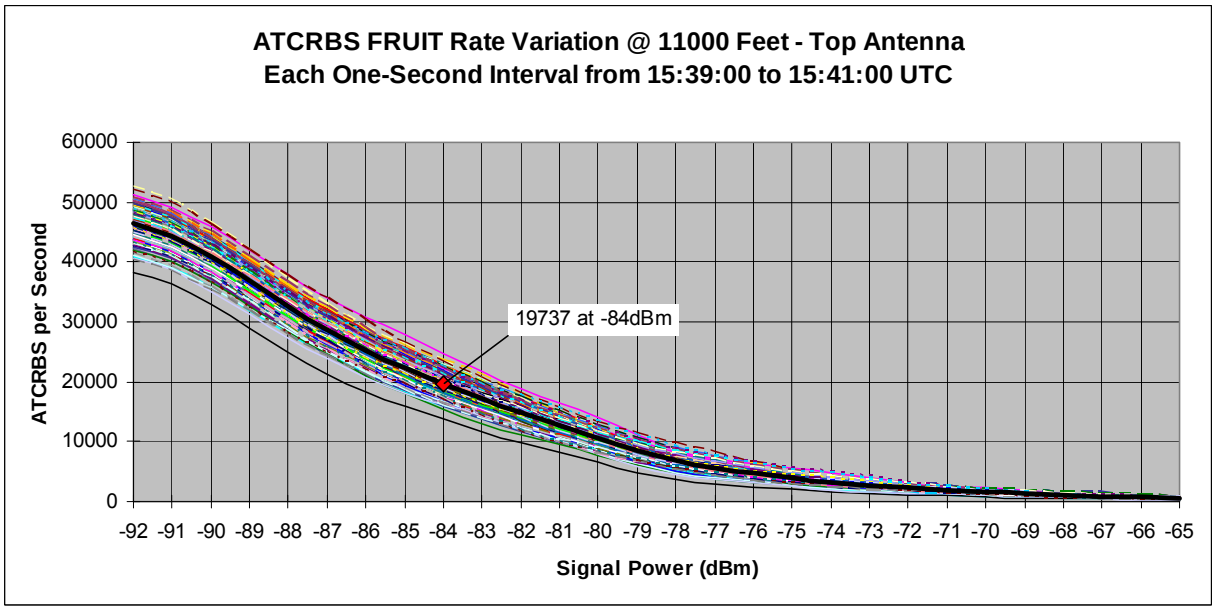

Figure 22: ATCRBS FRUIT rate at 11000 feet – 15:39:00 to 15:41:00

The average ATCRBS FRUIT rate was 19737 per second at –84 dBm. The rate varied from 13000 to 23000 per second when using the one-second intervals for the same data.

MODE S REPLY TYPE ANALYSIS.

The DF code composition of the Mode S replies was examined for all of the data collected at 23000 feet and 11000 feet. It became apparent that the UF/DF code composition percentages were different than those of the 1030 MHz data. Table 9 provides a summary of the results.

Table 9: UF/DF Code Composition

UF/DF Code Composition		
UF/DF Code	**Interrogation (%)**	**Replies (%)**
0	89	45.7
4	4.3	8.2
5	0.1	0.05
11	3.1	39.5
16	3.4	< 1.0
20/21	0.1	6.7

The 1030 MHz data indicated that more than 90% of the interrogations were related to TCAS (89% UF=0 and 3.4% UF=16). The reply data, however, indicated only 45.7% DF=0 and an insignificant amount of DF=16 replies. This is not surprising, as UF=16 is a broadcast interrogation, which requires no reply, and the only other UF=16/DF=16 combinations are used for TCAS coordination messages, which are rare. A surprising observation is that 39.5% of the replies were All-Call replies when only 3.1% of the interrogations were All-Calls. This is because Mode S Only All-Call interrogations solicit replies from ALL aircraft if not locked out. The reply rates for DF=20 and 21 are higher than what would normally be expected because Elwood and Bldg. 270 Mode S sensors were both using IIS=7 and requesting Extended Capability reports from all aircraft via UF=4 and 5 interrogations.

N-40 TRANSPONDER ANALYSIS.

Additional analysis was conducted comparing the interrogation and reply rate for the N-40 using the 1030 MHz and 1090 MHz data collected. Table 10 provides a summary of the interrogations addressed to N-40 and the resulting replies. There were an average of 32.5 interrogations per second addressed to N-40 during the two-minute test interval at 23000 feet. These resulted in averages of 32.2 replies per second from the top antenna and 35 from the bottom. The reply data includes DF=11 with IIS=0, the acquisition squitter replies that are broadcast without the need of an interrogation. The columns labeled TOP and BOTTOM do not necessarily mean that this is the antenna to which the aircraft's transponder directed the reply. Whenever a reply occurred, its amplitude exceeded the maximum value of the analog to digital converter quantizing the receiver output, so it was not possible to tell which antenna transmitted the reply. TOP and BOTTOM identifies the receiving antenna channel. There were occasional gaps in the data, which is probably why the numbers do not match exactly.

Table 10: Mode S Interrogations to N-40

Mode S Interrogations to N-40			Replies	
			Top	Bottom
Average Interrogations per second	# Interrogations to N-40 at 23000 ft.	32.5	32.3	35.0
	# Interrogations to N-40 at 11000 ft.	19.4	23.0	23.0

Table 11: ATCRBS Interrogations to N-40

ATCRBS Interrogations to and Replies from N-40				
	Mode A	Mode C	A + C	Replies (A + C)
Avg. # Int./Sec. @ 35000'	162	88	250	278
Avg. # Int./Sec. @ 23000'	182	97	279	257
Avg. # Int./Sec. @ 11000'	147	76	223	171

The ATCRBS interrogation and reply data is shown in table 11. As indicated, the reply rates are slightly lower than the interrogation rates measured, except at 35000 feet. The reply rates are expected to be slightly lower than the interrogation rates since the transponder will not always be available for reply. The reply data correlates with the interrogation data that shows that the ATCRBS interrogation rate at 23000 feet was higher than it was at 11000 feet by a significant margin.

A PRT analysis was performed on the reply data from N-40 during the test periods at 11000 feet and 23000 feet. At 11000 feet, replies to 21 of the 29 radars from Group A were identified Interrogations from only ten of these radars were identified for the same period. At 23000 feet, replies from 27 of the 29 radars were identified. Interrogations from only 19 of these radars were identified during this period. This correlates with earlier evidence to suggest that the transponder of N-40 is more sensitive than that of DATAS. Notably absent was radar 22, which was present in the 11000-foot sample. This is a radar with a PRF of 375 (all Mode A) interrogations per second. It had been detected at 11000 feet with 39 interrogations and 43 replies per beamwidth.

The suppression rate was considerably higher when N-40 was at 11000 feet than at any other time during the flight (refer to figure 12). This will significantly reduce the transponder availability to respond to any interrogations. Since the sensitivity of the N-40 transponder is greater than that of DATAS it will see more suppressions than DATAS, making the availability less than that indicated by DATAS. DATAS 1030 MHz data indicated that the availability was about 2% less at 11000 feet than at 23000 feet.

Table 12 contains the All-Call interrogation and reply data from N-40 for the two Geographical test area samples of two minutes each. The interrogation and reply counts are the totals for each of the two-minute intervals. The first column lists all radar sites identified during the flight even though there are not necessarily interrogations/replies associated with all of them during this interval. Additional comments regarding the data from each radar site are provided in the right column

Table 12: All-Call Interrogation/Reply Summary

			23000' - 15:09:09 to 15:11:09				11000' - 15:39:00 to 15:41:00				
Location of Site using IIS	**Range Rel to 23k (NMi)**	**Range Rel to 11k (NMi)**	**IIS**	**# Int.**	**No Lock-out**	**# Repl.**	**IIS**	**# Int.**	**No Lock-out**	**# Repl.**	**Comments**
(N-40 Acquisition Squitters)			0	0		555= >4/Sec.	0	0		368= >3/Sec.	Too many IIS=0 replies for squitters
WJH Tech Center – Bldg. 270	53	50	1	38		0	1	0		0	Locked out @ 23000, ? @ 11000
Islip, NY - ASR-9	120	85	2	26	26	110	2	141	141	149	All fringe targets, esp. @ 23000
Baltimore, MD-ASR-9 Newburgh, NY ASR-9	49	103	3	359		43	3	24	24	141	Baltimore seen to 174 NMi, Newburg to 157 NMi
JFK – Jamaica, NY ASR-9 Chantilly, VA (Dulles) ASR-9	110	45	4	220	220	310	4	172		0	Dulles seen to 120 NMi, Jamaica to 106 NMi
Camp Spring, MD, ASR-9	75	134	5	251	251	268	5	113	113	165	All fringe targets, 11000 more
Washington, DC ASR-9	78	138	6	139	139	179	6	0		0	Fringe targets @ 23000, none @ 11000
Elwood and Bldg. 270	53	50	7	175		62	7	126		66	2 Radars - All stochastic
Harrisburg, PA ASR-9	64	98	8	94	94	100	8	84	84	154	All fringe targets, more @ 11000
Philadelphia, PA ASR-9	28	37	9	215		0	9	152		0	Range 20-40 NMi, All Locked out
Newark, NJ ASR-9	99	34	10	205	205	285	10	146		0	Fringe @ 23000, Locked out @ 11000, back lobe most of the way
St. Alban, VT - FPS-67 Enroute	325	252	11	0		0	11	0		0	None
Benton, PA – FPS-67 Enroute	100	100	12	6		17	12	41		0	Poor coverage @ 23000, Locked out @ 11000
Coventry, RI ASR-9	222	166	13	0		0	13	0		0	None
Oakdale, PA - FPS-67 Enroute	205	250	14	0		0	14	0		0	None
West Cummington, MA - FPS-67 Enroute	206	150	15	49		29	15	0		0	Locked Out @ 23000, Below Line of sight @ 11000
		Totals		1777	935	1403		999	362	675	Replies do not include N-40

The beige cells indicate sites from which N-40 is locked out to All-Call interrogations, which elicit no replies from N-40. All of the interrogations from Elwood and Bldg. 270 (highlighted in green) use IIS=7 and have a probability of reply (Pr)=9, which indicates that the lockout should be ignored, and reply with a probability of 0.5. Note that the overall reply rate is approximately 50%.

Note that there are more than four acquisition squitters per second from N-40 when at 23000 feet, and more than three per second when at 11000 feet. There were no Mode S All-Call interrogations detected with IIS=0, which would elicit the same reply. (The data content of an All-Call reply to an ATCRBS/Mode S All-Call or a Mode S Only All-Call with IIS=0 is the same as the data content of an acquisition squitter.) Therefore, it was expected that the acquisition squitter rate would be one per second. ATCRBS/Mode S All-Call interrogations were not expected since no Ground interrogators use them, and these interrogations were not decoded on this flight for this reason. As a result, there was no way to identify these interrogations as the source of the extra squitters. Also, since TCAS and some Ground interrogators use an ATCRBS Only All-Call, which differs from an ATCRBS/Mode S All-Call only by the width of the P4 interrogation pulse (a wide P4 pulse is used for the ATCRBS/Mode S All-Call interrogation), the potential for Mode S replies resulting from a wide P4 pulse from a source of these interrogations is also a possibility.

Another observation from the data in table 12 is that there are instances when the number of All-Call interrogations and replies do not correlate. For example, at 23000 feet, DATAS detected 26 interrogations from IIS=2 (Islip ASR-9) over the two minutes and none of the interrogations were locked out. Although there were only 26 interrogations, 110 replies were detected from the onboard transponder during the same two-minute period. While at 11000 feet, there was good agreement between DATAS-detected interrogations and the number of onboard transponder replies (141 Vs. 149). The average range of the aircraft from the Islip interrogator site was 120 NMi at 23000 feet, and 85 NMi at 11000 feet. The difference between the number of interrogations detected and the number of onboard replies appears to be the result of All-Call interrogations that are not locked out. The further the interrogator is from N-40 (and therefore the weaker the signal), the greater the disparity between interrogations and replies. This indicates that the N-40 transponder has a better sensitivity than the DATAS transponder, and since the 1090 MHz replies were produced via the transponder of N-40, the reply counts exceed the interrogation count. On a per scan basis, the number of interrogations less per scan from the interrogator detected by DATAS reasonably explains these differences over the two-minute sample. The sensitivity of the DATAS transponder was known to be -75 dBm at the transponder. With 2 to 3 dB of cable loss between the transponder and the antenna, the sensitivity at the antenna was about the middle of the allowed range. The sensitivity of the N-40 transponder was only known to be within the allowed range of –68 dBm to –75 dBm at the antenna.

OTHER ANALYSIS.

Another surprising observation from the data analysis was the large distance from the interrogators (using the same IIS) that All-Call Interrogations were detected. The extreme cases in this data were interrogations detected from the Baltimore ASR-9 at 174 NMi and Newburgh, NY at 157 NMi. These points did not occur within the two-minute interval test data, but were found by examining data collected before and after the test intervals.

The Newark ASR-9 exhibited what was probably a backlobe (offset ~1.9 seconds from the main lobe) until the range exceeded 130 NMi.

The DF code distribution of Mode S replies is shown on figure 23 as a function of time.

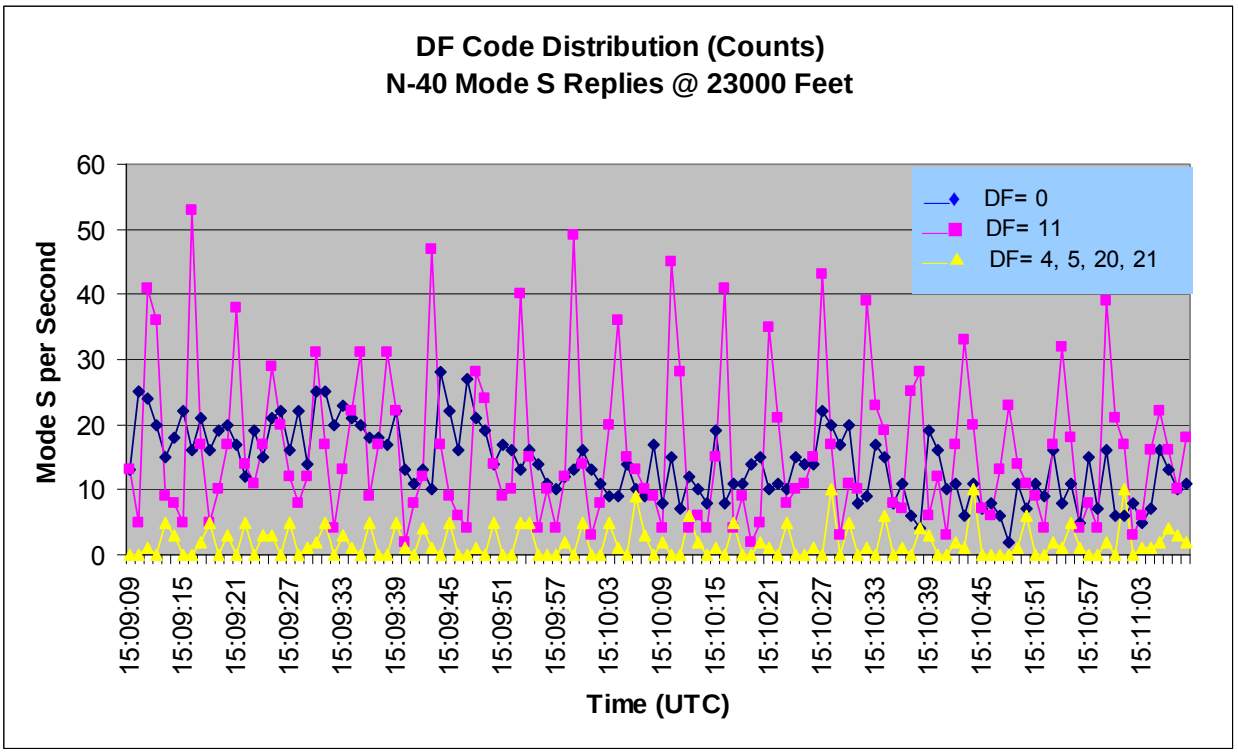

Figure 23: DF Code Distribution of Mode S Replies vs. Time

Of particular interest is the wide variation of DF=11 (All-Call) replies. The variation appears to be periodic, with the highest value of 53 replies in a single second at 15:09:16. Table 13 provides a breakdown for the peak second and the following nine seconds.

Table 13: All-Call Replies - IIS Vs. Time (Peak One-Second Interval)

All-Call IIS Vs. Time (Seconds)											
IIS_Dec	**Total**	**15:09:16**	**15:09:17**	**15:09:18**	**15:09:19**	**15:09:20**	**15:09:21**	**15:09:22**	**15:09:23**	**15:09:24**	**15:09:25**
0	555	7	5	3	5	5	2	8	5	11	6
2	110					6				4	
3	43	19				2					
4	310	6	5				7	6			
5	268	3	7				9				4
6	179	6					7				8
7	62			2						2	
8	100	5				4	1				4
10	285	7			5		7		6		7
12	17										
15	29						5				
Total	1958	53	17	5	10	17	38	14	11	17	29

The IIS values listed were all values seen during the two-minute interval, but some of them were not seen during this ten-second period. There were squitter replies (IIS=0) each second, and significantly more than one per second, as indicated previously.

During the peak second, there were 19 replies to IIS=3. There were two radars using this IIS during this period (Baltimore ASR-9 and Newburgh, NY ASR-9). As indicated, they were locked out after 15:09:20.

There were also two radars using IIS=4 (Jamaica, NY ASR-9 and Dulles ASR-9). The main beams of these two radars were apparently about one second apart during this period, as five or six replies per main beam is about the average. Neither of these two radars was locked out during this two-minute interval (15:09 to 15:11).

The backlobe of IIS=10 is also obvious from this data. Note the beams at 15:09:16, 15:09:19, 15:09:21, 15:09:23 and 15:09:25 in table 13.

The All-Calls of the majority of IIS codes are not locked out and they share a similar characteristic. They are all further than 60 NMi away from N-40 and therefore are not being tracked by any of the terminal systems (note that most are ASR-9 interrogators). For example, the Islip, NY ASR-9 radar is about 120 NMi away from N-40 when in the 23000-foot Geographic test area, and 85 NMi away when in the 11000 foot test area. N-40 replied to this IIS a total of 159 times in the four-minute period, or about 40 replies per minute. This is not significant by itself, but when considering that all other aircraft in the same airspace as N-40 are doing the same thing, the FRUIT rate is increased considerably. This is the reason that the replies from All-Calls represent about 40% of the FRUIT, but only about 3% of the interrogations. Ground-based Mode S interrogators that are actually tracking the aircraft keep them locked out and elicit no replies.

As discussed previously in the N-40 reply analysis, aircraft are exceeding the expected squitter reply rate. It should be approximately one per second for each aircraft. Note that the rate for the sample covered by table 14 shows a squitter rate from N-40 of 3.1 per second. These replies are apparently not caused by All-Call Interrogations with IIS=0, because none of them were seen during this period. As mentioned previously, this could be caused by interrogators using ATCRBS/Mode S All-Call interrogations, but no interrogators are known to use them. Since the

DATAS 1030 MHz system as set up for this flight did not save the data for ATCRBS/Mode S All-Call interrogations, future flights will incorporate this additional data to help determine the reason for the high observed squitter rate.

Table 14 shows the squitter rate per second for a few aircraft within the vicinity of N-40 when the 11000-foot sample was taken. Note that only four of them have squitter rates of less than one per second (the nominal rate) and most of those have a significant number spaced at more than 1.5 seconds (A802C0 has 15). This means that many of the squitters are spaced closer than the allowed 0.8 seconds. This indicates that the squitter rate is close to double what it is supposed to be. It is very doubtful that the transponders are squittering incorrectly. If the spacing is examined closely, it can be seen that there are many stretches of time where the squitters are spaced near the nominal one second rate. Then there appear to be many bursts of closely spaced ones. There were no All-Calls with an IIS=0, so that is not what is causing the All-Call replies with IIS=0 (squitter definition).

Table 14: Squitter Rates of Aircraft Near N-40

Address	**Squitters/Second**	**# Intervals > 1.5 Sec..**
A4AA47 (N-40)	3.10	0
A535C6	2.76	4
C00B7B	1.92	7
A438C3	1.91	5
A4F1ED	1.91	6
930E47	1.22	13
A91B2B	1.22	14
A39FB1	1.16	5
A09F19	1.10	12
ABB399	1.10	13
A3AA35	0.99	3
A4C6B7	0.98	11
A802C0	0.84	15
A52423	0.81	14

The data was examined from 15:39 to 15:41 (11000 feet altitude) that contained all replies via RMF. Figure 24 shows the squitter rate per aircraft for all aircraft present for the entire period.

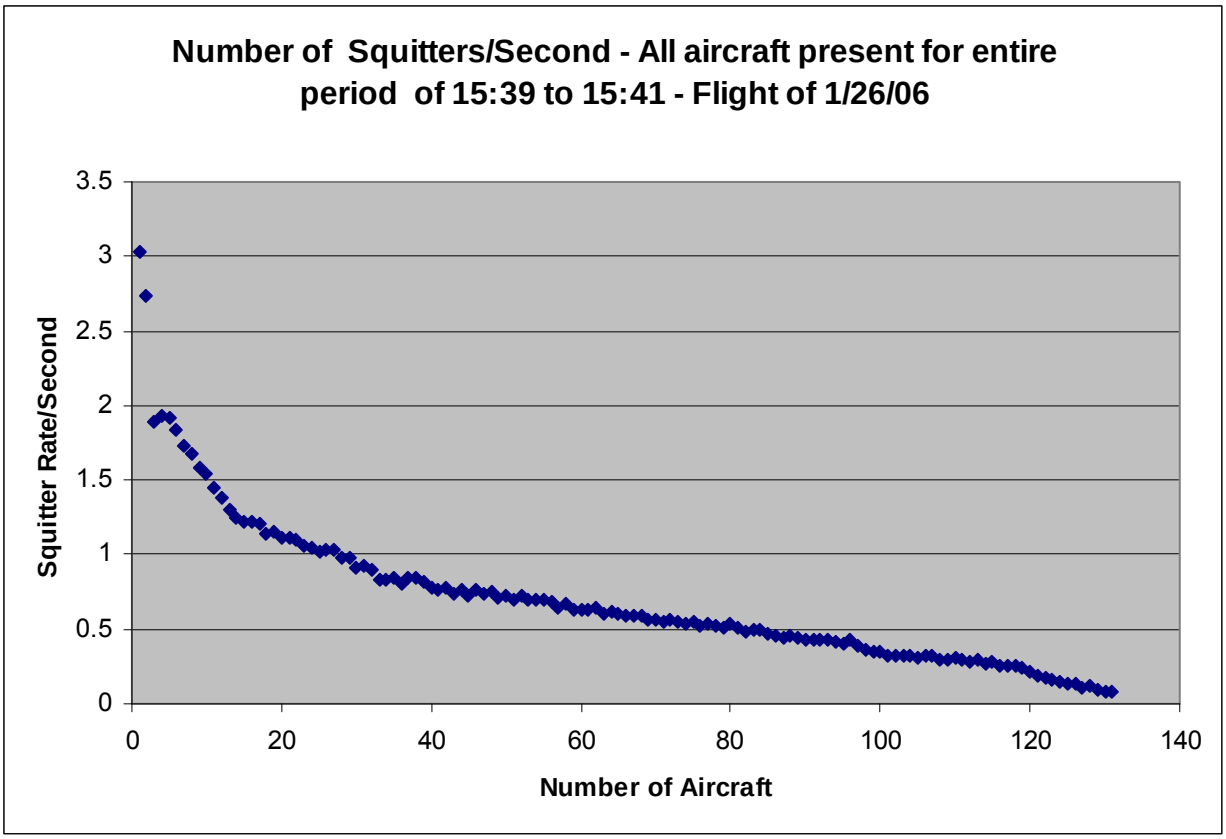

Figure 24: Squitters per Second from Aircraft – 15:39 to 15:41

As shown by figure 24, there were a total of 27 out of the 131 aircraft that had a squitter rate higher than one per second. This required further scrutiny since there are significant time gaps between squitters for most aircraft.

Figures 25 through 28 illustrate acquisition squitter data from four aircraft taken over a two minute period at 11000 feet (only while within range of N-40). Of these four samples, A78A24 is the closest to what the squitter rate is supposed to be (figure 25). Even though its average rate is correct, the data shows that this is only because a lot of squitters were missed (approximately 15). Intervals of two seconds indicate that a squitter was missed. They were averaged out, however, by those spaced much closer. It is hard to see any correlation between observed squitters and the nominal interval of one second in any other sample. The aircraft must be responding to interrogations with IIS=0 that produce All-Call replies. A possible explanation considered is the corruption of TCAS Whisper/Shout interrogations, which could cause the transponders to decode the P4 pulse as a wide pulse (1.6us). In that case they will respond with a Non Selective All-Call Reply (same as squitter). However, it is doubtful that this is the cause as it is happening far too often for that to be the case.

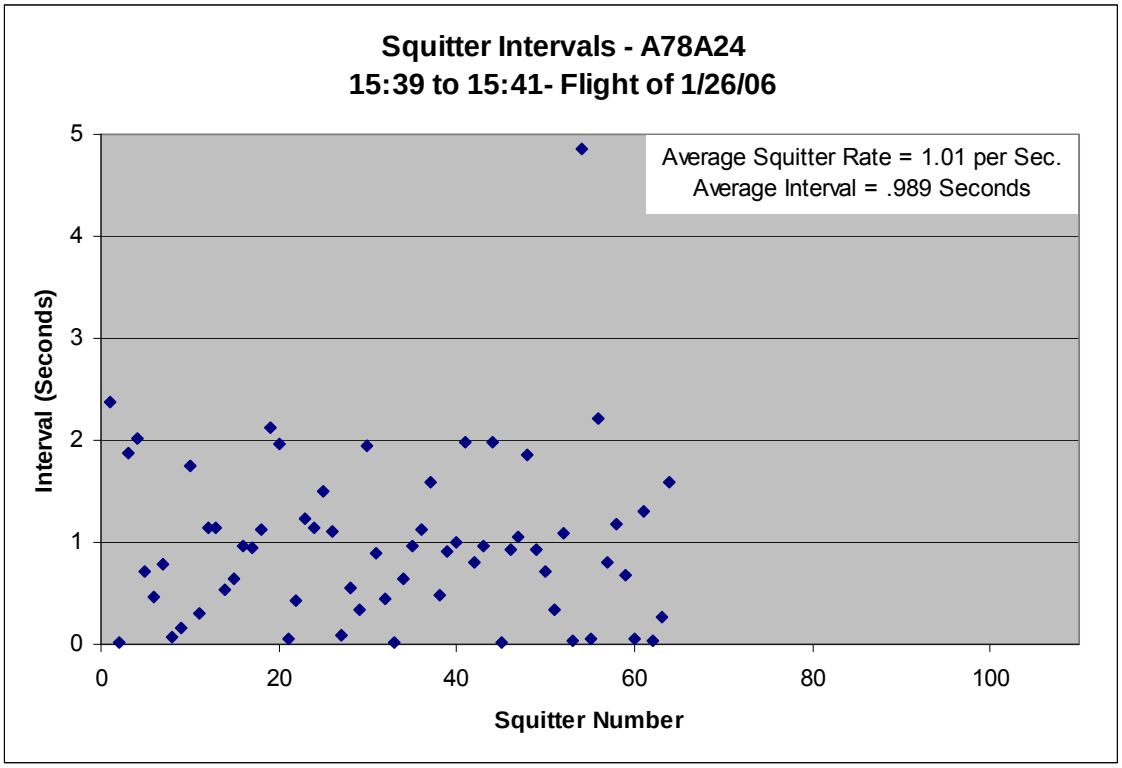

Figure 25: Squitters from Aircraft A78A24

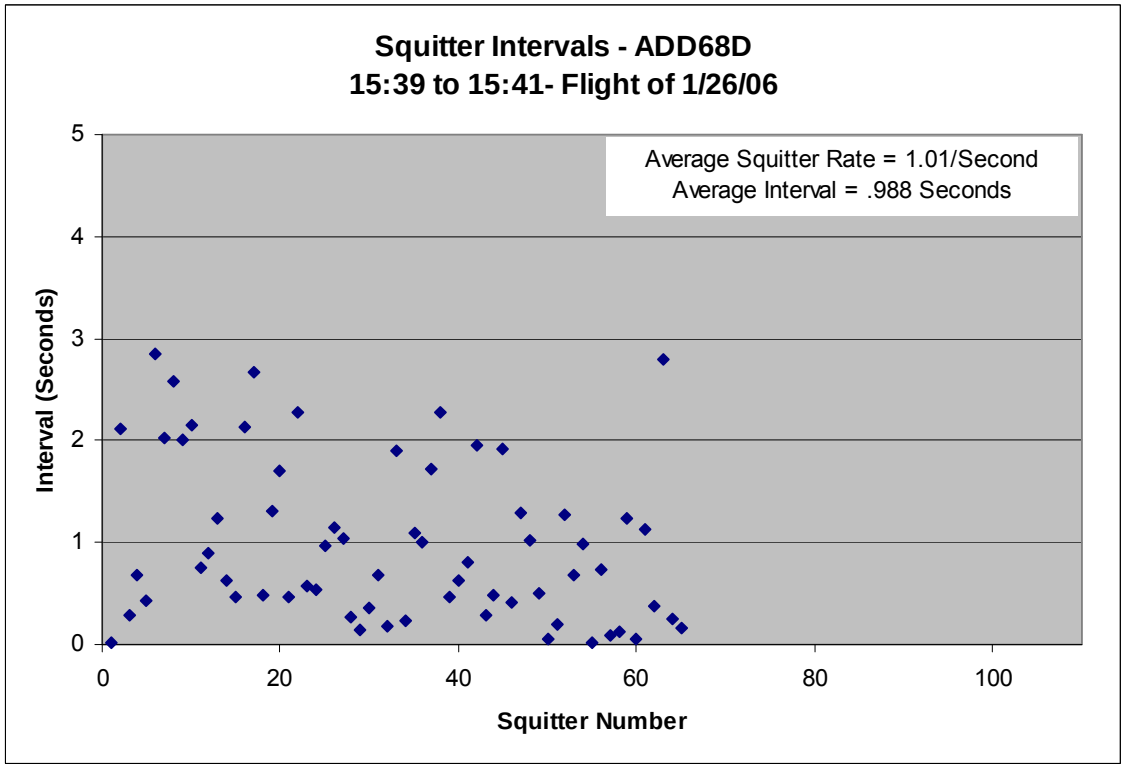

Figure 26: Squitters from Aircraft ADD68D

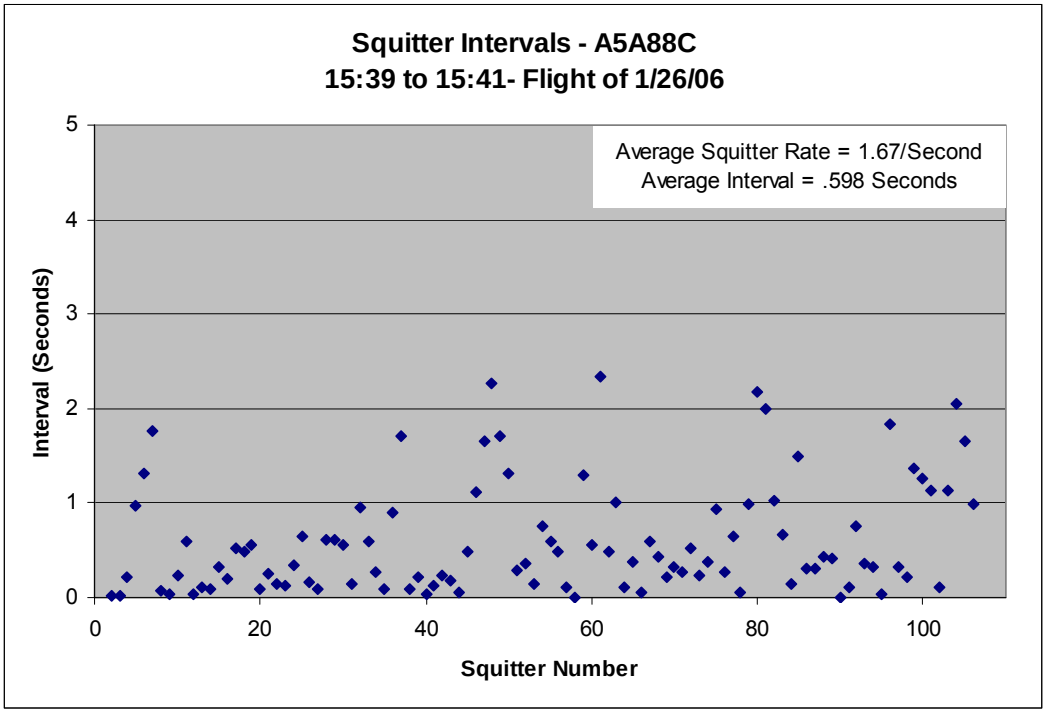

Figure 27: Squitters from Aircraft A5A88C

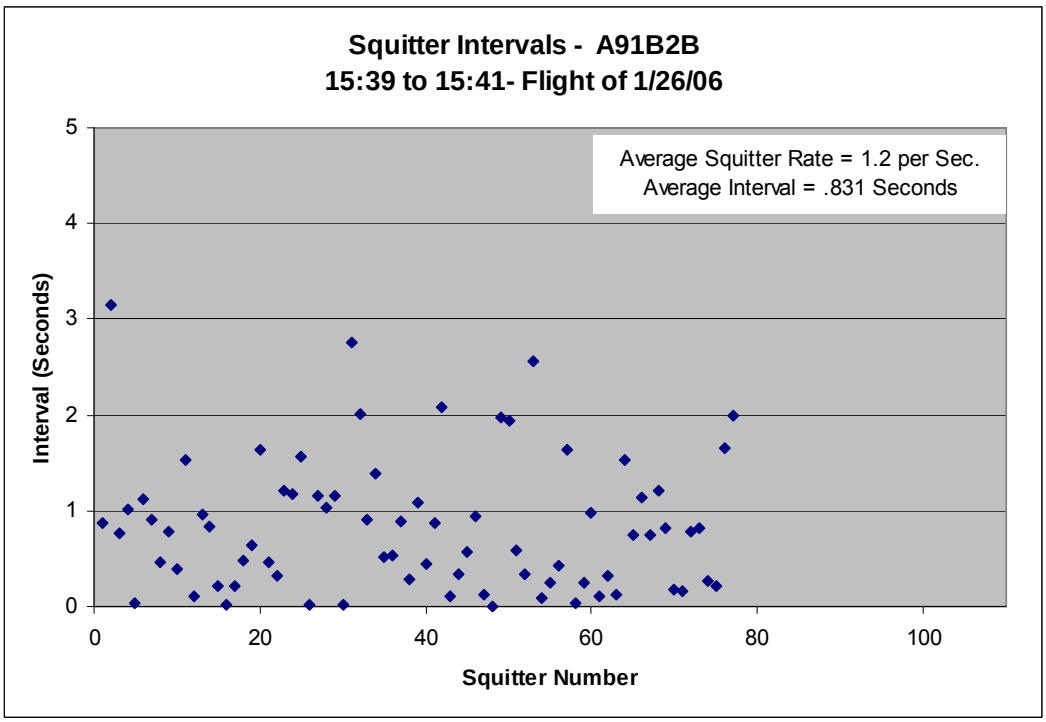

Figure 28: Squitters from Aircraft A91B2B

SUBSEQUENT TESTING AND ANALYSIS.

WJHTC SIMULATION. After the January 2006 flight test, a 1030 MHz data sample was collected via an antenna on the lab roof at the WJHTC to see if any ATCRBS/Mode S All-Call interrogations were detected. The antenna is a dish type with gain and a narrow beam dwell, so the signal levels are higher than would be seen by a transponder at the same range from an aircraft. A series of tests were conducted with various attenuators in line with the receiver.

Figure 29 provides a sample of that data. Approximately one Intermode (ATCRBS/Mode S All-Call) interrogation per second occurred during this data sample. Figure 29 shows the time difference between consecutive Intermodes on two different time scales. There is definitely a pattern of Intermode interrogations spaced at approximately five milliseconds. They also occur at a scan rate of 4.82 seconds. All are Mode A Intermodes, which are not used by FAA interrogators or TCAS.

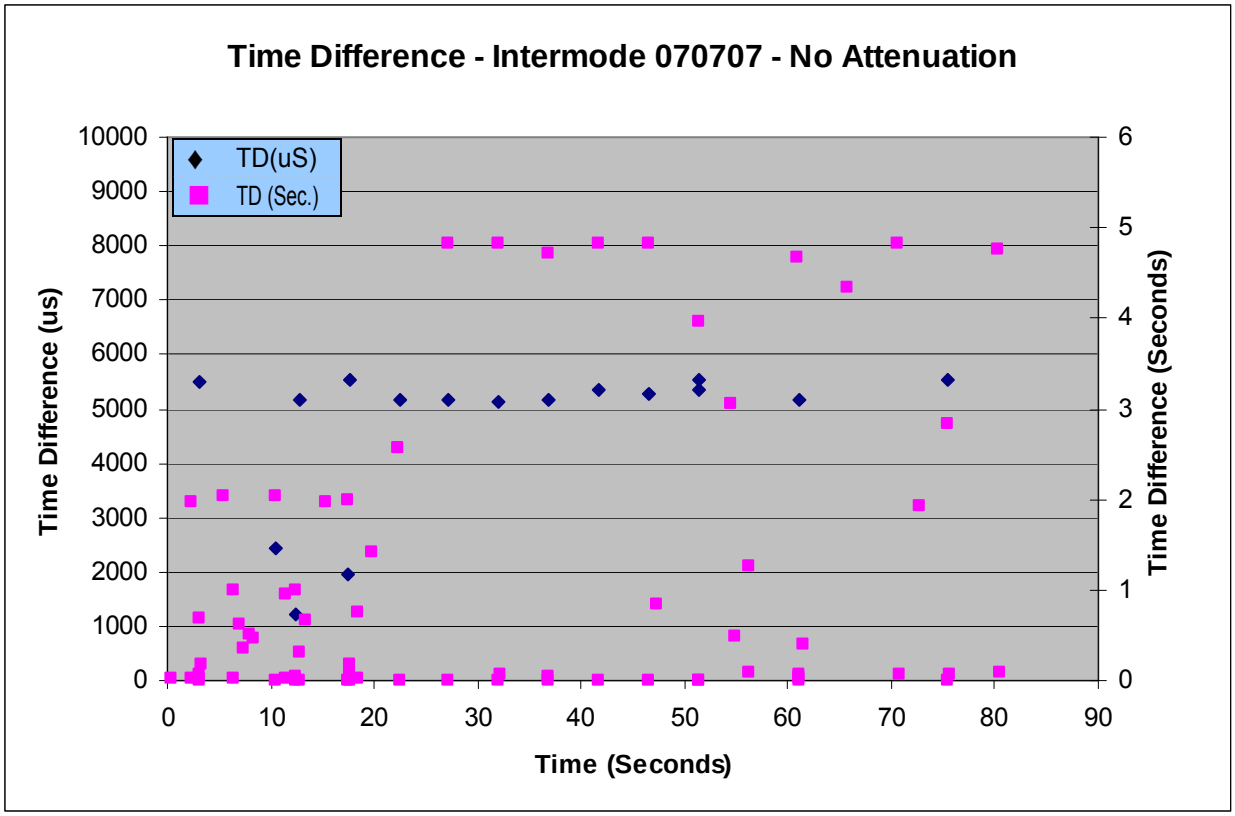

Figure 29: Intermode Interrogations seen via TC Rooftop Antenna

A second sample (collected with 6 dB attenuation in series) is shown, below,in figure 30.

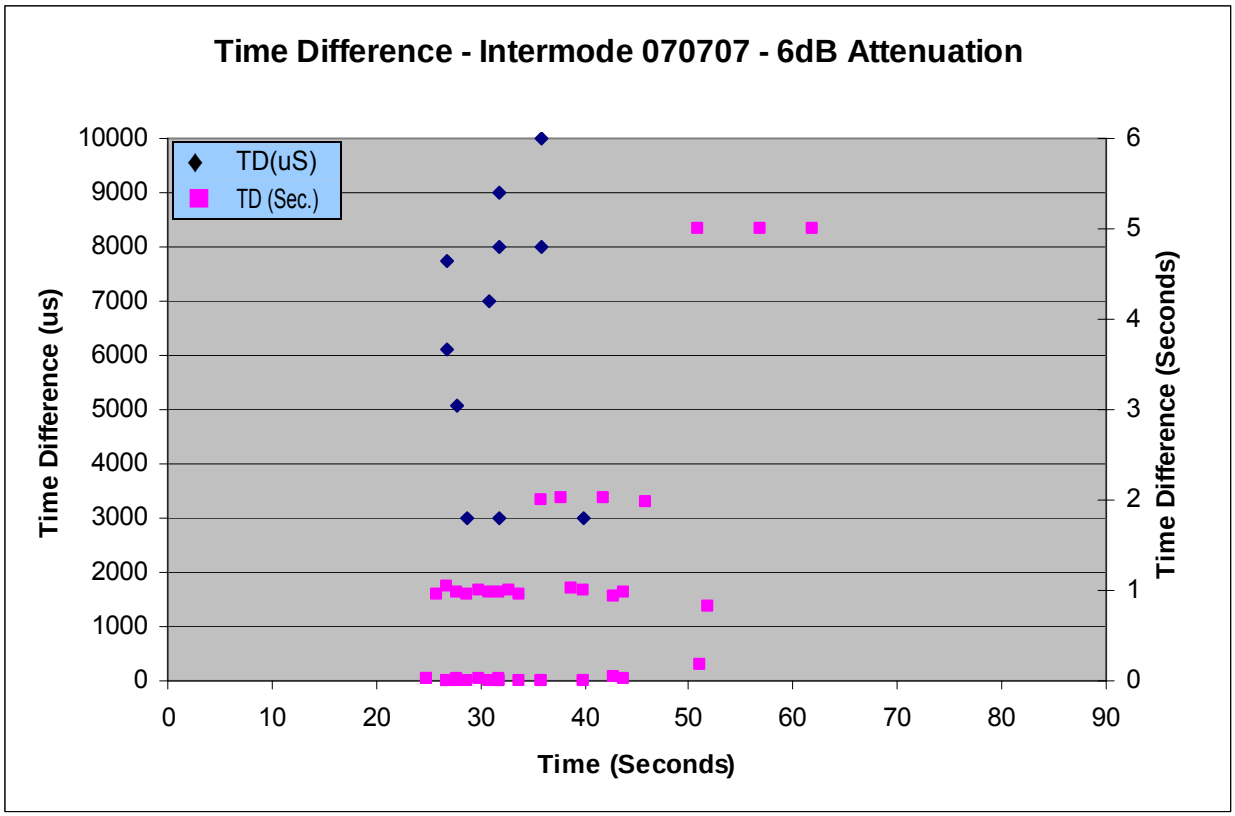

Figure 30: Intermode Interrogation Time Difference – 6 dB

This data shows a completely different characteristic. The timing fits TCAS exactly. The groups are spaced at approximately one second and the interrogations are spaced at approximately one millisecond. All of these interrogations are Mode C Intermode.

TRAFFIC COUNTS. Traffic counts in the region of the N-40 flight path were taken to assess the air traffic density during the flight test. Interference rates are influenced by the number of aircraft within transponder range since the number of replies generated on 1090 MHz result from both Ground and TCAS interrogations to the aircraft within their coverage volume. Additional radar data was collected during the entire day of the flight test and additional days to relate the traffic density during the flight test to the peak traffic experienced that day and relate it to typical and peak conditions on other days. Since 1090 MHz activity of interest to ADS-B receivers is typically -84 dBm and above, and considering the transmit power of typical Mode S transponders, the range of interest is about 100 NMi. The basis for comparison for other days used the traffic counts from the major radars providing coverage in the entire area. Additional statistics of onboard equipage were also extracted from the Elwood Enroute Mode S radar data. The traffic count collected during the flight test and the rest of the day indicated that the flight test traffic counts were not the peak of the day. Trend analysis of multiple days of radar data indicated that the peak occurs later in the day during the afternoon push. The peak traffic count measured in 2006 occurred during the Thanksgiving holiday in late November. Table 15 is the comparison of traffic counts as a function of range for these two dates. Models can be used to determine FRUIT rates that could be expected during future peaks based on the 2006 sample.

Table 15: Traffic Count Comparison of Flight Test and Peak 2006 Traffic

Range (NM)	Flight Test	Peak 2006
70	130	184
100	225	380
200	530	983
300	825	1515

EXTENDED SQUITTER PROBABILITY OF DETECTION VS. TARGET RANGE. One of the important products of the interference measurements is to determine ADS-B 1090 MHz Extended squitter receiver/decoder performance in high-interference situations. Since the RMF continuously recorded 1090 MHz reply output from the flight test, post processing of the recorded data with a DO-260A enhanced decoder for Extended squitters can be performed. Targets of opportunity that were transmitting Extended squitters were used to compile performance data. Ten minutes of data from the flight (15:35 to 15:45) was analyzed to produce the probability of detection as a function of target range. The aircraft was level at 11000 feet at this time.

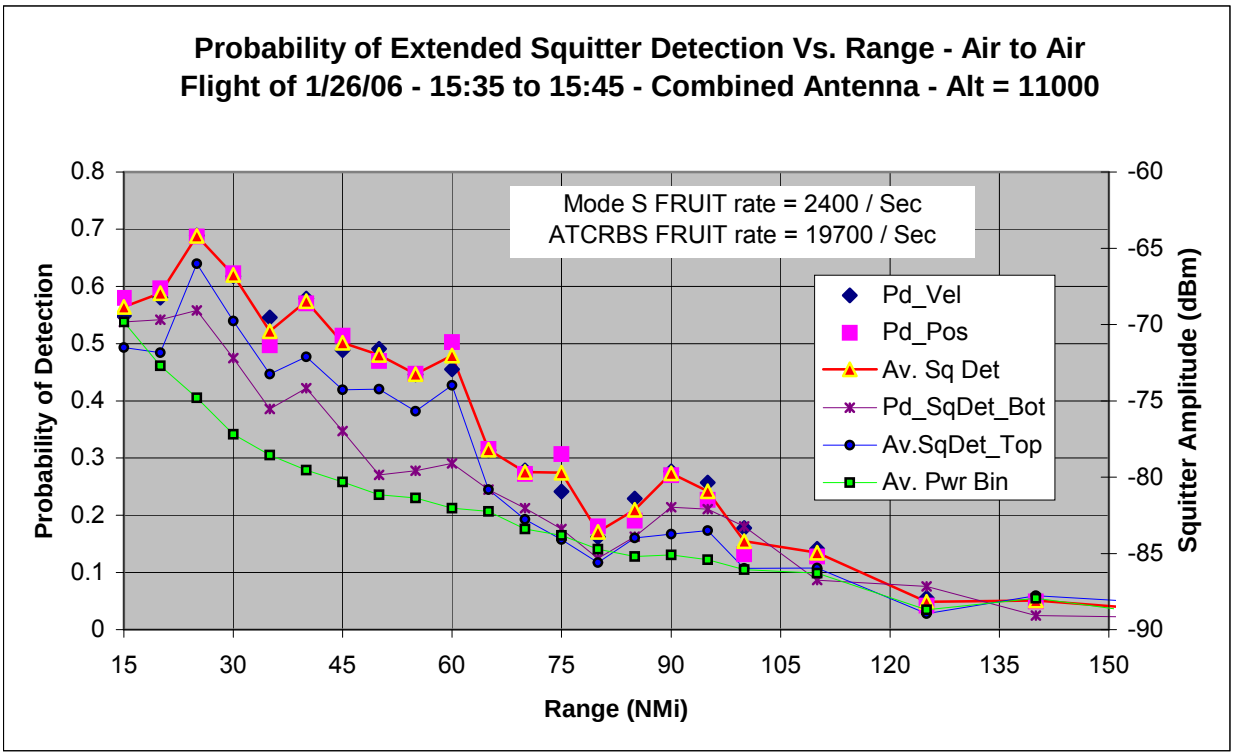

Figure 31: Probability of Detection Vs. Target Range

Detection was calculated for all targets within a range bin by determining how many Extended squitters were received from the theoretical value that were transmitted using the coverage time for each aircraft. Below 100 NMi, the bins were five NMi (e.g., the 30 NMi bin was from 27.5 NMi to 32.5 NMi, etc.). Above 100 NMi, the bins were fifteen NMi (bin label ±7.5NMi).

Figure 31 shows the detection using only the top (Av.SqDet_Top) or bottom (Pd_SqDet_Bot) antenna data, as well as the combined data from both (Av. Sq Det). Detection is significantly better when using data from both antennas.

"Pd_Vel" indicates the probability of detecting aircraft velocity data, "Pd_Pos" indicates the probability of detecting positional data, and the "Av. Pwr Bin" trace is the average power of all 1090 MHz Extended Squitters used in the calculation of Pd in each bin.

Detection was better on the top antenna for all ranges from 25 to 60 NMi. The biggest difference was at 50 NMi where the detection was better by 15%. At ranges below this, the detection was better on the bottom antenna. From 60 to 100 NMi, the detection was the same or slightly better on the bottom antenna.

As indicated on the plot, the average Mode S FRUIT rate during this period was 2400 replies per second, and the ATCRBS FRUIT rate was 19700 replies per second.

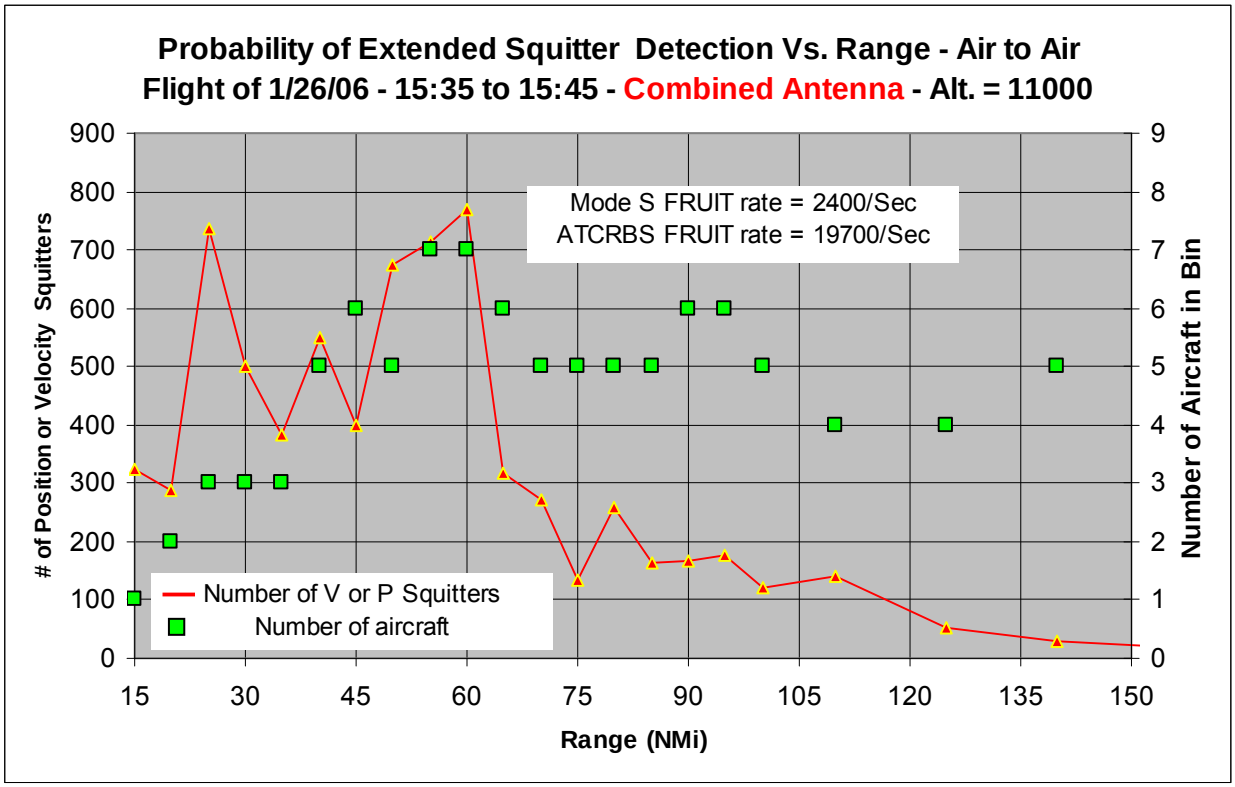

Figure 32: Probability of Position or Velocity Detection Vs. Target Range

Figure 32 shows the composition of the data in each range bin for the Pd vs Range calculation. The number of velocity or position squitters in the 25 NMi bin was 737 from three different aircraft. There were a total of 131 different aircraft in this sample. Because of the small sample size, the data can be skewed fairly easily. For example, the Pd at 60 NMi indicates 770 squitters from seven different aircraft, which appears to be out of line with the subsequent three range

bins. More than half the samples in the bin, however, are from a single aircraft, A12464, which had a Pd of about 56%.

The difference in the received reply power and the theoretical maximum (assuming a transponder output power of +54 dBm) is shown in figure 33 for the top antenna and figure 34 for the bottom antenna. This is not a very big sample as the most aircraft in a single bin is seven in the 55 and 60 NMi bins.

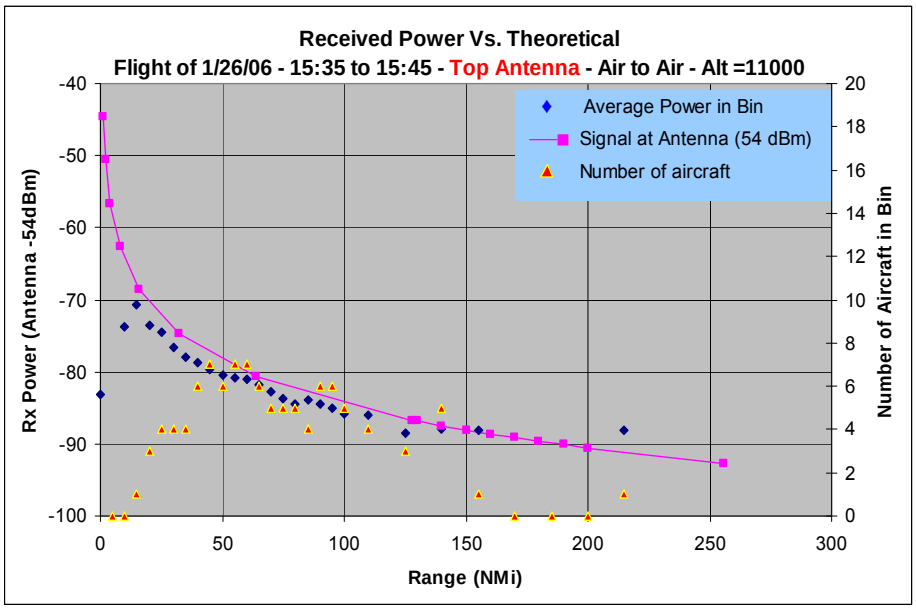

Figure 33: Received Power Vs. Theoretical (Top Antenna)

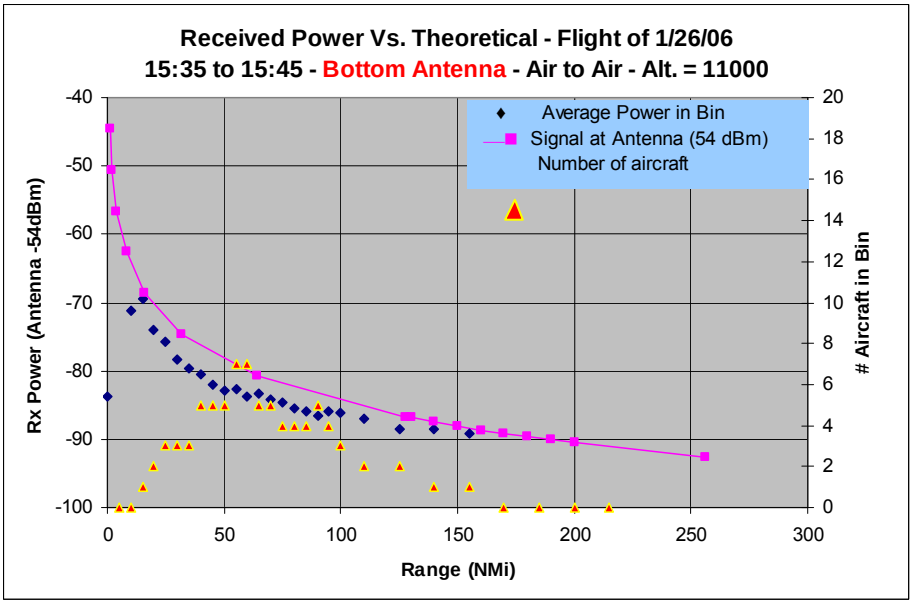

Figure 34: Received Power Vs. Theoretical (Bottom Antenna)

The top antenna appears to be closer to the theoretical value than the bottom antenna, but there are many other factors involved. This is a very small sample of aircraft. If an aircraft is below the N-40, the signals from the N-40 top antenna may be smaller because of shielding of either aircraft. The same is true for the bottom antenna with aircraft above.

Figure 35 shows the difference in the maximum and minimum power value for each bin.

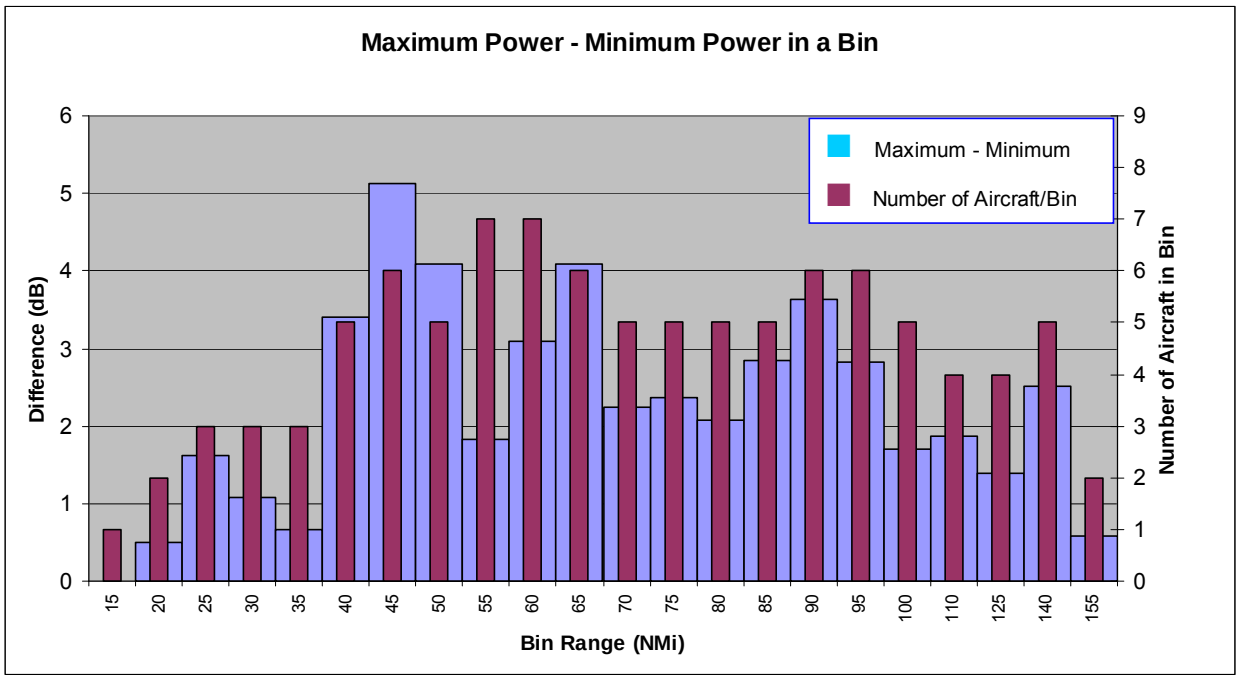

Figure 35: Maximum Power – Minimum Power in a Bin

The largest difference between maximum and minimum power was in the 45 NMi bin, where it was 5.1dB. The number of aircraft is also included on this plot (6 aircraft in the 45 NMi bin). This difference is far less than that measured for the air-ground link during data collections from Ground reception experiments.

FLIGHT TEST DATA MEASUREMENT SUMMARY AND COMPARISON

Table 16 summarizes the 1030 MHz and 1090 MHz data from the flight test. The summary is based on the two-minute sample taken at 23000 feet where both 1030 MHz and 1090 MHz data were successfully recorded. Note that there is about a 100% increase in the number of aircraft detected with each 100 NMi increment in range.

Table 16: Flight Test Data Summary

Mode S-equipped aircraft	85%
TCAS-equipped aircraft	85%
# aircraft within 100 NMi	200
# aircraft within 200 NMi	425
# aircraft within 300 NMi	850
1090 MHz ATCRBS > -84 dBm	23000 per Sec.
1090 MHz Mode S > -84 dBm	2500 per Sec.
ATCRBS interrogations	260 per Sec.
Mode S interrogations	500 per Sec.
TCAS Mode S interrogations	90%
SSR Mode S interrogations	10%
1090 MHz Mode S activity due to TCAS	50%
1090 MHz Mode S activity due to SSRs	50%

A comparison of the data collected from the flight test was made to previous flight tests. Measurements from flight tests in Los Angeles in 1999, and in Frankfurt in 2000, were compared to assess the differences between the areas. Frankfurt measurements were conducted prior to any Mode S Ground interrogator implementation in Europe, and the percentage of TCAS equipage was not as prominent as it is in the Northeast corridor today. Table 17 summarizes the comparison between the data measurements. Some of the data was not available from the Los Angeles 1999 flight test.

Table 17: Flight Test Data Comparison

	Flight Test 2006	**LA 1999**	**Frankfurt 2000**
Mode S-equipped aircraft	85%	34%	53%
TCAS-equipped aircraft	85%	--	40%
Number of aircraft within 100 NMi	200	150 (< ~75 NMi)	200
Number of aircraft within 200 NMi	425	--	400
Number of aircraft within 300 NMi	850	--	1200
1090 MHz ATCRBS > -84 dBm	23000/Sec.	17000/Sec.	25-30000/Sec.
1090 MHz Mode S > -84 dBm	2500/Sec.	1300/Sec.	1000/Sec.
ATCRBS interrogations	260/Sec.	100/Sec.	280/Sec.
Mode S interrogations	500/Sec.	--	200/Sec.
TCAS Mode S interrogations	90%	--	99%
SSR Mode S interrogations	10%	--	< 1%
1090 MHz Mode S due to TCAS	50%	75%	99%
1090 MHz Mode S due to SSRs	50%	25%	< 1%

CONCLUSIONS

The flight test data collection conducted on January 26, 2006 in the Northeast corridor indicates that a high RF (Radio Frequency) interference environment exists. ATCRBS (Air Traffic Control Radar Beacon System) reply rates on 1090 MHz (Megahertz) vary greatly over time and location. On average, when at an altitude of 23000 feet, the ATCRBS reply rate above -84 dBm (decibel/milliwatts) was measured at about 23000 per second. The rate varied from 17000 to 32000 per second. The Mode S FRUIT (False Replies Unsynchronized with Interrogation Transmissions) rate above -84 dBm was on average 2500 per second, and varied from 1800 to 3300 per second at this signal level.

About half of the Mode S 1090 MHz activity is due to TCAS (Traffic Alert and Collision Avoidance System) interrogations and half from Ground-based Mode S SSR (Secondary Surveillance Radar) interrogations. TCAS Mode S interrogations far outnumber Ground-based Mode S interrogations, but since each TCAS interrogation is addressed to a single aircraft, the impact is not as great as Ground-based All-Call interrogations. Mode S All-Call replies represent about 40% of the FRUIT, but All-Calls are only about 3% of the interrogations. Normally, Ground-based Mode S interrogators track Mode S-equipped aircraft and keep them locked out, which prevents excessive replies to All-Calls. Aircraft beyond tracking range of the Ground-based SSRs are not locked out and reply to all the All-Calls in the antenna main beam.

Measured 1030 MHz interrogation rates at 23000 feet were an average of 290 ATCRBS Mode A and C interrogations (combined), and Mode S interrogations averaged 500 per second with per second variations from 200 to 650 per second. The data collected on 1090 MHz Mode S replies from individual aircraft uncovered a DF (Download Format)=11 with IIS (Interrogator Identifier Subfield)=0 transmission rate of more than the nominal one per second. The DF=11 with IIS=0 is expected at once per second per aircraft, which is the Acquisition Squitter rate required by Mode S transponders. A DF=11 with IIS=0 can occur if All-Call Mode S interrogations are using UF=11 with IIS=0, or if an ATCRBS/Mode S All-Call (intermode) interrogation is used. Neither of these interrogations is supposedly in use at this time. Another possibility to explore is TCAS Whisper/Shout interrogations that may be misinterpreted as intermode, depending on the detected pulse width of the last interrogation pulse. Future data collections will focus on investigating this phenomenon.