AN/UPX-41(C) DIGITAL INTERROGATOR SYSTEM COMPATIBILITY WITH THE NATIONAL AIRSPACE SYSTEM

Chesapeake Fixed-Base Test

Miles Bellman, Volpe
Pratik Gandhi, Volpe
Allen Mackey, Volpe
Thomas Pagano, Regulus
Vaibhav Shah, Volpe
John Van Dongen, FAA
Leo Wapelhorst, Regulus

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Spectrum Engineering Services, AJW-1C
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John A. Volpe National Transportation Systems Center

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In 2012, the Navy requested spectrum certification for the shipboard AN/UPX-41(C) Digital Interrogator System, Software Version 5.5 with Mode 5. Current operating conditions for the Navy's AN/UPX-41(C) are the same as restrictions imposed on the AN/UPX-37 digital Identification Friend or Foe (IFF) interrogator. A proposed AN/UPX-41(C) Stage 4 certification was developed to allow the Navy to operate under less restrictive parameters but required that the Navy and FAA validate those proposed restrictions. This report provides the results of the validation effort. The effort conducted by the Volpe Center used modeling, simulation, and live testing to evaluate the AN/UPX-41(C) system's compatibility. The live testing, which occurred August 18-21, 2014 was conducted in its entirety using four AN/UPX-41(C) digital IFF interrogators at land-based test sites (LBTS). Prior to, and following the test, modeling, simulation, and analysis was performed to assess the impact of the proposed Stage 4 certification configuration on National Airspace System (NAS) Aeronautical Surveillance and Collision Avoidance Systems (ASCAS).

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Executive Summary

In 2012, the Navy requested spectrum certification for the shipboard AN/UPX-41(C) Digital Interrogator System, Software Version 5.5 with Mode 5. Current operating conditions for the Navy's AN/UPX-41(C) are the same as restrictions imposed on the AN/UPX-37 digital Identification Friend or Foe (IFF) interrogator. A proposed AN/UPX-41(C) Stage 4 certification was developed to allow the Navy to operate under less restrictive parameters but required that the Navy and FAA validate those proposed restrictions. This report provides the results of the validation effort.

The effort conducted by the Volpe Center used modeling, simulation, and live testing to evaluate the AN/UPX-41(C) system's compatibility. The live testing, which occurred August 18-21, 2014 was conducted in its entirety using four AN/UPX-41(C) digital IFF interrogators at land-based test sites (LBTS). Prior to, and following the test, modeling, simulation, and analysis was performed to assess the impact of the proposed Stage 4 certification configuration on National Airspace System (NAS) Aeronautical Surveillance and Collision Avoidance Systems (ASCAS).

The following three goals were established for the AN/UPX-41(C) test analysis, listed in order of importance:

- Goal 1: Collect data to validate that the Stage 4 criteria set forth in SPS18778/1 do not cause degradation of NAS ASCAS.
- Goal 2: Provide data that could be used to validate models and simulations of the impact AN/UPX-41(C) systems have on NAS ASCAS. The intent was that, once validated, a simulation could then be used to predict the impact of AN/UPX-41(C) systems, configured as described in Ref. 2, on NAS ASCAS for other geographic locations and scenarios for which live testing may not be feasible.
- Goal 3: Determine the extent (if any) to which the Stage 4 restrictions, and subsequent radio frequency assignments (RFA), can be relaxed without degrading NAS ASCAS.

It is Volpe's conclusion from the live testing, modeling, simulation, and analysis, after consultation with FAA subject matter experts (SMEs), that the proposed AN/UPX-41(C) system restrictions stated in SPS18778/1 have been validated as conservative, safe, and adequate to protect NAS ASCAS. The validation of the simulation against the data collection proved that the model was able to sufficiently predict 1030 MHz and 1090 MHz environments while appropriately qualifying the risks associated with using the tool for spectrum assignments. Further, increased flexibility for AN/UPX-41(C) system operations can be supported. Details of these conclusions are provided in the Summary of Results and Recommendations.

Summary of Results and Recommendations

Goal 1 was successfully completed based on the live test, modeling, and post-test analysis. Stage 4 Certification (SPS 18778/1) criteria for the AN/UPX 41(C) were validated as sufficient to prevent degradation to NAS ASCAS.

Goal 2 was successfully completed in that usable data was collected for validation of the Volpe Center 1030/1090 MHz Interference Simulator. Under this test effort, the simulation validation has been taken as far as possible with the provided resources. Any further refinements to reduce discrepancies would require increased scope for additional work and resources. The validation effort revealed the following observations:

- The simulation underestimates the transponder occupancy for the Air Traffic Control Radar Beacon System (ATCRBS) function of a Typical Mode A/C/S transponder by about 1% (the average difference between measured and simulated occupancy). The simulation underestimates the transponder occupancy for the Mode Select (Mode S) function of a Typical Mode A/C/S transponder by about 0.5% (the average difference between measured and simulated occupancy).
- The simulation overestimates total Mode S False Replies Unsynchronized in Time (FRUIT) by a factor of 1.5 to 2 (measured approximately 1500 FRUIT/sec rate versus simulated 2500 FRUIT/sec rate).
- The simulation underestimates total ATCRBS FRUIT by a factor of 2 or less (measured approximately 5500 FRUIT/sec rate versus simulated 3000 FRUIT/sec rate).
- To the extent that the Simulator replicates how the NAS would function for a specified set of signal sources based on an understanding of the way the NAS should operate, it is an effective tool in revealing the anomalies in how the NAS actually operates in terms of unexpected signal sources and/or effects. However, the validation effort has shown that there are caveats in using the simulation in its current form when assessing performance of ASCAS in a baseline environment or testing performance in an environment with new interrogators. Volpe can only account for the interrogators that are understood to be operating in a given area, and transponder models must be calibrated to replicate real world operation. The risk severity created by the discrepancies seen in the validation is dependent on the particular ASCAS in question as each system has a different sensitivity to changes in uplink or downlink interference. For each discrepancy, a general statement about the discrepancy's impact on the assessment of ASCAS performance can be made:
    - Simulated ATCRBS and Mode S function transponder occupancy that is lower than measurements will result in optimistic performance of ASCAS, except those that operate only on 1090 MHz, versus what would be expected in the real world environment.
    - Simulated ATCRBS FRUIT rates that are lower than measurements will result in optimistic performance of ASCAS versus what would be expected in the real world environment.

    - Simulated Mode S FRUIT rates that are higher than measurements will result in conservative performance of ASCAS versus what would be expected in the real world environment.
- Further validation and reconciliation is suggested to reduce error against measurements and increase confidence in simulation results. The main focus would be calibration of the transponder model and its handling of MTL+3dB and below power level interrogations. The current transponder model appears to underestimate ATCRBS replies and overestimate Mode S replies due to the transponder's idealized nature of only responding to MTL and above interrogations and lack of a probabilistic model to replicate real world transponder handling of low power level Mode S interrogations that can either generate ATCRBS replies or not be decoded entirely. Further suggestions for reconciliation can be found in the simulation validation discussion in Appendix F.

Goal 3 was successfully completed and increased flexibility for AN/UPX-41(C) system operations can be supported. Details of the recommended relaxation can be found in "Proposed Interim Update to the AN/UPX-41(C) Spectrum Certification Conditions (SPS-18778/1)", document number DOT-VNTSC-NAVSEA-15-02. Data collected from the August 2014 flight tests, which provide actual measurements of 1030 and 1090 MHz spectrum activity due to operation of AN/UPX-41(C) interrogators, has substantiated performance estimates and provided confidence in the ability to estimate their spectrum impact.

While the test configuration of the LBTS showed a negligible impact on NAS ASCAS performance, there is not sufficient data and analysis to determine overall safe operating limits for transponder occupancy and 1090 MHz FRUIT rates in a given environment to support all Navy operations of the AN/UPX-41(C) and guarantee acceptable performance for NAS ASCAS. The proposed relaxations were developed through negotiations with the FAA utilizing the existing FAA process and methodology in concert with AN/UPX-41(C) test data. This process provides sufficient margins to ensure the safe operation of the NAS but still allows for relaxations as compared to the restrictions imposed on the AN/UPX-37 interrogator and proposed Stage 4 certification.

Ultimately, spectrum restrictions for operation of the AN/UPX-41(C) can be revisited as part of the Identification Friend or Foe (IFF) Technical Working Group (TWG), which will develop a process that can be used as an overall spectrum allocation and management scheme.

Analysis, modeling, and simulation of the proposed AN/UPX-41(C) Stage 4 configuration brought to light some observations about various topics which are listed below.

- AN/UPX-41(C) System:
  - At the most, the ATCRBS function of a transponder, using Typical transaction times, will be occupied 1.03% within five nmi of one AN/UPX-41(C) system.
  - At the most, the ATCRBS function of a transponder, using Worst Case transaction times, will be occupied 1.21% within five nmi of one AN/UPX-41(C) system.
  - Outside of a <u>single</u> AN/UPX-41(C) system's sidelobe suppression (SLS) range (20 nmi), the 1030 MHz impact from the <u>single</u> AN/UPX-41(C) system's sidelobes and mainbeam is negligible and cannot be differentiated from the baseline 1030 MHz environment.
  - Based on measurements, there were about 18 ATCRBS replies on average at 10 nmi and about 10 ATCRBS replies on average at 140 nmi elicited by an AN/UPX-41(C) interrogator from a single aircraft. When these replies are received by any surveillance system besides the AN/UPX-41(C) that elicited them, they are called False Replies Unsynchronized in Time (FRUIT).
  - From the traffic counts in the vicinity of the flight test aircraft for Day 3 and Day 4 data collections, which alternated the LBTS Active and Off, the ATCRBS FRUIT contribution due to the LBTS operation measured and calculated were in good agreement. The 1090 MHz ATCRBS reply impact of an interrogator is a function of the aircraft density within its surveillance volume and expected and measured AN/UPX-41(C) interrogator impact to FRUIT based on the densities during the flight tests provides confidence that AN/UPX-41(C) contribution to FRUIT can be reasonably estimated.
- Traffic Alert and Collision Avoidance System (TCAS) (related to the AN/UPX-41(C)):
  - Assuming the AN/UPX-41(C) system causes 20 replies per mainbeam and assuming four operating interrogators, the TCAS Mode S receiver will potentially experience 4560 replies per second for an aircraft density that is twice the high density 2020 baseline used in the FAA Spectrum Mitigation Activity. This results in a probability of track in support of an RA in time to alert at the required range of 12.8 nmi range of 0.995, significantly above the required 0.90.
- Automatic Dependent Surveillance – Broadcast (ADS-B) Air-to-Air (related to the AN/UPX-41(C)):
  - The predicted change in ADS-B air-to-air performance, based on the ATCRBS FRUIT per second induced by the proposed AN/UPX-41(C) Stage 4 configuration, is negligible considering that the change in update rate was less than 10% of the maximum allowed time between state vector updates needed to support applications at different aircraft pair ranges (10 to 90 nmi).

- Secondary Surveillance Radar (SSR) (related to the AN/UPX-41(C)):
    - Analysis of recorded data showed no detectable impact from the operation of the proposed AN/UPX-41(C) Stage 4 configuration on probability of detection (P_d), identity reliability and confidence, altitude reliability and confidence, false target rate, 0000 code rates, number of hits, ATCRBS FRUIT rates, Mode S FRUIT rates, and interrogation and reinterrogation rates.
    - Analysis of FAA SSR and AN/UPX-41(C) mainbeam overlaps showed neither a trend of increasing interrogation/reinterrogation rates nor a decrease in ATCRBS hit counts for the victim FAA SSR.
- Secondary Surveillance Radar (not related to the AN/UPX-41(C)):
    - There are more Mode S roll call or selectively addressed interrogations from a Mode S SSR intended for aircraft within 10 nmi (average 15.5 per beam dwell) of the SSR than for aircraft beyond 10 nmi (average 1.43 per beam dwell) of the SSR. Aircraft within 10 nmi of the SSR almost always require roll call reinterrogation within the same beam dwell as the first interrogation in the beam dwell, directed by the SSR tracker's prediction of the victim aircraft's earliest likely azimuth, is rarely received by the victim aircraft. Precision of azimuth prediction for aircraft within 10 nmi has a high degree of uncertainty because aircraft can move very quickly across many different azimuths relative to the SSR in a short amount of time.
    - This is due to conservative estimates of earliest likely azimuth by the SSR surveillance processing function for aircraft within 10 nmi of the SSR.– a conservative estimate of earliest likely azimuth
    - The timings of only the first 21 addressed interrogations to a specific aircraft in a beam dwell are recorded by the Mode S SSR. The count of the number of interrogations over 21 is stored in a bit called Retry Overflow Count.
    - Analysis of the Richmond SSR showed a high false target rate due to a test target causing ring around.
    - NHK Radar - Data loss experienced due to loss of feed seen on Day 1 and Day 2 of Test.
    - Improved Interrogator Sidelobe Suppression (IISLS) – BI-5 radars at ACY and RIC are using Improved Interrogator Sidelobe Suppression technique to combat false targets from reflections.
- Automatic Dependent Surveillance – Broadcast (ADS-B) Ground Radios (related to the AN/UPX-41(C)):
    - Recorded data proved to be inconclusive in determining impact from the proposed AN/UPX-41(C) Stage 4 configuration due to network throttling of many duplicate target reports by Harris and it is recommended to not record or analyze this type of data in the future to determine interference impacts.

    - The simulated radio most impacted saw only a 2% decrease in squitter reception rate due to the proposed AN/UPX-41(C) Stage 4 configuration.
- Automatic Dependent Surveillance – Broadcast Ground Radios (not related to the AN/UPX-41(C))
    - Future testing of ADS-B ground radios should include recording of downlink format (DF) 17 squitter received at ADS-B ground radio stations.
- Multilateration (MLAT) (related to the AN/UPX-41(C)):
    - Simulated aircraft position detections per second and simulated remote unit (RU) elicited replies per second for the MLAT system located at Ronald Reagan Washington National Airport (DCA) decreased by 0.58% and 0.29%, respectively, due to the proposed AN/UPX-41(C) Stage 4 configuration for the MLAT interrogation scheme illustrated in F.2, Table 39. This is a negligible change in performance.
    - Line of sight limits prevented aircraft on the surface of DCA from receiving LBTS interrogations in simulations; hence, the decrease in detections from this specific scenario came only from the addition of ATCRBS FRUIT interference received at MLAT RUs that was induced by LBTS interrogations of aircraft not on the surface of DCA.
    - The reported results are unique to the DCA-LBTS configuration and do not necessarily reflect the impact to an MLAT system in a different location. In a configuration where aircraft are within line-of-sight of AN/UPX-41(C) 1030 MHz interrogations, probability of position detections would be influenced by induced transponder unavailability. However, the additional impact of the transponder unavailability would depend upon the configuration of the AN/UPX-41(C) systems. If sidelobes did not overlap, the effect would be negligible, but overlapping sidelobes may push MLAT performance beyond acceptable limits. Further study would be required to determine this breaking point.
- Unaccounted for interrogation sources that were discovered when comparing measurement and simulation data. The following should not be misconstrued as a shortcoming of the Simulator. The Simulator can only account for the interrogators that are understood to be operating in a given area.
    - There were much higher than expected Mode 1 and Mode 4 interrogation rates around the Norfolk area. It is unclear what caused this activity and the Naval Air Systems Command (NAVAIR) Naval Air Warfare Center Aircraft Division (NAWCAD) plans to conduct flight tests to investigate this further.
    - There were high levels of Mode A replies to Mode 4 interrogations after the Southern tip of New Jersey that did not drop to nominal values until the William J. Hughes Technical Center (WJHTC) Convair 380 (N39) turned Northwest on Day 3. It is unknown what caused this activity and NAWCAD plans to conduct flight tests to investigate this further.

- There were bursts of Mode A and C interrogation rates South of the Norfolk area that were three times the nominal values normally seen around Norfolk. The interrogations appeared to come from the Norfolk area which would indicate that they were not attributed to the LBTS. However, it is unknown what caused this activity and NAWCAD plans to conduct flight tests to investigate this further.
- The AN/UPX-41(C) systems on Wallops Island appeared to generate more interrogations than expected. At least one known contributing factor were nearby buildings that created reflections.
- The activity described in the above bullets makes allocation of 1030 MHz and 1090 MHz spectrum to the AN/UPX-41(C) and other platforms more difficult since a margin must be allocated to accommodate unexpected activity such as this.

- Simulation:
  - By removing discrepancies that were known to not be simulated or at least not simulated to the extent shown in the measurements, as described in F.4.6, the simulated ATCRBS function of a Typical Mode A/C/S transponder's occupancy average percent difference with measurements is 15%, declining to 10% if 1030 MHz contributions from the Norfolk and Atlantic City areas are removed. This is a better assessment of how well the Simulator replicated what was known to be operating. The remaining 10% error is at least partially due to excess clear Mode A and Mode C interrogations created by building reflections near the LBTS at Wallops Island that could not be simulated.
  - Uplink Format 4/5 Reply Rates - The simulation under estimates replies to uplink format (UF) 4/5 interrogations in some areas by 1 per second. This is described in more detail in F.4.3.
  - UF11 Reply Rates - The simulation over estimates replies to UF11 interrogations by a factor of 2. This is described in more detail in F.4.3.
  - Mode A Reply Rate - The simulated Mode A reply rate for periods when LBTS are Off matches well with the rate of measured clear Mode A replies (only Mode A replies triggered by Mode A interrogations, not, for example, low-level Mode S interrogations); however, the total measured Mode A reply rate, including replies to Mode 4 (0%-40% of total Mode A replies depending on location in the circuit) and low-level Mode S (0%-70% of Mode A replies depending on location in the circuit) interrogations, averages 60% greater than the simulated Mode A reply rate. When the LBTS are Active, just the measured clear Mode A reply rate averages about 50% higher at peak than the simulated Mode A reply rate. This discrepancy is likely due, at least in part, to an idealized transponder model that does not reply to sub-MTL interrogations unlike a real world transponder, ground-based military interrogators that were not simulated because of incomplete

information, and multipath effects for which there is no mechanism in the simulation.

- Mode C Reply Rate - The simulated Mode C reply rate for periods when LBTS are Off matches well with the rate of measured clear Mode C replies (Mode C replies triggered by Mode C interrogations not, for example, low-level Mode S interrogations). The total measured Mode C reply rate, including replies to Mode 4 (0%-23% of total Mode C replies depending on location in the circuit) and low-level Mode S (0%-20% of total Mode C replies depending on location in the circuit) interrogations, averages 10% greater than the simulated Mode C reply rates. When the LBTS are Active, just the measured clear Mode C reply rate averages about 30% higher at peak than the simulated Mode C reply rate. This discrepancy is likely due, at least in part, to an idealized transponder model that does not reply to sub-MTL interrogations unlike a real world transponder, ground-based military interrogators that were not simulated because of incomplete information, and multipath effects for which there is no mechanism in the simulation.
- TCAS Mode C Transmission Rates - The simulated TCAS Mode C transmission rates were two-thirds of the measured rates. This is because the N39 TCAS unit is allowed to do a maximum of 119 Mode C interrogations per second while the Simulator is programmed to allow only a maximum of 83 Mode C interrogations per second. It is unclear which interrogation rate is “correct” according to TCAS MOPS and indeed it is known that interrogation rates can vary to comply with the interference limiting inequalities. A study of the NAS TCAS population and their interrogation rates would be required to determine the most accurate representation for a simulation.
- ATCRBS FRUIT Rate - The trend of the simulated ATCRBS FRUIT rate matches well with the measured ATCRBS FRUIT rate except for areas around Norfolk. The measured ATCRBS FRUIT rate is greater than the simulated rate by a factor of two or less. The discrepancy is due, at least in part, to excess interrogations and the ensuing replies created by building reflections near the LBTS at Wallops Island that could not be simulated. The discrepancy can also likely be attributed to real life transponders that generate ATCRBS replies from low level Mode S interrogations as well as ATCRBS replies that occur for interrogations received below minimum trigger level (MTL) as the measured ATCRBS reply rate averages 50 more per second than simulations; however, more investigation is required. Neither of these behaviors is currently modeled in the Simulator.
- Mode S FRUIT Rates - The trend of the simulated Mode S FRUIT rate matches well with the measured Mode S FRUIT rate; however, the simulated Mode S FRUIT rate is greater than the measurements by a factor of about 1.5 to 2. The

discrepancy could, in part, be attributed to Mode S replies that occur in the simulator from low-level Mode S interrogations that in real life are either misinterpreted and generate ATCRBS replies or remain undecoded generate no reply at all; however, this requires more investigation.

- Simulated 1090 MHz Antenna - The simulation uses a 0 dB gain omni-directional antenna for reception of 1090 MHz signals. This does not model the peaks, nulls, and fading that normally characterize fuselage-mounted antennas.
- Aircraft Equipage – Aircraft position, speed, altitude, heading, transponder type, ADS-B and TCAS equipage, and ICAO address can be derived from Surveillance and Broadcast Services (SBS) network target reports. Unfortunately, only ADS-B-equipped aircraft will have all of these fields populated and can be reliably assigned with a Mode S transponder and TCAS and ADS-B unit. All other aircraft are assigned equipage based on location, speed, altitude, and proximity to airports. A more robust and complete database of parameters of aircraft flying in the NAS would help make simulation aircraft equipage more accurate.

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1. Background

The Navy requested spectrum certification for the AN/UPX-41(C) Digital Interrogator System used in the AN/UPX-29(V) Identification Friend or Foe (IFF) System (which utilizes the 1030/1090 MHz frequency pair) as installed in CG 47, DDG 51, LHD 1, LHA (R), and CV(N) class chips (Ref. 1) controlled by the Cooperative Engagement Capability (CEC). The Stage 4 certification was accepted by the joint agency Spectrum Planning Subcommittee (SPS) in the May 2012 meeting and signed by the National Telecommunications and Information Administration (NTIA) on June 22, 2012 (Ref. 2).

Key wording in the Certification of Spectrum Support is provided below; added information is in brackets [ ]. Notable in this context is that the Federal Aviation Administration (FAA) is designated by the NTIA as the national coordinator for the 1030/1090 MHz frequency pair.

> The Spectrum Planning Subcommittee has reviewed this system under the provisions of Chapter 10 of the NTIA Manual, noting that the receiver of the subject system is tuned to center frequency 1090 MHz and the AN/UPX-41(C) has the capability to transmit at 4000 watts peak power [Note: separately, Section 1 of Ref. 2 states that 2000 watts is the approved power level], recommends that:
>
> 1. NTIA certify Stage 4 spectrum support for the AN/UPX-41(C) Digital Interrogator System (Shipboard), as specified in Section 1 when operated in conjunction with the OE-120( )/UPX antenna, the AN/UPX-29(V), the AN/UPX-24(V) interface Version 2.1.2., controlled by the CEC, and the interrogation strategy of no more than one 360 degree Mode 4 interrogation scan out of every seven scans. It is recognized that this system has a back-up antenna that will only be used in emergencies and the Navy acknowledge that no more than one back-up antenna will be in operation in the National Airspace System (NAS).
>
> … [text omitted] ...
>
> 5. Navy be aware that the FAA is conducting 1090 MHz congestion and IFF implementation studies to assess the future viability of the 1090 MHz spectrum environment and the performance of NAS aeronautical surveillance and collision avoidance systems. The results of these studies will determine the limitations of future non-NAS interrogator operations in the US&P [United States and Possessions]. The Navy agrees to begin operations of the AN/UPX-41(C) digital interrogator under the following conditions when operating within 100 NM of the US&P. Ships shall maintain the following separation when operating 4 ship interrogators at the same time within the same geographic area, as defined as 250 NM from the next closest ship interrogator:

a. 50 NM from the center point of FAA designated High Aircraft Density Areas as provided in SPS-18692/1 [Ref. 3].

b. 30 NM from the center point of FAA designated Low and Medium Aircraft Density Areas as provided in SPS-18692/1.

6. Navy, when operating less than 4 ship interrogators at the same time within the same geographic area, as defined as 250 NM from the next closest ship interrogator when operating within 100 NM of the US&P, ships must maintain a 30 NM separation from the US&P coast.

… [text omitted] ...

8. The FAA and the Navy agree to conduct joint testing to validate the initial operations conditions within a target of three to six months of the date of this signed spectrum certification. (Ref. 2)

Based on the above requirement, the Navy and FAA conducted the required joint testing. This document presents the test findings and associated analysis.

1.1. Test Goals

The primary purpose of this test was to collect data to validate that the proposed AN/UPX-41(C) Stage 4 operation restrictions set forth in Ref. 2 were sufficient to prevent degradation of NAS Aeronautical Surveillance and Collision Avoidance Systems (ASCAS).

A second purpose of this test was to provide data that could be used to validate a simulation of the impact of AN/UPX-41(C) interrogators on the NAS. The intent was that, once validated, this simulation could then be used to predict the impact of AN/UPX-41(C) interrogators, configured as described in Ref. 2, for other scenarios — i.e., number and location of AN/UPX-41(C) interrogators (coastal waters, airborne, and land based); number and location of NAS systems — for which live testing may not be feasible.

The third purpose of this test was to determine the extent (if any) to which the Stage 4 restrictions, and subsequent radio frequency assignments (RFA), could be relaxed without degrading NAS systems. An aggregate analysis that includes all military IFF activity may be required to achieve this outcome.

1.2. Test Overview

1.2.1. Test Plan Development

A test plan was developed over 15 months that included input from the Volpe Center, FAA ASCAS Subject Matter Experts (SME), FAA Spectrum Engineering Services (SES) and Navy SMEs. During the test development, the parties negotiated the use of land-based test sites (LBTS) as surrogates for ship-based interrogators to replicate the Stage 4 configuration since it was cost prohibitive to use ships underway.

Please refer to Ref. 4 which includes the Test Plan and associated details of the test.

1.2.2. Systems Under Test

The basic methodology for determining the extent to which new 1030/1090 MHz systems interfere with existing NAS ASCAS is to operate the new system in conjunction with the NAS ASCAS. This process includes establishing one or more test scenarios that cycles the new system Active and Off for a duration long enough to evaluate possible impacts to NAS ASCAS. The following sections outline the systems utilized during this test.

Navy AN/UPX-41(C) Land-Based Test Sites

The new systems in the Chesapeake Fixed-Base Test were four Navy AN/UPX-41(C) digital interrogator systems, configured as described in Section 1, with important properties given in Table 1. The area involved and shows the extent of the Land-Based Test Sites (LBTS) mainbeams the location of the LBTS are provided in Figure 1 and Table 2, respectively.

Table 1. AN/UPX-41(C) System Important Properties

Parameter		Value	Notes
Power		2000 W	Able to operate to 4000 W, but only certified to 2000 W.
Pulse Repetition Frequency (PRF)		250 Hz	
Rotation Rate		4.096 sec	
Interrogation Interlace Pattern	*Scans 1-6*	5/1, 2, 5/3(A), C	Mode 5 supermoded with SIF or Mode 4 interrogations, as indicated by slash (/). Mode 5 is always the first challenge.
	Scan 7	5/4, 1, 5/4, 2, 5/4, 3(A), 5/4, C	

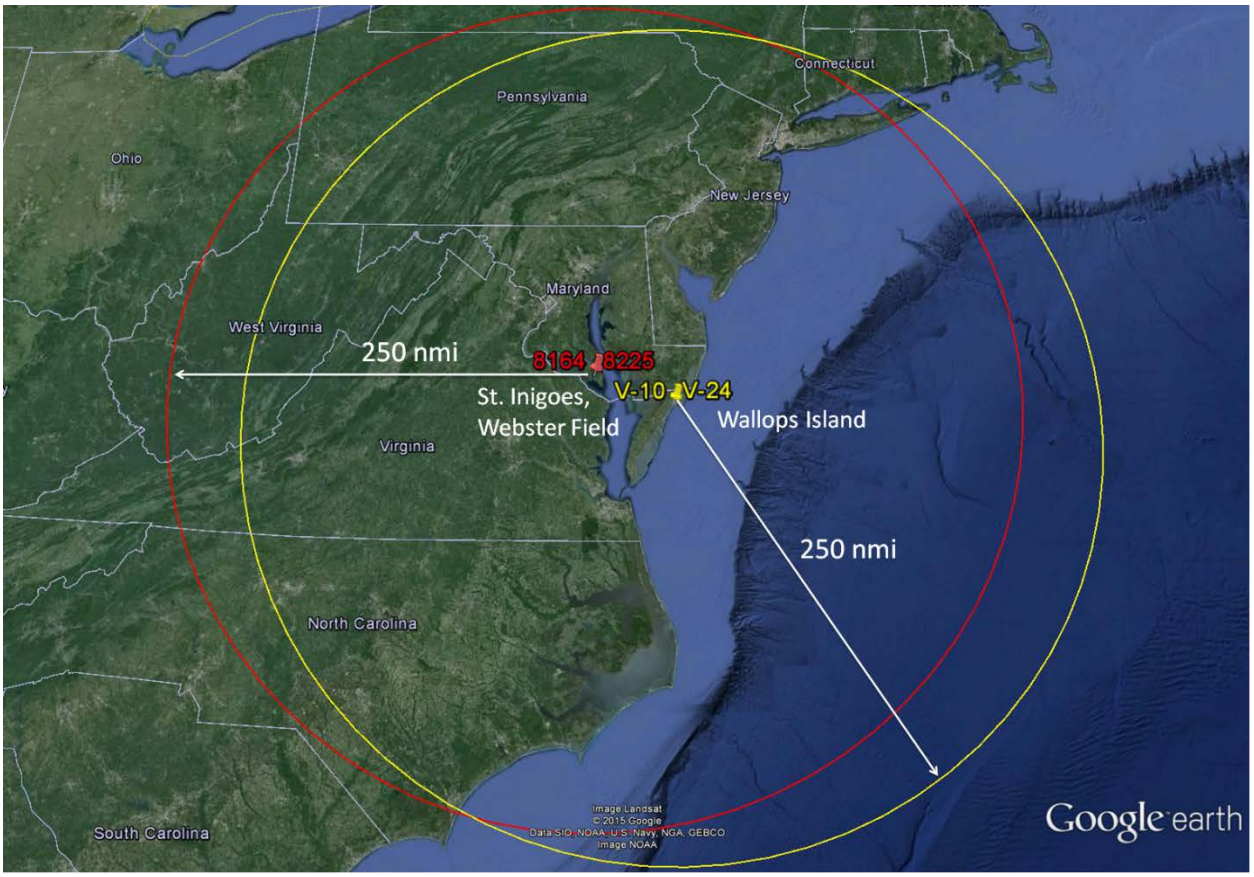


Figure 1. Location of Navy AN/UPX-41(C) Land-Based Test Sites and Mainbeam Coverage Ranges

Table 2. Location of Navy AN/UPX-41(C) Land-Based Test Sites

Sites	8225	8164	V-10	V-24
Latitude	38.136226	38.137657	37.856798	37.862263
Longitude	-76.432809	-76.437150	-75.466394	-75.457063

Two AN/UPX-29(V) IFF systems with AN/UPX-41(C) interrogators were located at the NAWCAD Ship/Shore Electronic Systems facility at Webster Field in St. Inigoes, Maryland. The NAWCAD building numbers 8225 and 8164 were used as identifiers for these two interrogators. These buildings do not have ship combat systems and are stand-alone AN/UPX-29(V) systems with Ships Self-Defense System (SSDS), CEC, and AEGIS simulators.

Two AN/UPX-29(V) IFF systems with AN/UPX-41(C) interrogators were located at the Naval Sea Systems Command (NAVSEA) Surface Combat Systems Center (SCSC) on Wallops Island, Virginia. The SCSC building numbers V-10 and V-24 were used as identifiers for these two interrogators. V-24 houses a configuration which is representative of SSDS, Carriers (CVN) and Amphibious class ship installations, and V-10 houses the configuration which is representative of AEGIS Cruisers (CG)/Destroyers (DDG) installations.

These interrogators were selected for a combination of reasons:

- Availability – Interrogators were in-place and some previously had authorizations to transmit. The authorizations had lapsed and were temporarily reauthorized for this experiment. The previous assignments had temporary sector blanking requirements which were removed for 360-degree operation during this test.
- Economics – Using land-based interrogators eliminated the need for one or more ships to be put to sea. This resulted in significant fuel and labor cost savings, and enabled the Test to be conducted over a longer duration than would be possible using ship-based interrogators.
- Location – The planned test interrogators were located close to the high-density northeast air traffic corridor, ensuring a test that stressed ASCAS in an environment close to the worst case that could be seen in the NAS.

Secondary Surveillance Radars

The impact of the proposed AN/UPX-41(C) Stage 4 configuration on secondary surveillance radar (SSR) was addressed through analysis of data recordings at eight SSR sites in the vicinity of the LBTS. The SSR sites are summarized in Table 3 and shown in Figure 2 with maximum surveillance range rings. Their symbols and range rings are color-coded by model type:

- Yellow / Mode S – Washington Dulles International Airport (IAD), Ronald Reagan Washington National Airport (DCA), Andrews Air Force Base (ADW), and Norfolk International Airport (ORF)
- White / ATCBI-5 – Richmond International Airport (RIC)
- Blue / ASR-11 (AN/GPN-30, Condor MK2D) – Patuxent River Naval Air Station (Trapnell Field, NHK)
- Green / ATCBI-6M – Oceana, Virginia (QVR)
- Teal / ATCBI-6 – The Plains, Virginia (QPL)

Table 3. SSR Measurement Sites

Symbol	Location	Owner	Model	Domain	Max. Range	Traffic Density	On-Site Collection
ADW	Andrews AFB, MD	FAA	Mode S	Terminal	60 NM	High	Yes
DCA	Reagan Airport, VA	FAA	Mode S	Terminal	60 NM	High	Yes
IAD	Dulles Airport, VA	FAA	Mode S	Terminal	60 NM	High	Yes
ORF	Norfolk Airport, VA	FAA	Mode S	Terminal	60 NM	Medium	Yes
RIC	Richmond Airport, VA	FAA	ATCBI-5	Terminal	60 NM	Medium	No
NHK	Patuxent River NAS, MD	Navy	ASR-11	Terminal	120 NM	High	No
QVR	Oceana, VA	FAA	ATCBI-6M	En Route	250 NM	—	No
QPL	The Plains, VA	FAA	ATCBI-6	En Route	200 NM	—	No

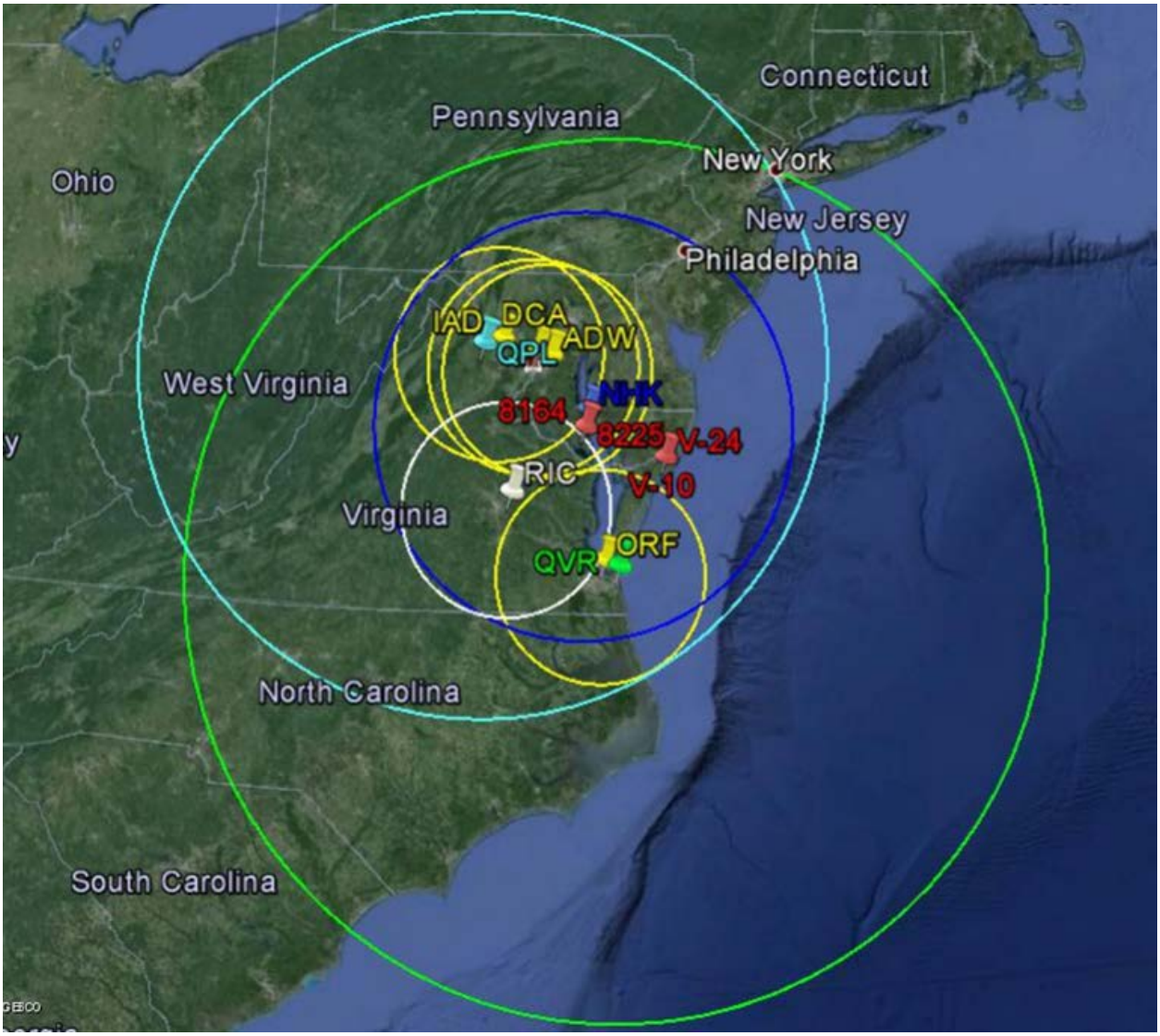


Figure 2. Coverage Area for SSR Measurement Sites

Automatic Dependent Surveillance – Broadcast Ground Radios

The impact of the proposed AN/UPX-41(C) Stage 4 configuration on Automatic Dependent Surveillance – Broadcast (ADS-B) ground radios was addressed through analysis of data recordings at ten ADS-B ground radio station locations in the vicinity of the LBTS as well as through simulation. The ten ADS-B ground radio locations are given in Figure 3 and Table 4. An aircraft above an ADS-B ground station at sufficient altitude is visible to all four LBTS. For the two AN/UPX-41(C) interrogators at NAWCAD/St. Inigoes, the minimum reception altitudes above nine of the ten sites (the exception being SV143-01) are less than 2,500 feet. Moreover, the region within a 60 NM radius of each ADS-B site is entirely within the coverage range of all four AN/UPX-41(C) interrogators.

Table 4. ADS-B Ground Radio Station Measurement Sites

Service Volume (SV)	Latitude	Longitude	Location
SV171-03	39.1033030	-77.1541929	Montgomery County, MD
SV017-01	38.9786983	-76.3092971	Stevensville (Queen Anne's County), MD
SV186-02	38.8579988	-77.0443940	Reagan National Airport, VA
SV186-01	38.8495016	-77.0410037	Reagan National Airport, VA
SV036-01	38.5493946	-76.9495082	Indian Head (Charles County), MD
SV247-01	38.4909010	-76.1355972	Cambridge (Dorchester County), MD
SV158-04	37.5242972	-76.7640925	Middle Peninsula Regional Airport, West Point (King William County), VA
SV158-01	37.4076962	-77.5215912	Chesterfield County Airport, VA
SV171-02	37.2513986	-75.9744072	Cape Charles (Northampton County), VA
SV143-01	36.6819608	-76.6010589	Suffolk Executive Airport, VA

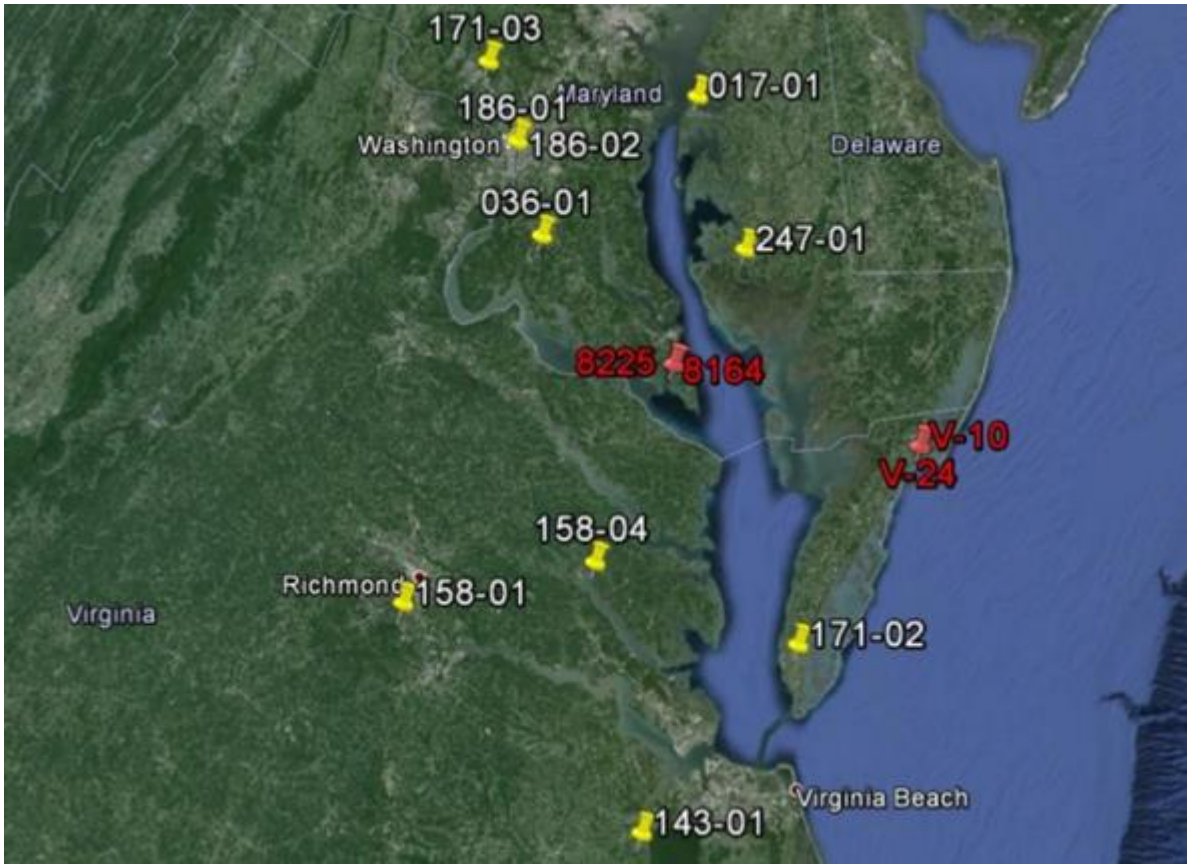


Figure 3. ADS-B Ground Radio Station Measurement Sites

Multilateration

The impact of the proposed AN/UPX-41(C) Stage 4 configuration on Airport Surface Detection Equipment, Model X, (ASDE-X) Multilateration (MLAT) systems was addressed by simulation. The nearest ASDE-X installation to the LBTS was at DCA. The minimum altitude visible to the

LBTS was only 986 ft, MSL. Thus, aircraft on the surface of DCA would not have been visible to the LBTS and the only interference to the MLAT system would have come from False Replies Unsynchronized in Time (FRUIT) elicited by the LBTS. After consultations with MLAT SMEs, it was determined that instrumenting the ASDE-X system to record data for the test would not be cost effective considering the lack of interference expected.

Traffic Alert and Collision Avoidance System

The impact of the proposed AN/UPX-41(C) Stage 4 configuration on Traffic Alert and Collision Avoidance Systems (TCAS) was addressed by analysis using data recorded on board the Convair 380 (N39).

Automatic Dependent Surveillance – Broadcast Air-to-Air

The impact of the proposed AN/UPX-41(C) Stage 4 configuration on the ADS-B air-to-air link was evaluated by analysis using data recorded on board N39 in conjunction with 1090 MHz interference mitigation studies.

1.2.3. Major Test Activities

The following outlines the test activities and the dates of execution:

- **July 15-17, 2014**: Pre-test/dry-run involving personnel and procedures to be utilized during live testing as well as LBTS and ground-based ASCAS and data collection systems.
- **August 11-15, 2014**: Recorded SSR data in support of determining thresholds for DEGRADED BUZZER.
- **August 18-21, 2014**: Live testing involving LBTS and ground- and aircraft-based ASCAS and data collection systems.
    - August 18 – Baseline airborne and ground-based data recording.
    - August 19-21 – Airborne and ground-based data recording with LBTS cycled Active and Off
        - 30 minute intervals
        - 5 minute intervals when airborne measurements were conducted
        - Stair-step configuration (1 on, 1 off, 2 on, 2 off, etc) during holds
        - August 19 included airborne sidelobe data collection

Table 5 defines nomenclature used throughout this report when referring to the test days.

Table 5. Day Label Key

Day	Time (EDT)	Key
Monday, August 18, 2014	0500 – 1700	Day 1
Tuesday, August 19, 2014	0500 – 1700	Day 2
Wednesday, August 20, 2014	0500 – 1700	Day 3
Thursday, August 21, 2014	0500 – 1700	Day 4

2. Airborne-based Data Collection and System Analysis

2.1. Summary

This section discusses the airborne measurements conducted by the William J. Hughes Technical Center (WJHTC) to assess the impact of the proposed AN/UPX-41(C) Stage 4 configuration on the 1030 MHz and 1090 MHz environments as well as the performance assessments of the airborne surveillance systems, TCAS and ADS-B Air-to-Air.

2.1.1. 1030 MHz Measurements

At the most, the Typical and Worst Case ATCRBS function of a transponder will be occupied 1.03% and 1.21%, respectively, within five nmi of one AN/UPX-41(C) system. Outside of a single AN/UPX-41(C) system's SLS range (20 nmi), the 1030 MHz impact from the single AN/UPX-41(C) system's sidelobes and mainbeam is negligible and cannot be differentiated from the baseline 1030 MHz environment.

2.1.2. 1090 MHz Measurements

Based on measurements, there were about 18 ATCRBS replies on average at 10 nmi and about 10 ATCRBS replies on average at 140 nmi elicited by an AN/UPX-41(C) interrogator from a single aircraft. When these replies are received by any surveillance system besides the AN/UPX-41(C) that elicited them, they are called False Replies Unsynchronized in Time (FRUIT). From the traffic counts in the vicinity of the flight test aircraft for Day 3 and Day 4 data collections, which alternated the LBTS Active and Off, the ATCRBS FRUIT contribution due to the LBTS operation measured and calculated were in good agreement. The 1090 MHz ATCRBS reply impact of an interrogator is a function of the aircraft density within its surveillance volume and expected and measured AN/UPX-41(C) interrogator impact to FRUIT based on the densities during the flight tests provides confidence that AN/UPX-41(C) contribution to FRUIT can be reasonably estimated.

2.1.3. Airborne Surveillance System Performance

Traffic Alert and Collision Avoidance System (TCAS)

With a worst case assumption that the AN/UPX-41(C) system causes 20 replies per mainbeam and assuming four operating interrogators, the TCAS Mode S receiver will potentially experience 4560 ATCRBS replies per second for an aircraft density that is twice the high density 2020 baseline used in the FAA Spectrum Mitigation Activity. This results in a probability of track in support of an RA in time to alert at the required range of 12.8 nmi range of 0.995, significantly above the required 0.90.

Automatic Dependent Surveillance – Broadcast (ADS-B) Air-to-Air

The predicted change in ADS-B air-to-air performance, based on the ATCRBS FRUIT per second induced by the proposed AN/UPX-41(C) Stage 4 configuration, is negligible considering that the change in update rate was less than 10% of the maximum allowed time between state vector updates needed to support applications at different aircraft pair ranges (10 to 90 nmi).

2.2. Flight Test

The test of the proposed AN/UPX-41(C) Stage 4 configuration included the deployment of a specially equipped test aircraft to make airborne measurements to assess the impact on the 1030 MHz and 1090 MHz environments. The WJHTC provided a Convair 380 (N39) and test engineers to facilitate the data collection and post-test analysis.

The aircraft flew on four test days. On Day 1, N39 flew a baseline flight around the eastern Maryland, Virginia, and Washington, D.C. areas with no LBTS operating in order to record baseline NAS 1030 and 1090 MHz environments. On Day 2, N39 flew in support of determining the impact of the AN/UPX-41(C) system's sidelobes on transponder occupancy. For this test, the aircraft generally flew right over and past each LBTS at low altitude (6,000 feet) as they were operating individually to record occupancy and suppression data. On Day 3, the aircraft flew at approximately 20,000 feet in a route mimicking the flight path from Day 1. There were two holding patterns executed, one on the eastern side of the circuit, and one to the west. On Day 4, a similar route was flown again but with a lower altitude (9,000 feet). On this test day, there was one holding pattern executed in the east. During Days 3 and 4, all four LBTS were simultaneously cycled Active and Off every 5 minutes. The 5 minute cycling facilitated the comparison of 1030 MHz and 1090 MHz environments with and without the AN/UPX-41(C) systems' impact. The flight path for Day 3 is shown in Figure 11 and the flight path for Day 4 is shown in Figure 18. The flight paths for the SLS test are shown in A.2.

2.3. Recording and Analysis Tools

The airborne test equipment is described in Section 9.5 of the Test Plan.

2.4. 1030 MHz – Sidelobe Suppression Characteristics

Since the AN/UPX-41(C) system will have the most impact on transponder occupancy when aircraft are within range of the sidelobes of the radiating antenna, an analysis of its sidelobe characteristics was performed. An interrogator not only contributes to a transponder's occupancy as the mainbeam passes and replies are triggered, but occupancy also occurs when in the range of sidelobes that begin to trigger suppressions. As the distance between the aircraft and the antenna decreases, the sidelobe pattern can have a greater effect on the transponder. Close enough to the antenna, the sidelobes can completely surround the aircraft antenna and the transponder would be

suppressed by every interrogation other than the mainbeam. The purpose of the airborne measurement of the sidelobe suppression was to determine the sidelobe suppression (SLS) range of the AN/UPX-41(C) and to show the impact on transponder occupancy as a function of aircraft range from the AN/UPX-41(C).

The airborne test portion of Day 2 was dedicated to flying profiles designed to measure the SLS characteristics of the LBTS. The test was coordinated between the test pilots and the LBTS's personnel to activate each of the four sites one at a time while N39 flew 40 nmi radials to and from the site. With the Wallops Island sites (V10 & V24), the aircraft flew on a straight path from northeast to southwest past the sites. With the two LBTS located at Webster Field (8164 & 8225), the aircraft flew from east of the sites, turned around right over the site, and flew back to the east. This was required due to airspace restrictions. Following the flight over the four individual sites, the aircraft flew two passes over the two co-located Wallops Island sites while they were both active. For all SLS tests, the aircraft maintained an altitude of 6,000 feet. The flight profiles are shown in A.2.

Transponder occupancy is subject to variations due to different design characteristics of different transponder models and manufacturers. The requirements stated in the transponder Minimum Operational Performance Standards (MOPS) allow for a range of performance variables that directly affect occupancy such as suppression duration, that is required to be between 25 and 45 microseconds, and reply dead time that shall not exceed 125 microseconds. The work of technical committees predicting future interference environments and future NAS performance with growth in air traffic have to consider these variations in transponder operation. International Civil Aviation Organization (ICAO) has incorporated guidance for transponder parameter performance sets which include Typical and Worst Case. The Typical parameters are a value set that has been determined to be average based on data from measurements from production transponders that operate in the airspace. The Worst Case parameters use the maximum allowable by the MOPS. The post processing for the test flights was performed using both parameter sets. A complete description of the Typical and Worst Case parameters is included in A.1.

The maximum LBTS SLS effect on transponder occupancy can be calculated for the condition in which the victim transponder is in the full sidelobe of the interrogator. The following calculations estimate that the maximum impact from a single LBTS on ATCRBS function transponder occupancy, using Typical transaction times, will be about 1%, and, using Worst Case transaction times, will be about 1.2%:

Typical:

1024 (total interrogations per scan) – 40 (approx. main beam) = 984 total suppressions

984 x 41 (Typical suppression duration in microseconds) = 40,344 µs

10 (approx. main beam Mode A) x 88.7 µs (Typical reply incl. dead time) = 887 µs

10 (approx. main beam Mode C) x 101.7 µs (Typical reply incl. dead time) = 1017 µs

40,344 µs + 887 µs + 1017 µs = 42,248 µs

42,248 µs / 4,096,000 µs (duration of one scan) = 0.0103 or **1.03% occupancy**

Worst case:

1024 (total interrogations per scan) – 40 (approx. main beam) = 984 total suppressions

984 x 47 (Worst Case suppression duration in microseconds) = 46,248 µs

10 (approx. main beam Mode A) x 157.0 µs (Worst Case reply incl. dead time) = 1570 µs

10 (approx. main beam Mode C) x 170.0 µs (Worst Case reply incl. dead time) = 1700 µs

46,248 µs + 1570 µs + 1700 µs = 49,518 µs

49,518 µs / 4,096,000 µs (duration of one scan) = 0.0121 or **1.21% occupancy**

The flight tests of the four individual sites was intended to provide eight data sets to assess the SLS impact on the test aircraft as a function of range. Analysis of the data revealed that there were significant interfering conditions that compromised the use of four of the data sets for making a meaningful assessment. It was determined that site 8225 did not have properly working SLS and a source of high level interference to the south of the Wallops Island sites impacted the data. Of the four remaining data sets, external interference also had some influence on the measured results. There is a deeper analysis of all of these conditions and findings provided in Appendix A.

It should be understood that the tests were conducted in a live air traffic environment and that in addition to the LBTS, there were multiple SSRs and TCAS aircraft interrogating N39. Therefore, there was always some level of transponder occupancy not attributed to the LBTS. In all of the plots in this section, the data shows the total occupancy or suppression rate which includes activity from both civil and airborne interrogators in the environment, as well as the LBTS.

Figure 4 shows a compilation of the measured transponder occupancy for the ATCRBS function of a Typical transponder from the four test flights used for analysis of the LBTS SLS characteristics. When N39 is inside the LBTS SLS range (20 nmi), the measured ATCRBS function occupancy represents the impact from both the AN/UPX-41(C) system and the background environment. To remove the systematic error due to the changing background environment for each run, a least squares fit was used to estimate the background effects outside of 20 nmi and the plots were adjusted to this level. Each data point is the average ATCRBS function occupancy for the number of samples recorded for each rounded 1-nmi increment.

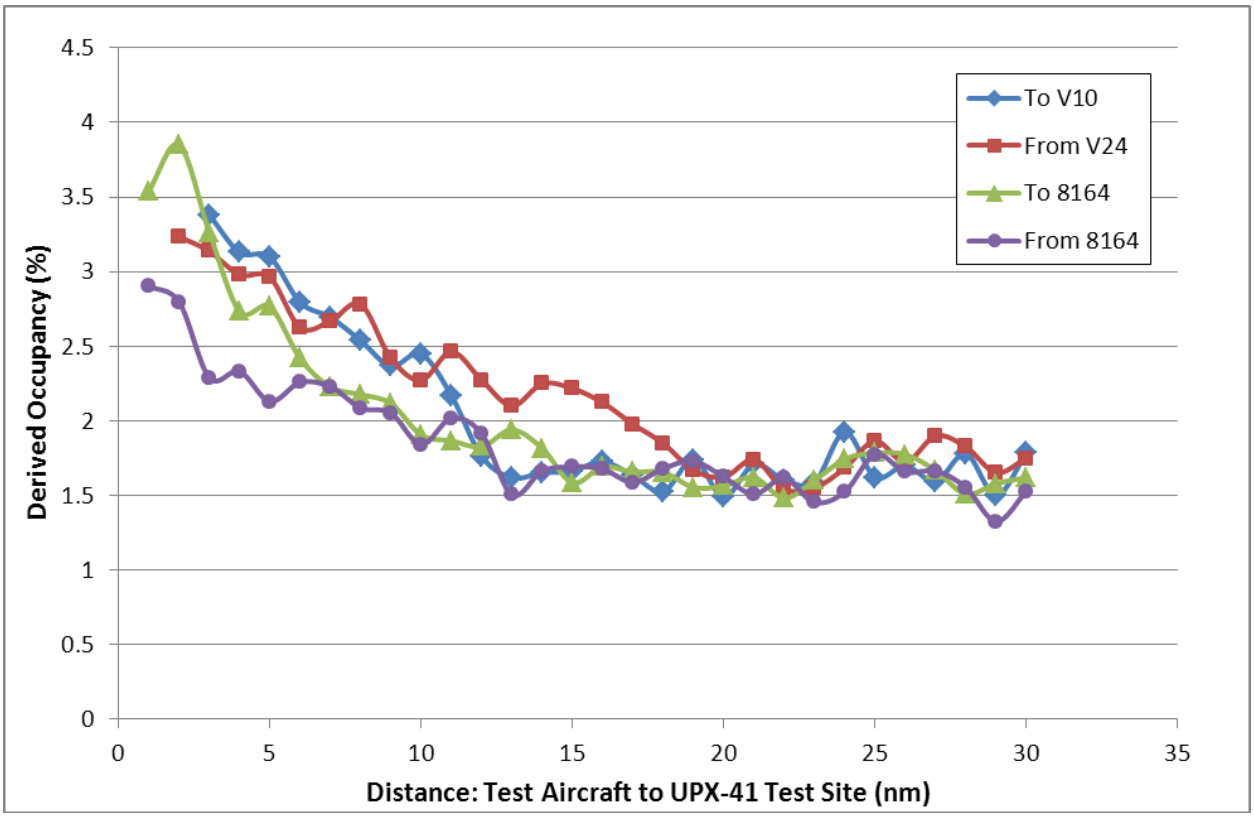


Figure 4. SLS Test Typical ATCRBS Function Occupancy

Figure 5 shows a plot of the ATCRBS function transponder occupancy for the four data sets with a logarithmic trend line added, and Figure 6 is a similar plot of a Worst Case transponder.

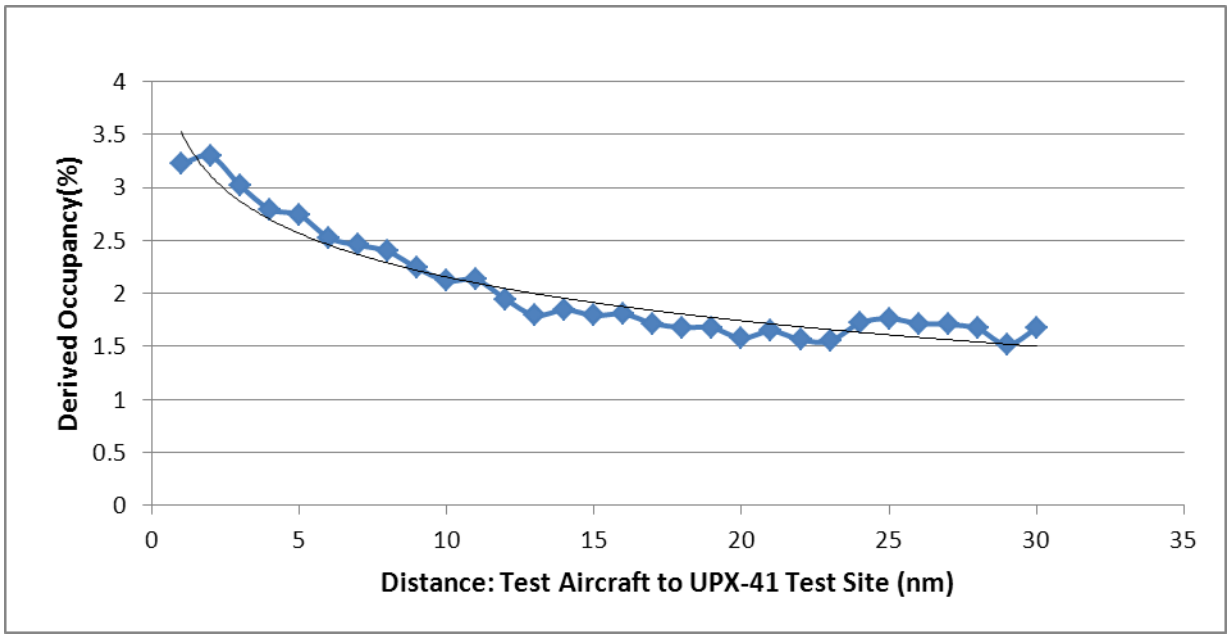


Figure 5. SLS Test Typical Average Measured ATCRBS Function Occupancy

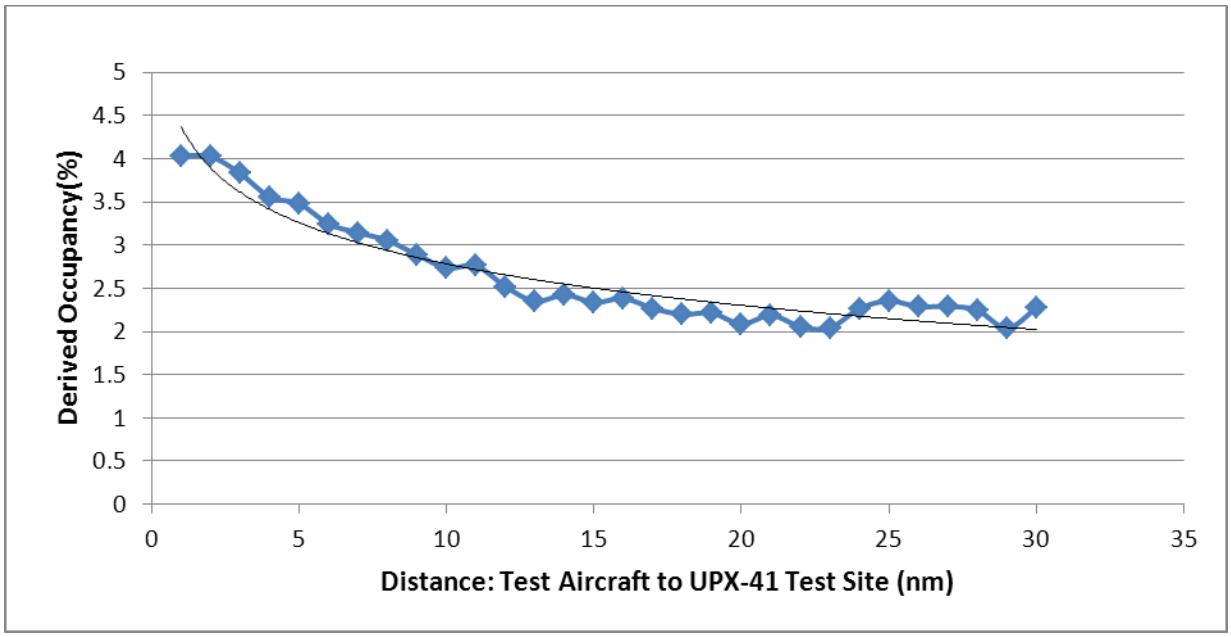


Figure 6. SLS Test Worst Case Average Measured ATCRBS Function Occupancy

In both of the average measured ATCRBS function occupancy plots (Figure 5 and Figure 6), the maximum impact is about 0.5% higher than the calculated maximum. This assessment is done by comparing the baseline occupancy (the average between 20 and 30 nmi) and the peak at close range. As stated earlier, there was some level of interference during some of the test. Referring to Figure 4, the plot of 'from 8164' best matches the expected occupancy. A deeper analysis included in Appendix A showed a higher than expected number of suppressions for both 'to V-10' and 'from V-24' possibly due to multipath, and there was also a burst of Mode A interrogations and suppressions for a brief period at the end of the 'to 8164' test. These likely contributed to a higher measured value for those flight segments. It is reasonable to conclude from this small sample of test data that the AN/UPX-41(C) impact on the ATCRBS function transponder occupancy begins at a range between 15 and 20 nmi and peaks within 5 nmi of the interrogator to the expected maximum impact of 1.0% to 1.2%. Additional occupancy of about 0.5% can be attributed to other factors such as multipath and uncertainty in operation directly over the sites.

Sidelobe suppression does not impact the Mode S function of a transponder. An assessment of Mode S function transponder occupancy was made to determine if there was any unexpected impact from the LBTS. Figure 7 shows a compilation of all SLS test runs over the four LBTS. The purpose of this graph is to show the trend and any test anomalies. Because of data similarity, only Mode S function transponder occupancy with Worst Case times is shown here. The AN/UPX-41(C) system's SLS only blocks the transponder's ATCRBS replies, leaving the transponder unoccupied to receive and reply to Mode S interrogations. However, for non-suppressing ATCRBS interrogations, a transponder's reply and recovery intervals do create

occupancy blocking the Mode S function so it is important to measure the AN/UPX-41(C) system's impact on Mode S function as well.

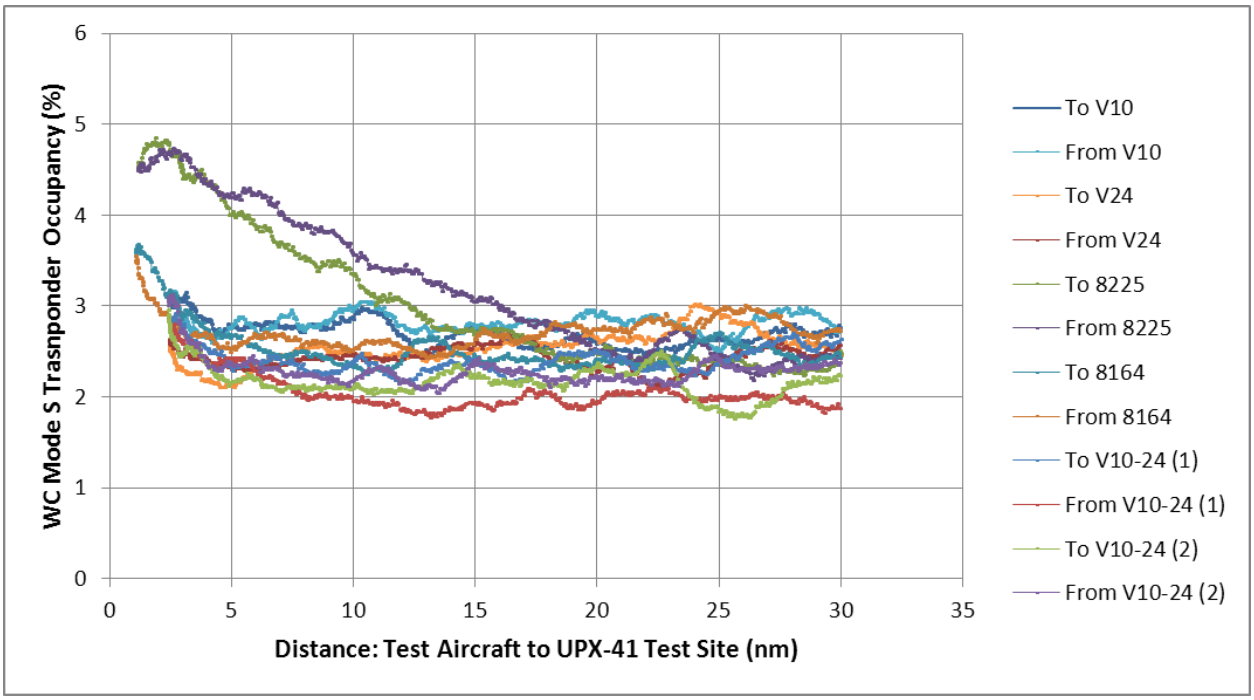


Figure 7. SLS Test Worst Case Mode S Function Occupancy

In the Mode S occupancy plots, the 'to' and 'from' site 8225 plots show a much different trend than the other sites. This was analyzed to determine the cause. It was found to be due to a problem with the SLS at this site that caused replies to Mode 3/A and Mode C interrogations received from sidelobes. There was significant analysis done to investigate this anomaly and this is included in A.2.3. Excluding site 8225, generally the Mode S function occupancy shows an increase of 0.5% only at very close range (less than 5 nmi). Further analysis determined that the increase is due to additional Mode 3/A and Mode C replies that indicate a reduced SLS operation when nearly directly over the interrogators.

Figure 8 shows a plot of the count of suppressed interrogations of various types that were detected from the flight over site 8164 in every 4-second interval. Again, the following plots show the total measured suppressions from everything in the environment, not just the LBTS. The conversion from UTC to EDT (local time) is -0400 hours. The plot is color coded to show the different interrogation types. Because the AN/UPX-41(C) system has a 4.096-second antenna rotation and a 250 PRF interrogation rate, the maximum suppression count by each type from the site under test will be about 250 in 4 seconds. This maximum rate less the main beam could occur when an aircraft is close enough to be completely in the SLS pattern. The plot shows that this rate was briefly reached when the aircraft was less than 5 nmi from the site. The plot also shows that the estimated range at which the effects of sidelobe suppression begin to impact ATCRBS function transponder occupancy is about 20 nmi. Beyond 20 nmi, the LBTS SLS is

negligible. The plot in Figure 8 was processed with Typical transponder parameters. Figure 9 shows the same sidelobe suppression rate data using parameters that go beyond the ICAO defined Worst Case parameters. For Figure 9, in addition to applying the ICAO Worst Case parameters, the sensitivity was increased by 1 dB and the P2 amplitude acceptance was set to -8 dB relative to P1 for this analysis. These settings make the post-process mimic a transponder that is the most sensitive to suppressions. The data in Figure 9 does not show a significant increase in the suppression range compared to a Typical transponder shown in Figure 8, but does show an increase in the number of suppressions of each type when in SLS.

Deeper analysis indicated that there was a short duration, high PRF burst of Mode A interrogations and suppressions when the aircraft was near site 8164 that caused the brief high suppression peak. The signature analysis and power level of this event indicates that 8164 was the source. A deeper analysis of this is included in A.2.4.

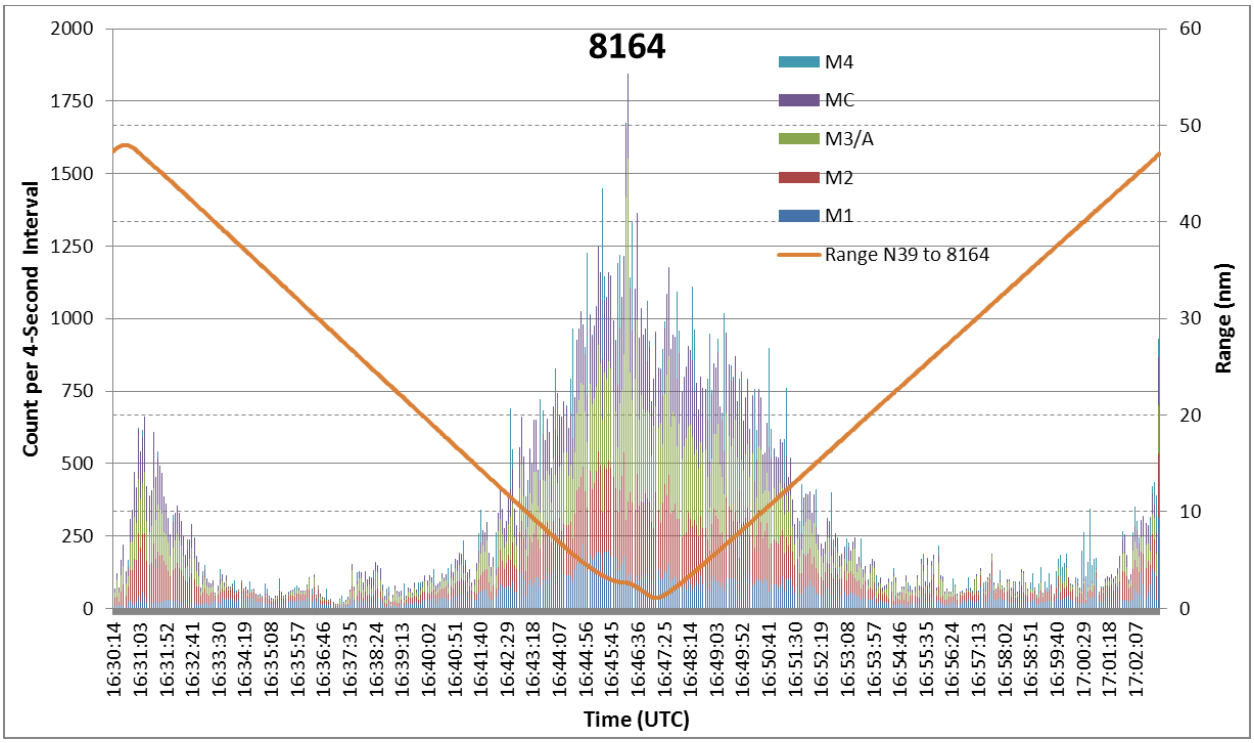


Figure 8. Site 8164 + Environment, Sidelobe Suppressions by Interrogation Type

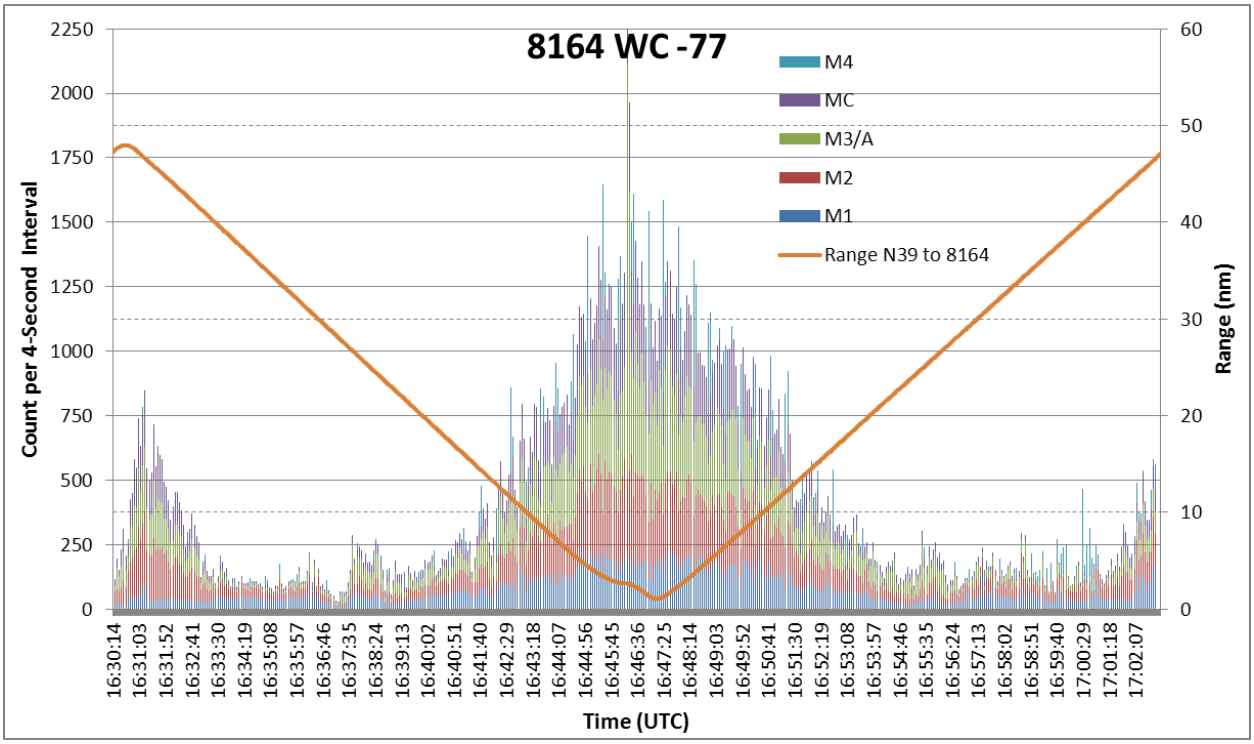


Figure 9. Site 8164 + Environment, Sidelobe Suppressions by Interrogation Type, *Enhanced* Worst Case

Figure 10 shows the 4-second interval suppression count for the flights over Wallops Island when both V10 and V24 were operating. In this case, the two co-located sites could contribute up to 500 suppressions of each Mode per 4-second interval and this rate is reached in close proximity to the sites. It has been determined that the elevated suppression activity between the sites was from another interrogator.

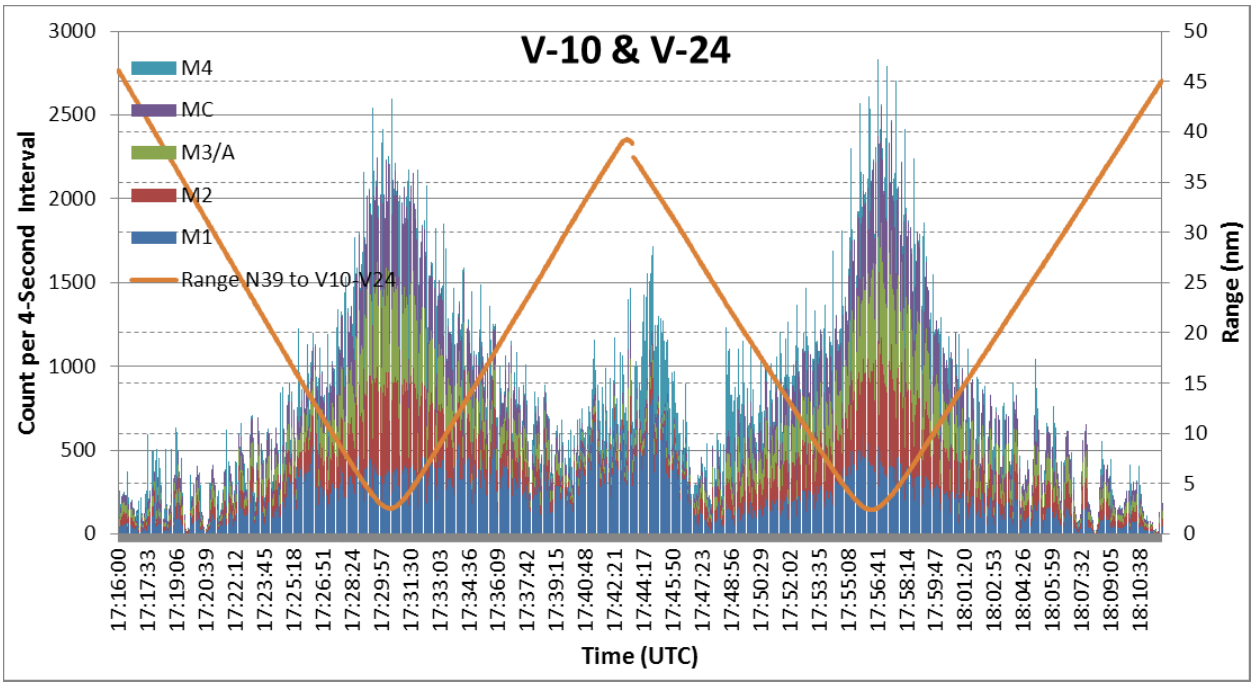


Figure 10. Sidelobe Suppressions by Interrogation Type during Test of Two Sites (V10 & V24) Operating

2.5. 1030 MHz – Transponder Occupancy Impact

As was detailed in Section 2.4, the ATCRBS function transponder occupancy will be most impacted when aircraft are within the sidelobe suppression range of a 1030 MHz interrogator such as the AN/UPX-41(C). The SLS tests were designed to specifically measure the range and impact of the sidelobe suppressions. On Days 3 and 4, N39 flew a circuit around the eastern Maryland/Virginia area while all four LBTS were cycled Active and Off every 5 minutes. The purpose of these tests was to gauge the impact of four interrogators on aircraft within range of all four sites (not necessarily within SLS range). The Active-Off cycling provided the ability to compare transponder occupancy when the LBTS were interrogating with transponder occupancy when they were not interrogating. A plot of N39's flight path for Day 3 is shown in Figure 11.

In the following series of plots (Figure 12 to Figure 17), the Typical ATCRBS function transponder occupancy is shown from the test flight on Day 3. The aircraft flew at an altitude of 20,000 feet for most of the flight. The red data points indicate when the four LBTS were Active, and the blue data points indicate when they were off. The green data points are during the transitions. The darker bands are a 30-second average. Also shown is the range from the site pairs, with gold for the distance from the Wallops Island sites and silver for the distance from the Webster Field sites. The aircraft flew two holding patterns, one on the eastern side of the circuit and the other on the western side (Figure 13 and Figure 16, respectively).

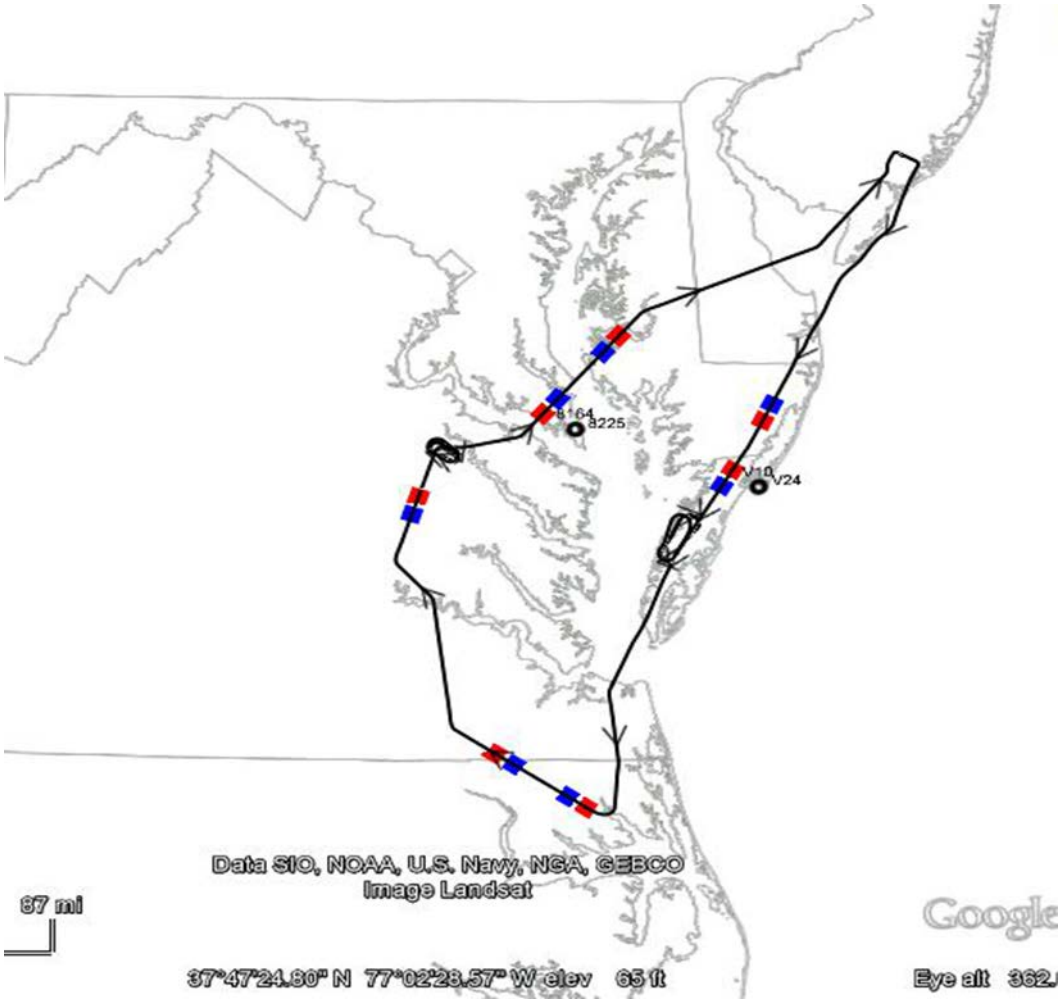


Figure 11. Day 3 Flight Path

(Note: In Figure 11 the red (Active) and blue (Off) highlighted segments indicate the location of the selected data samples for 1090 MHz measurement summarized in Section 2.6.1 Table 6.)

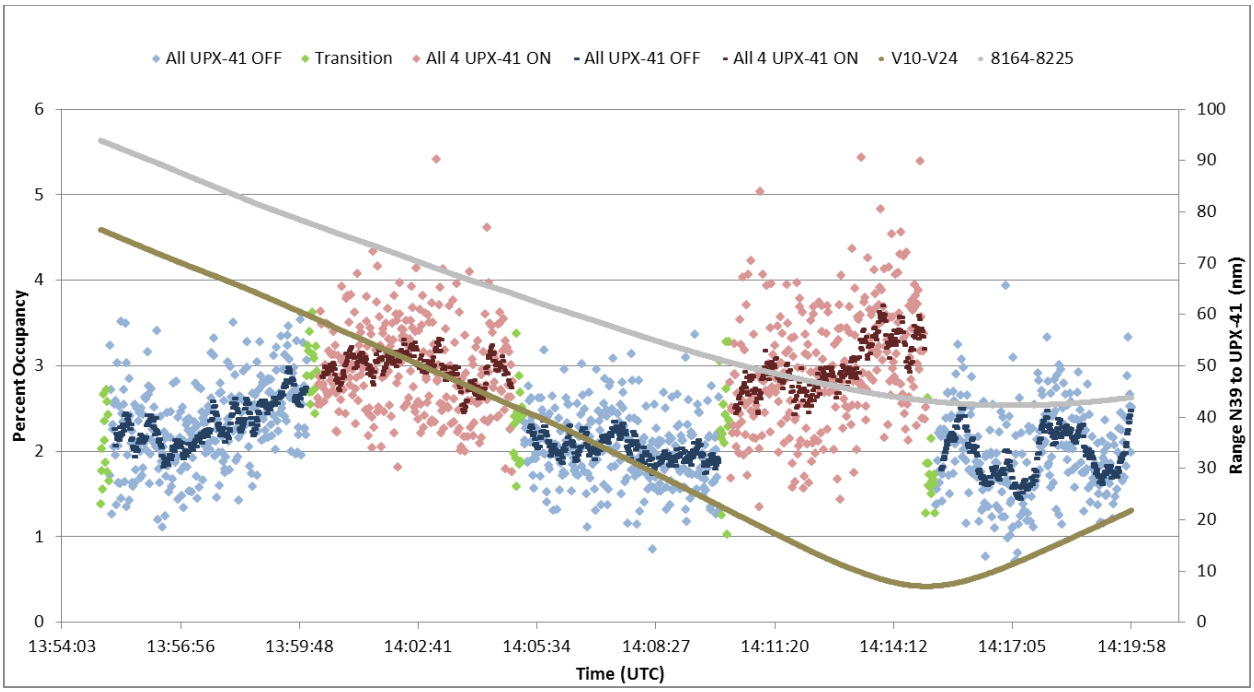


Figure 12. Plot #1, Day 3 ATCRBS Function Transponder Occupancy

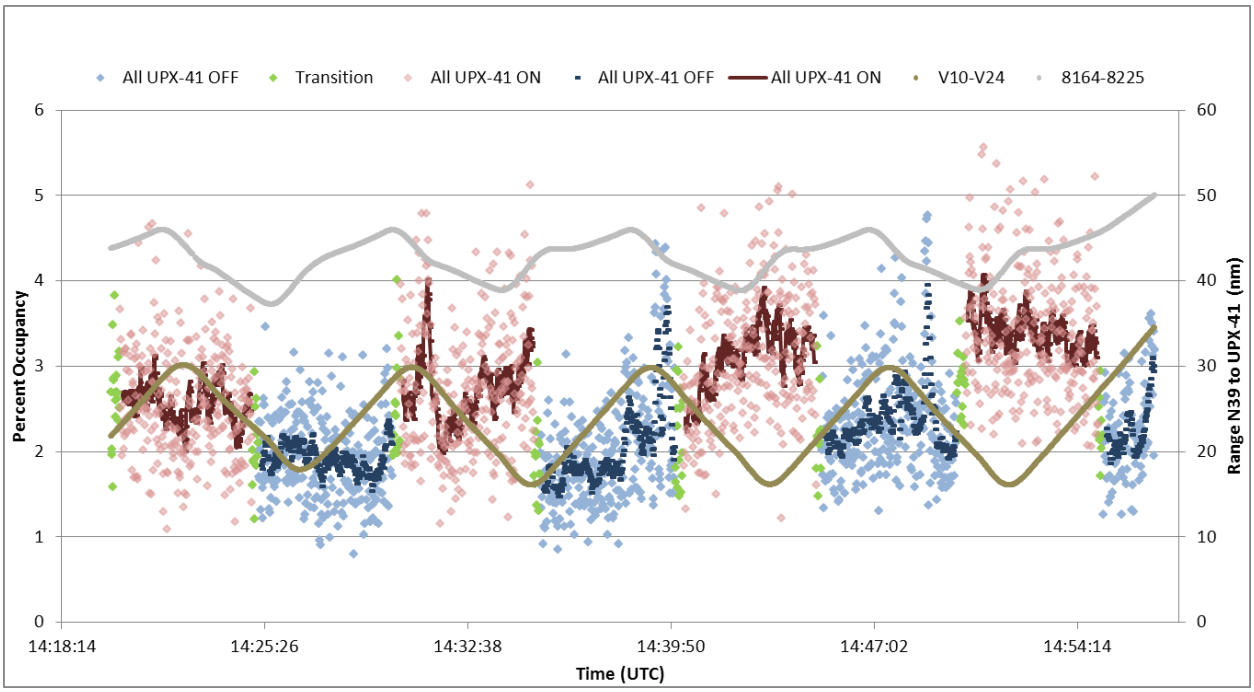


Figure 13. Plot #2, Day 3 ATCRBS Function Transponder Occupancy

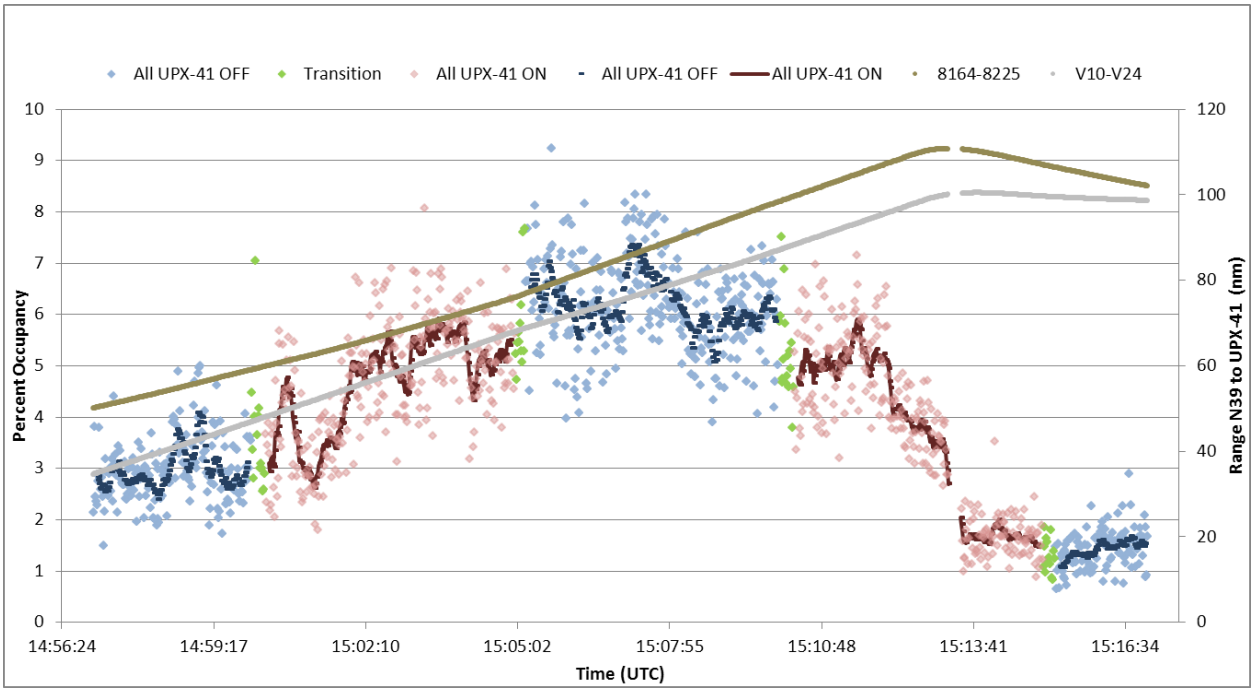


Figure 14. Plot #3, Day 3 ATCRBS Function Transponder Occupancy

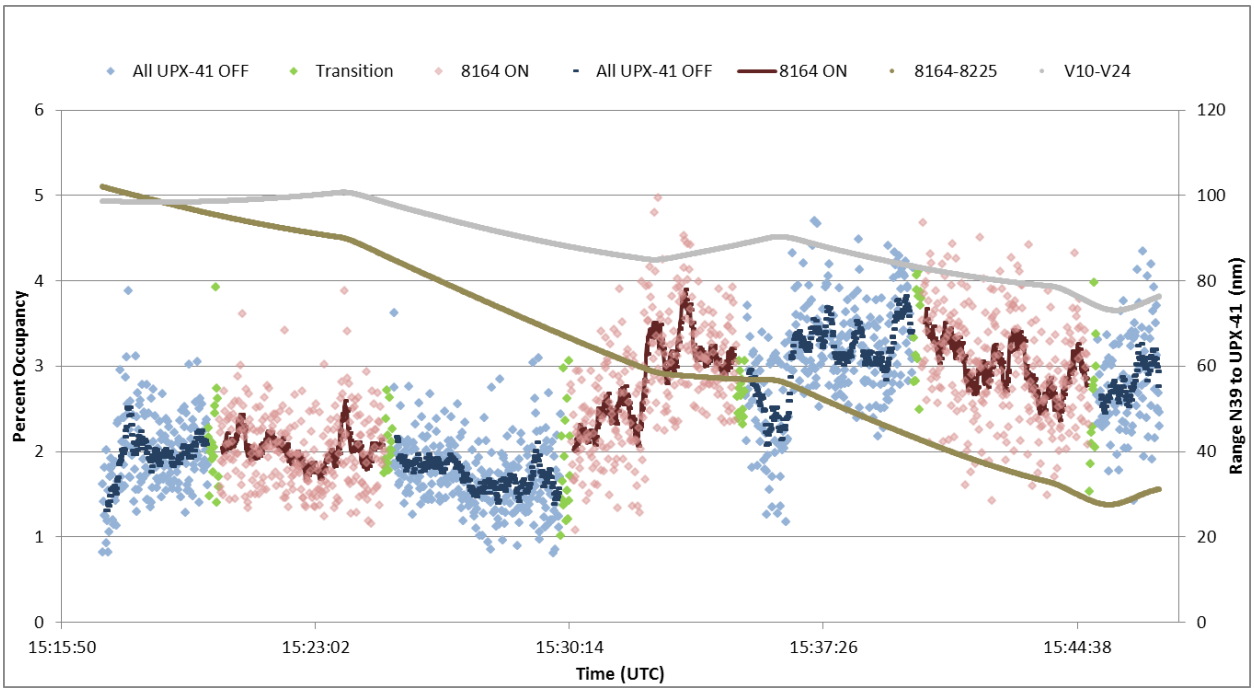


Figure 15. Plot #4, Day 3 ATCRBS Function Transponder Occupancy

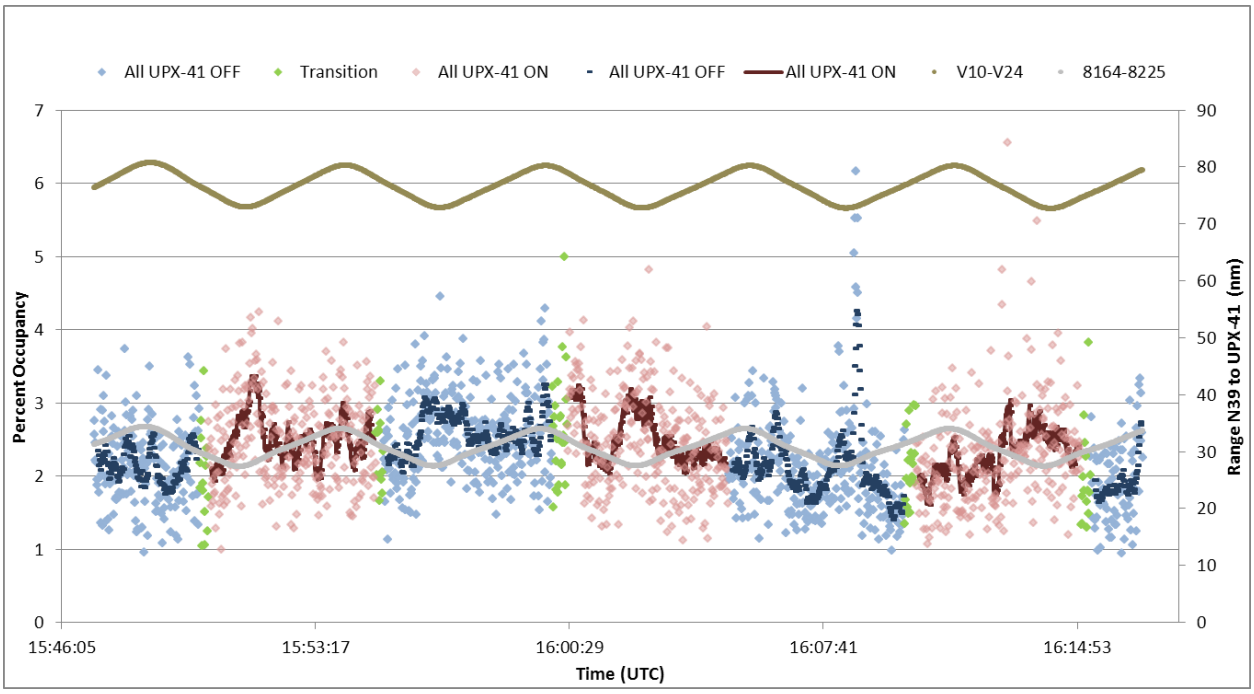


Figure 16. Plot #5, Day 3 ATCRBS Function Transponder Occupancy

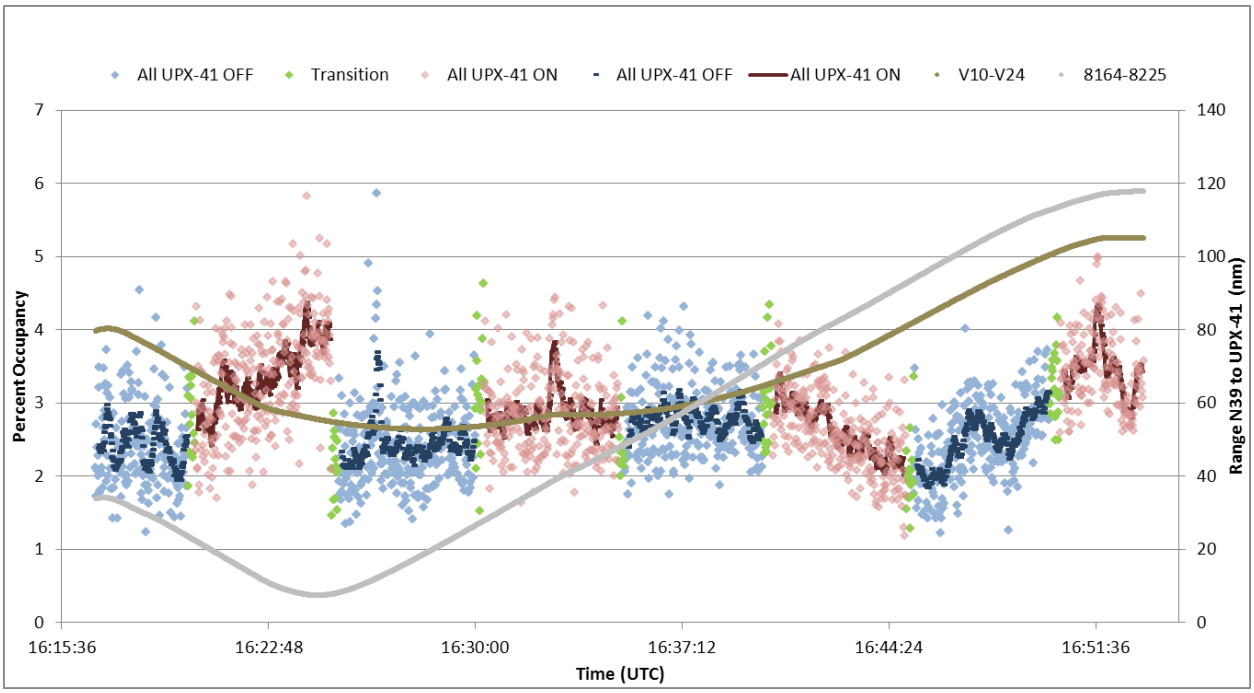


Figure 17. Plot #6, Day 3 ATCRBS Function Transponder Occupancy

On Day 4 N39 flew a similar route but at the lower altitude of 9,000 feet. The flight path is shown in Figure 18. Also, the Day 4 flight included one hold on the eastern side of the circuit. The following series of plots show the Day 4 ATCRBS function transponder occupancy. The plots have the same format and color coding as the Day 3 plots.

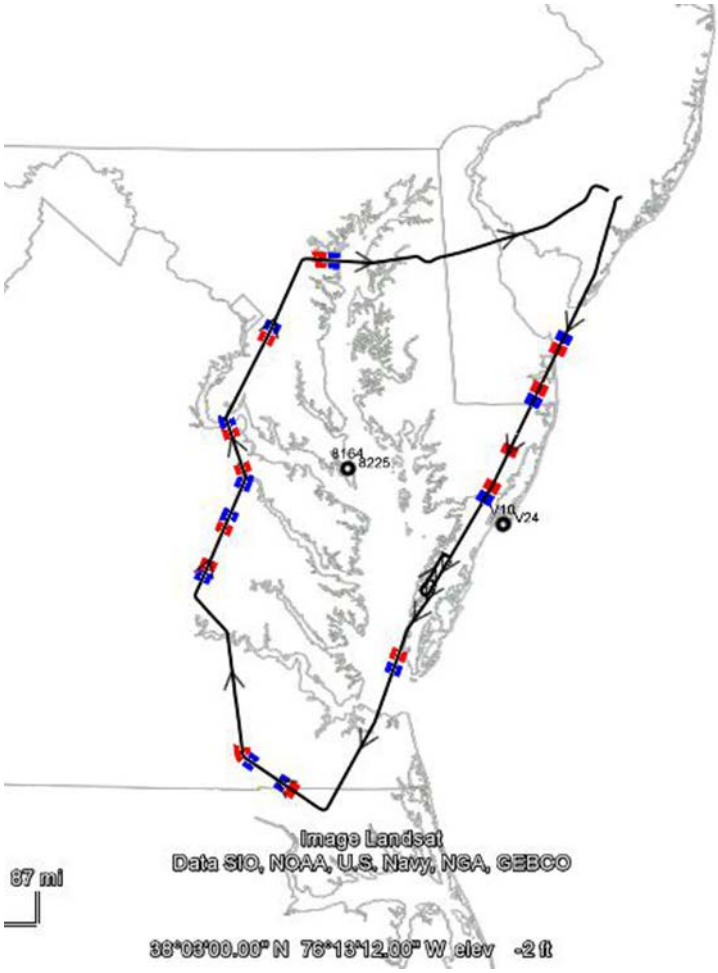


Figure 18. Day 4 Flight Path

(Note: In Figure 18 the red (Active) and blue (Off) highlighted segments indicate the location of the selected data samples for 1090 MHz measurement summarized in Section 2.6.2 Table 7.)

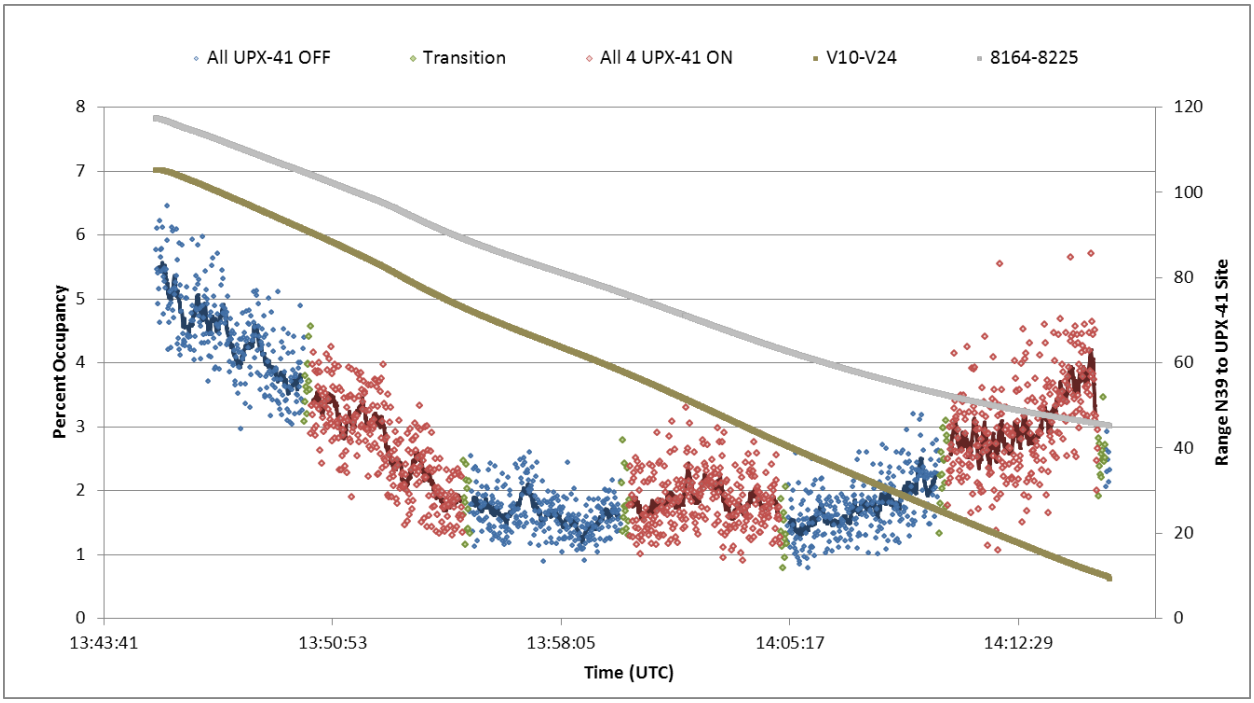


Figure 19. Plot #1, Day 4 ATCRBS Function Transponder Occupancy

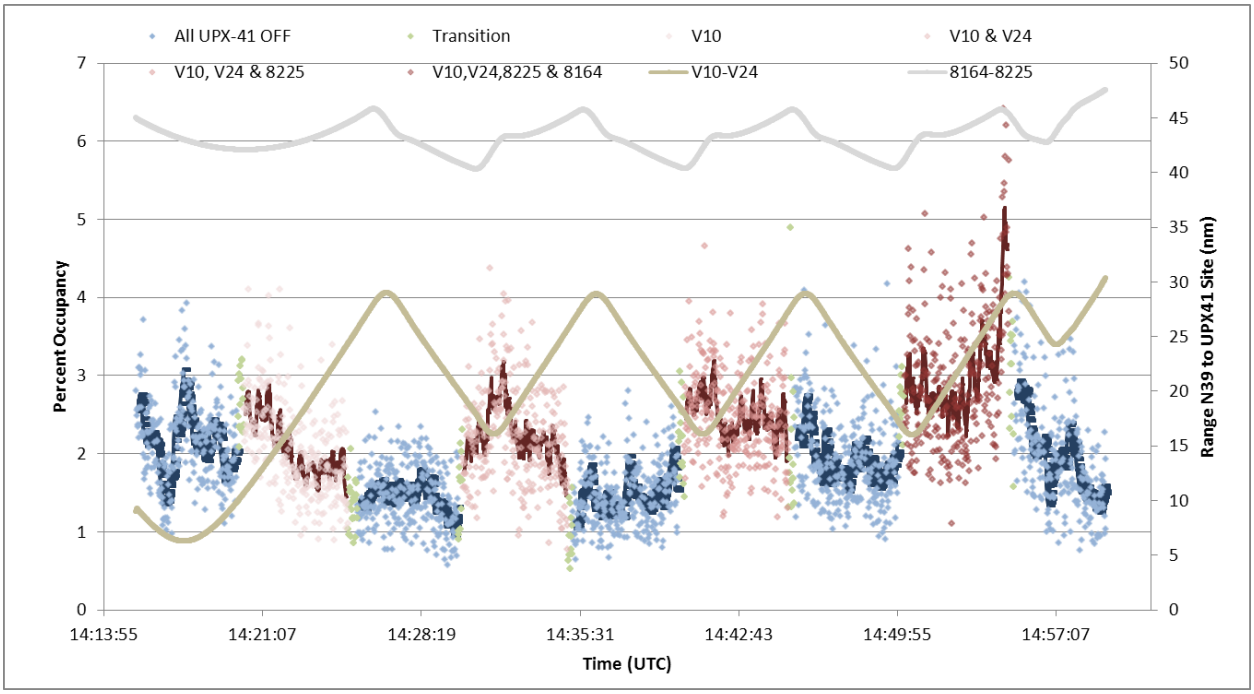


Figure 20. Plot #2, Day 4 ATCRBS Function Transponder Occupancy

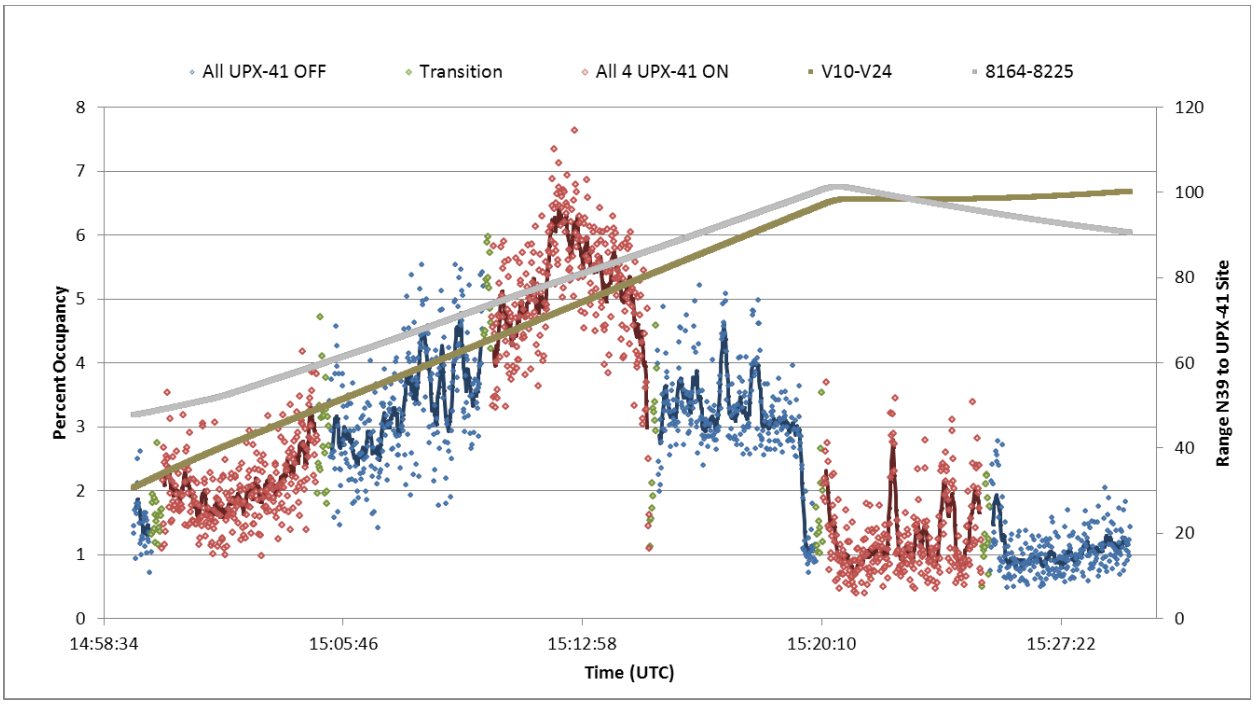


Figure 21. Plot #3, Day 4 ATCRBS Function Transponder Occupancy

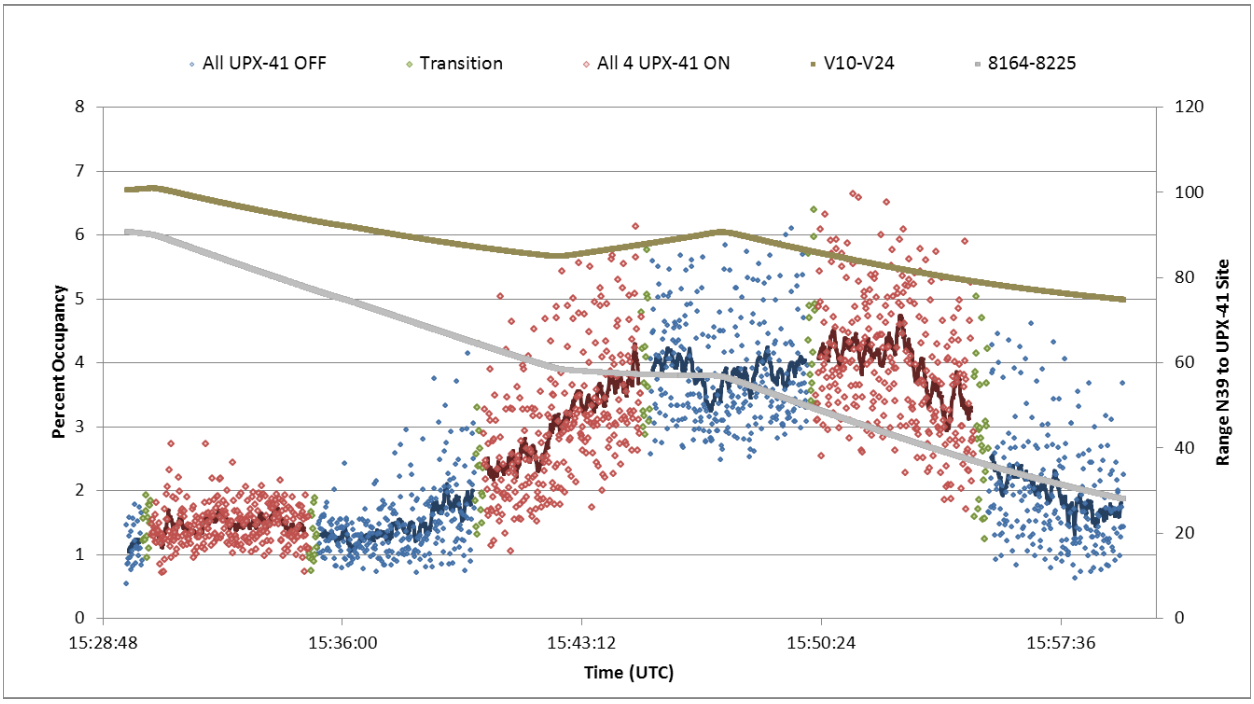


Figure 22. Plot #4, Day 4 ATCRBS Function Transponder Occupancy

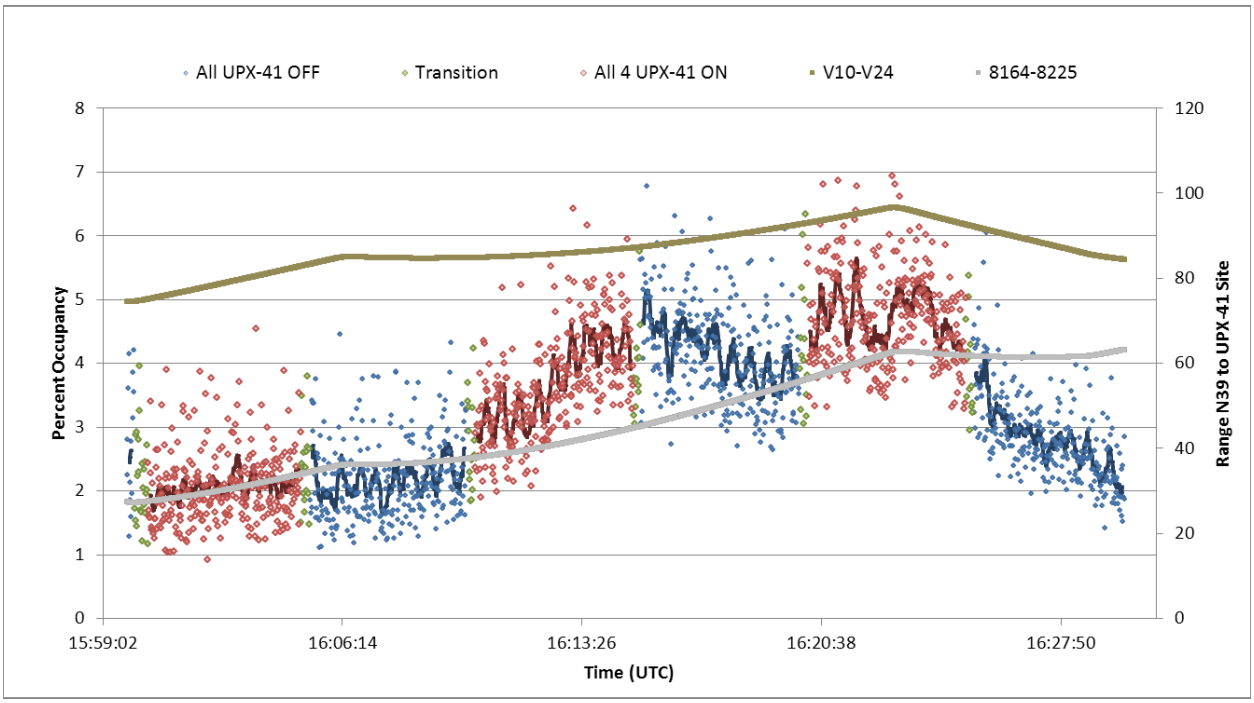


Figure 23. Plot #5, Day 4 ATCRBS Function Transponder Occupancy

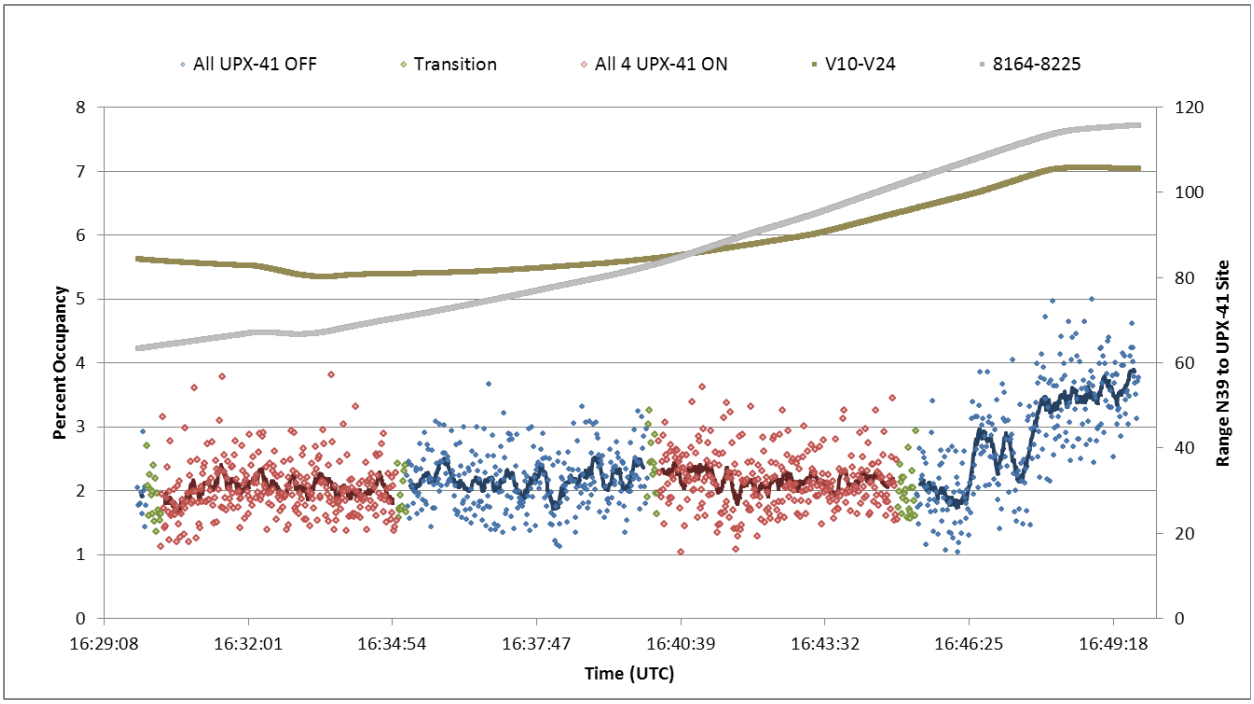


Figure 24. Plot #6, Day 4 ATCRBS Function Transponder Occupancy

In the preceding series of ATCRBS function transponder occupancy plots from Days 3 and 4, the average occupancy varies significantly from as low as about 1% to as high as about 7%. The variations appear to be related more to where the aircraft is located than any effect from the

LBTS. There were some 5-minute cycles that showed an apparent higher occupancy when the LBTS were Active than an adjacent Off cycle. These occurred when N39 was in close range to at least one of the site pairs. These can be observed in the following figures: Figure 12 2nd Active-cycle, Figure 13 the latter 3 Active-cycles during the hold, Figure 17 1st Active-cycle, and Figure 20 with each Active-cycle during the hold. In each case, the increased ATCRBS function occupancy coincided with being less than 20 nmi from a site pair. The occupancy increase is most likely caused by sidelobe suppressions rather than interrogation/reply activity from the LBTS. From this data, it can be concluded that the AN/UPX-41(C) system's impact on transponder occupancy measured here is consistent with what was measured in the Day 2 sidelobe suppression tests, and that when the aircraft is beyond SLS range, the impact on transponder occupancy is indistinguishable from the sum of all sources of occupancy in the varying environment.

2.6. 1090 MHz – FRUIT Rates

N39 was equipped to record 1090 MHz log video that was post-processed to measure Mode S and ATCRBS FRUIT rates as a function of amplitude. The signals were recorded from both top and bottom mounted omni-directional antennas and processed separately, providing a measure of the 1090 MHz environment from those two perspectives. The Mode S FRUIT was processed with a -84 dBm minimum trigger level (MTL) and the ATCRBS with a -79 dBm MTL.

The data recorded on Days 3 and 4 were processed for 1090 MHz FRUIT analysis because the 5-minute Active/Off cycles enabled a comparison of samples with and without the four LBTS transmitting.

The AN/UPX-41(C) system's interrogation formats do not trigger Mode S replies and therefore, were not expected to have an effect on the Mode S FRUIT environment. However, in order to provide a complete test and to rule out any unexpected effects, the Mode S FRUIT environment data was analyzed along with the ATCRBS FRUIT environment. As expected, it was determined that the LBTS had no measureable effect. Detailed results of this analysis are included in A.4 and are summarized here.

The AN/UPX-41(C) system's interrogation sequence includes ATCRBS Modes 3/A and C and previous analysis has determined that Mode 4 interrogations can elicit some ATCRBS replies. Therefore, it is expected that there would be some measurable effect on the 1090 MHz ATCRBS FRUIT environment. The results of the analysis are summarized here and the details of the analysis are included in A.4.

The 1090 MHz FRUIT rate varies considerably with the location of the moving aircraft. Because of this, the process of comparing FRUIT rates from the 5-minute intervals with the four LBTS Active versus Off was reduced to using only 60 second samples on each side of a transition. In

addition, only samples with a stable FRUIT rate was measured through the transitions (not trending up or down).

2.6.1. 1090 MHz – FRUIT Rates Day 3

Table 6 shows a summary of the measured Mode S and ATCRBS FRUIT rates from Day 3.

Table 6. Summary of AN/UPX-41(C) Impact on 1090 MHz FRUIT – Day 3

Day 3	Mode S						ATCRBS					
	Top Antenna			Bottom Antenna			Top Antenna			Bottom Antenna		
Transition Time	LBTS Off	LBTS Active	Delta	LBTS Off	LBTS Active	Delta	LBTS Off	LBTS Active	Delta	LBTS Off	LBTS Active	Delta
14:10	1452.0	1287.9	-164.1	1637.5	1474.9	-162.6	3811.7	4244.4	432.7	4952.6	5374.5	421.9
14:15	1067.4	1083.1	15.7	1186.7	1199.9	13.2	3554.5	4440.8	886.3	4386.1	5136.5	750.4
15:15	733.9	691.1	-42.8	771.0	686.2	-84.8	3108.2	3542.3	434.1	3947.3	4275.4	328.1
15:20	978.8	1052.3	73.5	1090.3	1153.0	62.7	4729.6	4821.8	92.2	5253.9	5274.9	21.0
15:40	1219.6	1229.7	10.1	1240.8	1303.9	63.1	5049.9	5424.8	374.9	5584.5	6051.3	466.8
16:25	1569.4	1483.0	-86.4	1748.7	1699.2	-49.5	5234.7	6226.6	991.9	6805.7	7775.8	970.1
16:30	1731.7	1721.5	-10.2	1927.4	1889.2	-38.2	5446.1	6416.9	970.8	6738.2	7571.8	833.6
Average	1250.4	1221.2	-29.2	1371.8	1343.8	-28.0	4419.2	5016.8	597.6	5381.2	5922.9	541.7

Because the 1090 MHz environment was often varying up or down during the Test due to geography or turning of the aircraft, only samples not trending up or down during the beginning of a time period were selected to measure the contribution from four LBTS. In Table 6 the measured FRUIT rate from the selected samples for Mode S and ATCRBS, and top and bottom antennas are compared when the interrogators were Active versus Off, with the difference shown in the 'Delta' columns. The average rates and deltas are shown in the bottom row with the deltas highlighted. The small average deltas with the Mode S FRUIT on both antennas is likely just measurement variations in the environment that do not cancel out because of the small sample size. The ATCRBS FRUIT deltas from the two antennas are much greater showing an increase of about 598 and 542 ATCRBS FRUIT per second on the top and bottom antennas, respectively.

2.6.2. 1090 MHz – Day 4

Table 7 shows a summary of the measured AN/UPX-41(C) system's impact on Mode S and ATCRBS FRUIT as well as a calculation of the impact based on the number of aircraft and AN/UPX-41(C) system's interrogations.

Table 7. Summary of AN/UPX-41(C) Impact on 1090 MHz FRUIT – Day 4

Day 4	Mode S			ATCRBS			
	Top Antenna (Measured)			Top Antenna (Measured)			Calculated Delta
Transition Time	LBTS Off	LBTS Active	Delta	LBTS Off	LBTS Active	Delta	
14:00				5085.1	5255.5	170.4	510.0
14:05	1615.0	1563.4	-51.6	4032.0	4840.3	808.3	614.0
14:10	1373.2	1386.0	12.8	4195.3	5216.2	1020.9	621.0
14:15	1211.3	1300.4	89.1	4228.1	4891.2	663.4	670.0
15:05	1186.6	1134.0	-52.6	5191.3	5547.2	355.9	602.0
15:25	893.2	816.1	-77.1	3266.9	3272.0	5.1	433.0
15:30	1006.9	956.9	-50.0	4064.1	4415.8	351.7	437.0
15:50	1324.4	1304.4	-20.0	5361.5	6223.4	861.9	471.0
15:55	1284.6	1343.9	59.3	4795.3	5972.5	1177.2	441.0
16:00	1246.1	1275.3	29.2	5106.0	5544.9	438.9	518.0
16:05	1292.8	1243.3	-49.5	5287.5	5729.5	442.0	504.0
16:15				6086.1	6394.7	308.6	651.0
16:25	2469.9	2425.3	-44.6	9219.5	9529.6	310.1	755.0
Average	1354.9	1340.8	-14.1	5070.7	5602.5	531.9	555.9

On Day 4, N39's altitude was 9,000 feet. Because of the lower altitude, the 1090 MHz FRUIT analysis used only the top antenna data. The measured results were similar to Day 3. Here the difference when the LBTS were operating shows about an additional 530 ATCRBS replies per second.

As a reasonableness check to the above measured ATCRBS reply contribution due to the LBTS operating, a calculation of the expected extra ATCRBS reply count from the LBTS is included. This calculation was based on the number of targets (from LBTS target report data) and the number of replies from the mainbeam each antenna scan. The number of aircraft within coverage of the LBTS that are within the range of the onboard 1090 MHz receiver (~60 nmi for a sensitivity of -79 dBm) determine the expected reply count. The number of Mode A and C replies per mainbeam dwell of the AN/UPX-41(C) interrogators varies depending on the range between the aircraft and the interrogator. Measurements show that there are about 18 replies on average at 10 nmi from the interrogator and about 10 replies at 140 nmi. Assuming a mid-range reply count of 14, the following calculation yields:

$$\frac{14 \text{ (replies per mainbeam)} \times 40 \text{ (aircraft)} \times 4 \text{ (number of interrogators)}}{4.096 \text{ (scan time in seconds)}} = 546.9 \text{ replies per second}$$

The above calculation is simplified because it uses an average number of replies per beam dwell and assumes the number of aircraft within the flight test aircraft 1090 MHz, 60-nmi receiver range are within reception range of all four interrogator sites. Measurements showed that there was an average of about 40 aircraft that fit the criteria during most of the testing on Day 4 so the calculation yields a result very similar to the measured data. Still, the 1090 MHz ATCRBS reply impact of the interrogator is a function of the aircraft density within the surveillance volume within which the AN/UPX-41(C) interrogator operates. Since the 1090 MHz environment is constantly changing with respect to the number of aircraft within airborne receiver range, it is suggested that a simplified calculation, as shown above, with number of aircraft as the

independent variable, can be used to predict 1090 MHz impact due to AN/UPX-41(C) interrogator operation in a given area.

2.7. Traffic Alert and Collision Avoidance System

TCAS surveillance is required for both Mode S and ATCRBS transponder equipped aircraft. The AN/UPX-41(C) impact to TCAS is due to two potential factors: (1) Reduced transponder availability of a transponder that TCAS interrogates caused by: suppressions caused by the AN/UPX-41(C) transmissions or interrogations decoded by the transponder resulting from AN/UPX-41(C) transmissions that induce a reply cycle and (2) 1090 MHz replies from other transponders within the TCAS surveillance due to AN/UPX-41(C) transmissions. These replies may overlap replies that the TCAS receiver is attempting to decode either passively or from TCAS interrogations.

TCAS operates on a one second surveillance update interval. TCAS Mode C Surveillance acquisition requires 3 consecutive replies in 3 one second interrogation cycles and a 4th within the next 5 surveillance update intervals following the 3rd of the three consecutive replies. Generally one to two replies are received per Mode C target each one second surveillance cycle. Mode C tracks, once established, are dropped if six consecutive surveillance update intervals occur without a reply.

TCAS Mode S Surveillance acquisition is from monitoring acquisition squitters. Basically 3 or more squitters are required to initiate a track for interrogation. Two replies with the altitude and valid Q bit initiates a valid track. Six surveillance update intervals without a reply drops a track with 16 attempts allowed over the interval when in close range.

For consideration of the AN/UPX-41(C) system's impact on TCAS, the same assumptions that FAA Spectrum Mitigation Activity uses for TCAS analysis can be applied:

1. TCAS Mode S surveillance is the most vulnerable
2. Desired Mode S signal level has to be 2 dB or more above ATCRBS interference to be decoded
3. Desired Mode S signal level has to be 5 dB or more above Mode S interference to be decoded

For purposes of analyzing the AN/UPX-41(C) system's impact on TCAS, aircraft density that is twice the current high density 2020 baseline is used. The resulting density consists of 228 aircraft within 30 nmi and 456 aircraft within 60 nmi of the center of density. If the AN/UPX-41(C) system is assumed to cause 20 replies per mainbeam and assuming four operating interrogators, the TCAS Mode S receiver will potentially experience 4560 replies per second. The resulting probability of track in support of an RA in time to alert at the required range of 12.8 nmi range is 0.995, significantly above the required 0.90. Therefore, TCAS performance is supported for the increase

in ATCRBS FRUIT of 4560 replies per second in the high density aircraft scenario assuming 2 times the traffic density used as the 2020 baseline of the Spectrum Mitigation Activity.

2.8. Automatic Dependent Surveillance – Broadcast Air-to-Air

This section is devoted to discussion of the AN/UPX-41(C)'s impact on the viability of the FAA's ADS-B 1090 MHz air-to-air link. The Radio Technical Commission for Aeronautics (RTCA) developed DO-338, Minimum Aviation System Performance Standards (MASPS) for ADS-B, specifying the required 95% state vector update rates required to support specific air-to-air application ranges using the ADS-B 1090 Extended Squitter (ES) payload. Unfortunately, the availability of the 1090 MHz band for meeting the update rates needed is in jeopardy for high density areas. In 2006, the FAA's Surveillance and Broadcast Services (SBS) Program office (ADS-B system owner) labeled this congestion as high risk meaning that program success was likely to be jeopardized if no mitigations were undertaken to stem the congestion. In light of this, SBS has initiated multiple 1090 MHz spectrum congestion studies to determine mitigations for reducing interference. While some easily implementable mitigations have been identified, removal of the Terra Fix and a modified Mode Select (Mode S) interrogation sequence, and are in the process of implementation, more mitigations are required to be able to meet the performance metrics for ADS-B air-to-air. Therefore, at this time, any new interrogators added to the environment must prove that their impact to ADS-B air-to-air update rates is negligible.

The required air-to-air update rates for the application ranges, as given in Table 23, are taken from the *2012 FAA 1090 MHz Spectrum Mitigation Alternatives Analysis (Interim Report)* (Ref. 5), herein referred to as the Mitigation Analysis, and are derived from the DO-338 MASPS as well as input from SBS engineers. The update rates are applicable to class A1 and A3 avionics. The FAA study uses the Johns Hopkins University Applied Physics Laboratory (JHUAPL) Civil Airspace 1090 MHz Extended Squitter (CATS) simulation platform to predict update intervals for transmitter-receiver pairs at the application ranges in Table 8. Using many probes that squitter 1090 MHz ADS-B and Traffic Information Service - Broadcast (TIS-B) signals, CATS simulates ADS-B receiver performance at the chip level by injecting a statistical FRUIT interference environment converted into individual timed FRUIT signals at the receiver to determine its ability to correctly decode the signals. The analysis given in Appendix B, and summarized below, leverages the work done in Ref. 5 to demonstrate the impact of the proposed AN/UPX-41(C) Stage 4 configuration on ADS-B air-to-air update rates.

Table 8. ADS-B Air-to-Air Update Interval Requirements

Range	10 nmi	20 nmi	40 nmi	60 nmi	90 nmi
95% Update Interval	3 sec	7 sec	12 sec	12 sec	12 sec

The AN/UPX-41(C) system only generates ATCRBS FRUIT. As such, it was shown that a comparison could be made to the ADS-B air-to-air update rate sensitivity case where all legacy sliding window SSRs, FAA and Department of Defense (DoD), were converted to monopulse operation since this only changes the ATCRBS FRUIT/sec component of the interference source. The additional ATCRBS FRUIT/sec generated during the Test was shown to be about 550/sec. By assuming a linear change in update rates keyed to the change in ATCRBS FRUIT/sec, Table 9 was created. The Mitigation Analysis found the change in update rates between a 2035 baseline environment and the same environment with all legacy sliding window SSRs converted to monopulse. Since the update rate change was based on a change in ATCRBS FRUIT/sec of 6849, a much smaller change in update rates was computed for the proposed AN/UPX-41(C) Stage 4 configuration's generation of only 550 ATCRBS FRUIT/sec (bottom line of Table 9 highlighted in yellow).

Table 9. Change in ADS-B Air-to-Air Performance with Monopulse SSR Mitigation and AN/UPX-41(C) Stage 4 Configuration for 2035 and 1.7%/year Air Traffic Growth Rate

	A1-to-A1			A3-to-A3				
Range	**10 nmi**	**20 nmi**	**40 nmi**	**10 nmi**	**20 nmi**	**40 nmi**	**60 nmi**	**90 nmi**
Requirement	3 s	7 s	12 s	3 s	7 s	12 s	12 s	12 s
2035 Baseline	1.1 s	4 s	28 s	0.7 s	1.4 s	4 s	9 s	23 s
Δ 2035 Baseline to Monopulse	0.0 s	1 s	12 s	0.0 s	0.2 s	1 s	3 s	10 s
Update Rate Increase with Stage 4	0.0 s	0.08 s	0.96 s	0.0 s	0.02 s	0.08 s	0.24 s	0.8 s

The predicted change in ADS-B air-to-air performance, based on the ATCRBS FRUIT/sec elicited by the proposed AN/UPX-41(C) Stage 4 configuration, is negligible considering that the change in update rate is less than 10% of the maximum allowed time between updates for each application range. To further bound this result, note that performance changes are based on predicted 2035 performance since there are no published performance tables for the 2014 environment. The expected change in update rate performance against a 2014 baseline would be less than what has been shown here.

The analysis summarized in this section is specific to the Test and should only act as a guideline for the impact that the proposed AN/UPX-41(C) Stage 4 configuration will have in other areas of the country. In the future, this type of analysis should be conducted with FRUIT rates normalized by aircraft count to account for regional differences in aircraft densities. Finally, because the FAA considers 1090 MHz spectrum interference on post-2020 ADS-B air-to-air performance to be a high risk, this analysis should be revisited once interference mitigations have been selected by the FAA to demonstrate the update rates expected in the new baseline 1090 MHz environment.

3. Ground-based Data Collection and System Analysis

3.1. Secondary Surveillance Radars

3.1.1. Summary

Analysis of recorded data showed no distinct impact from the operation of the proposed AN/UPX-41(C) Stage 4 configuration on probability of detection (Pd), identity reliability and confidence, altitude reliability and confidence, false target rate, 0000 code rates, number of hits, ATCRBS FRUIT rates, Mode S FRUIT rates, and interrogation and reinterrogation rates.

3.1.2. Recording and Analysis Tools

Two publicly available FAA-developed software tools were used for analysis of SSR performance metrics. The Radar Beacon Analysis Tool (RBAT, Ref. 6) provides track-level analysis of all SSR systems (ATCBI-5, ATCBI-6/6M, ASR-11, Mode S) while the Mode S Analysis Tool (MSAT, Ref. 7) provides interrogation- and reply-level data analysis for Mode S SSRs. The real-time (RT) RBAT variant, RT-RBAT, was used for monitoring SSR performance during the Test. Real-Time Aircraft Display System (RTADS) and Mode S Data Analysis Software (MDAS) were additional tools used to monitor live performance of tracks during the Test and analyze Mode S DE files, respectively. Description of recording and analysis tools is provided in C.1.

3.1.3. Baseline Data Recordings

Initially, the real-time SSR P_d was going to be compared to the threshold of 96% (below which remedial action by maintenance personnel is mandatory) given in the Quick Analysis of Radar Sites (QARS) Procedures in Ref. 8 to determine if a DEGRADED BUZZER needed to be initiated. However, analysis of data collected during the dry run in July 2014 showed that twenty scan averages (about one hundred seconds) of P_d in RT-RBAT, at times, fell below the 96% threshold which was written for analysis of thirty minute data samples. Sample size plays an important role in real-time performance statistics; with a small sample size, any deviation away from the normal performance of tracks will be magnified and can make the P_d highly volatile. To fairly assess SSRs during the test, baseline data was collected and analyzed for the week prior to the Test. Maximum and minimum performance P_d was produced for use during the Test to aid real-time analysts in determining whether a DEGRADED BUZZER was appropriate.

3.1.4. Real-time Performance Monitoring and Test Data Recordings

At the WJHTC, two RT-RBAT and one RTADS workstation were setup to allow for live monitoring of the SSRs under Test. Eight SSRs, ADW, DCA, IAD, ORF, NHK, QPL, QVR, and RIC, had been previously identified in the Test Plan for in-depth analysis to determine if the

proposed AN/UPX-41(C) Stage 4 configuration caused degradation of SSR performance in the NAS. More information regarding real-time monitoring of systems can be found in C.2.

3.1.5. Measurement Analysis

LBTS Active and Off cycling periods were in five minute intervals when N39 was flying and thirty minute intervals when it was not. Cycling of the LBTS allowed for comparison of performance metrics between Active and Off periods to determine the interference impact from the proposed AN/UPX-41(C) Stage 4 configuration. Table 10 shows the parameters that were analyzed for each type of system. As an example, P_d for site ADW using Day 4's time bins is shown in Figure 25. There is no trend of P_d dropping with respect to LBTS Active periods. Full description of parameters and results can be found in C.3. The Mode S SSR site ADW is used as the representative SSR for the post-test analysis as shown in C.3 with full analysis available in Ref. 9. Also, sites DCA, IAD, ORF, NHK, RIC, QPL, and QVR followed similar trends and their results are also available in Ref. 9. In addition, SSR SMEs reviewed the analysis of all eight SSRs under test and concluded there was no observable impact to SSR operation from the LBTS.

Table 10. System Analysis Parameters

	System Type				
Parameters	**ASR-11**	**ATCBI-5**	**ATCBI-6**	**ATCBI-6M**	**Mode S**
Probability of Detection	x	x	x	x	x
Number of Targets/scan	x	x	x	x	x
Mode 3/A Reliability	x	x	x	x	x
Mode 3/A Confidence	x	x	x	x	x
Mode C Reliability	x	x	x	x	x
Mode C Confidence	x	x	x	x	x
Number of ATCRBS Hits		x			x
False Target Rate	x	x	x	x	x
0000 Code Percentage	x	x	x	x	x
Interrogation Rate					x
Reinterrogation Rate					x
ATCRBS FRUIT Rate					x
Mode S FRUIT Rate					x
Beam Overlap Analysis		x			x

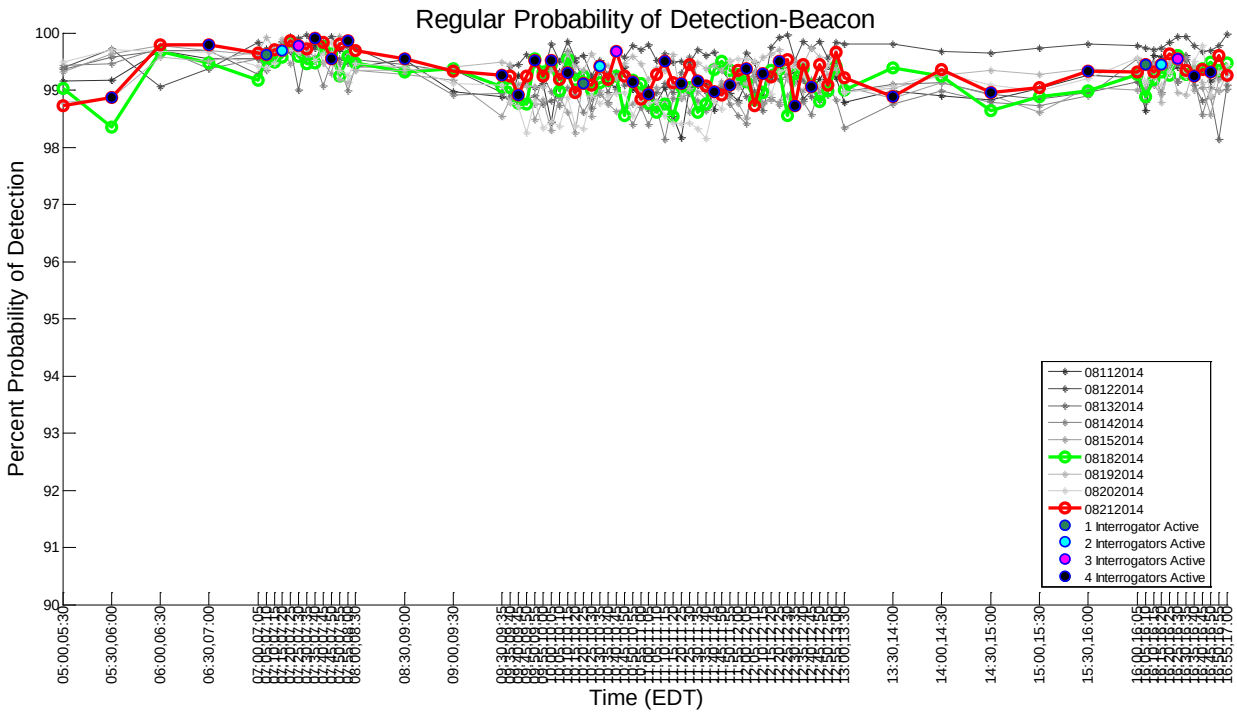


Figure 25. ADW – Day 4 – Probability of Detection

3.2. Automatic Dependent Surveillance – Broadcast Ground Radio Analysis

3.2.1. Summary

To determine if the ADS-B ground radio reception probability was negatively impacted from the addition of the proposed AN/UPX-41(C) Stage 4 configuration in the NAS, ten ADS-B ground radios, as identified in Section 1.2.2, were analyzed for changes in performance. Analysis of data recorded during the Test proved inconclusive in determining if ADS-B ground radios had been impacted due to the data's inability to provide insight into reception probability of downlink format (DF) 17 squitter which generates ADS-B target reports. Therefore, further analysis of ADS-B ground radios was conducted using the Volpe Simulator, which showed a small, but insignificant impact to DF17 squitter reception. If target update rates at an ADS-B ground radio are to be evaluated in the future, recording of DF17s at the radio site is recommended.

3.2.2. Recording and Analysis Tools

SBS Analysis Tool (SAT)

SBS Analysis Tool (SAT), which is a Windows-based application used by, but not limited to, ADS-B analysts, field technicians, and system maintenance personnel throughout the various FAA facilities, was used for analyzing SBS Monitor data extraction or Capture files that contain SBS data. SBS data contains ASTERIX Category 33 messages (CAT033) (Ref. 10) which hold

ADS-B and TIS-B target reports. The SAT program also has a real-time variant, RT-SAT, which was used for monitoring system performance during the Test. Finally, SAT has a queue function which allows for automation of data analysis after an initial setup.

3.2.3. Real-time ADS-B Ground Radio Performance Monitoring

Two RT-SAT workstations were setup to monitor SBS performance and NAS sensor health. ADS-B message update rates were monitored using RT-SAT to determine if there was an increase in average time between updates for aircraft in a CTV with respect to LBTS activity. The first RT-SAT workstation monitored average update rate for all targets within the ZDC and ZNY Composite Traffic Volumes (CTV). The second RT-SAT workstation monitored average update rates per radio for the ten radios of interest. Similar to RT-RBAT, both monitoring of ADS-B update rates and recording of SBS data, were done simultaneously by RT-SAT.

3.2.4. ADS-B Ground Radio Measurement Analysis

Analysis Limitations

The ADS-B surveillance service provider, Harris, employs bandwidth throttling of redundant ADS-B target reports to reduce network and computer resource waste. At medium to high altitude, an aircraft will typically be within RLOS of many ADS-B radios. Instead of having every radio send redundant targets reports, a limited number of radios are allowed to send duplicate target reports to the Service Delivery Points (SDPs) based on criteria set by Harris to reduce network congestion. Therefore, even if a radio can create a target report for an aircraft, it doesn't mean that the target report will be sent to the SDPs. This biases the analysis of target report update rates for individual aircraft-radio pairs upwards from the expected one second update rates. This jeopardized the ability to determine if spectrum interference was causing target report update rates to change when the LBTS were Active. The analysis of the measured data is available in D.1.

3.2.5. ADS-B Ground Radio Simulation Analysis

Due to the limitations of analyzing recorded data for determining impact from the proposed AN/UPX-41(C) Stage 4 configuration to ADS-B ground radios, the Volpe 1030/1090 MHz Simulator was used to simulate the impact that would be seen at ADS-B radio sites if all redundant messages were sent to SDPs. See F.2 for Simulation setup.

Three radios sites, SV036-01, SV171-02, and SV186-02 were studied through simulation and their properties and locations are available in D.2. Results for SV036-01 are presented below; SV171-02 and SV186-02 are in D.2.

The simulation was run for 28.672 seconds – equal to seven rotations of the AN/UPX-41(C) – with the four simulated LBTS Off and then Active. The change in failure of squitter reception with the addition of the simulated LBTS in the environment is shown in Table 11 for SV036-01.

Table 11. SV036-01 – ADS-B Squitter Reception Overlaps and Failures

SV036-01	Off			Four AN/UPX-41(C) Active		
Boresight	**Squitter per second**	**Overlaps per second**	**Failures per second (%)**	**Squitter per second**	**Overlaps per second**	**Failures per second (%)**
48°	391.81	977.82	186.98(47.72%)	382.67	1058.52	187.19(48.92%)
138°	187.29	306.64	56.36(30.09%)	186.04	352.36	59.19(31.81%)
218°	245.43	439.28	85.17(34.70%)	244.70	486.43	88.00(35.96%)
308°	323.97	831.26	134.35(41.47%)	317.38	876.36	133.58(42.09%)

There was a small increase in percentage of failures per second when the simulated LBTS were added to the environment. The failures increased due to additional ATCRBS FRUIT in the environment elicited by the simulated LBTS systems. ATCRBS FRUIT for radio SV036-01 is shown in Figure 26 with simulated LBTS Active and Off.

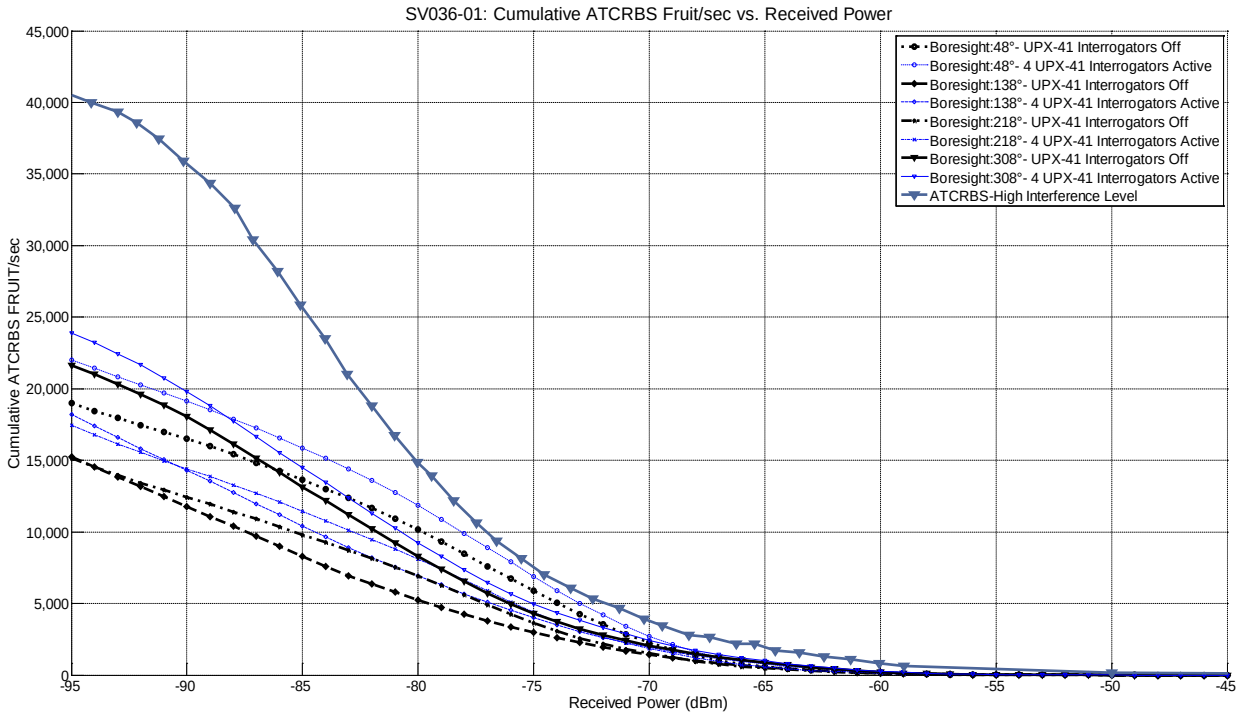


Figure 26. SV036-01 – Cumulative ATCRBS FRUIT/sec vs. Receiver Power Level (dBm)

In Figure 26, received signal power in dBm is on the x-axis and FRUIT is on the y-axis. Black lines show FRUIT curves for scenarios with simulated LBTS Off and blue lines represent

scenarios when simulated LBTS are Active. The ATCRBS high interference level FRUIT curve is the FRUIT distribution under which the ADS-B, Automatic Dependent Surveillance – Rebroadcast (ADS-R), and TIS-B services must be provided for FAA-labeled high density areas. Similar graphics for Mode S FRUIT curves are shown in D.2.

Figure 27 shows the number of aircraft that fall into each update rate bin for radio SV036-01's 90° sector antenna with 48° boresight. The blue bars and red bars in Figure 27 represent simulations in which simulated LBTS were Off and Active, respectively. The x-axis represents update rate bins in seconds and the y-axis shows the number of aircraft that are present in each update rate bin. Notice that the number of aircraft with update rates between zero and one seconds drops when simulated LBTS were Active. This is because additional ATCRBS FRUIT in the environment that was elicited by simulated LBTS steps on ADS-B squitter messages which caused more failures than in the baseline case. The aircraft which were no longer part of the zero to one second bin moved to the longer update rate bins.

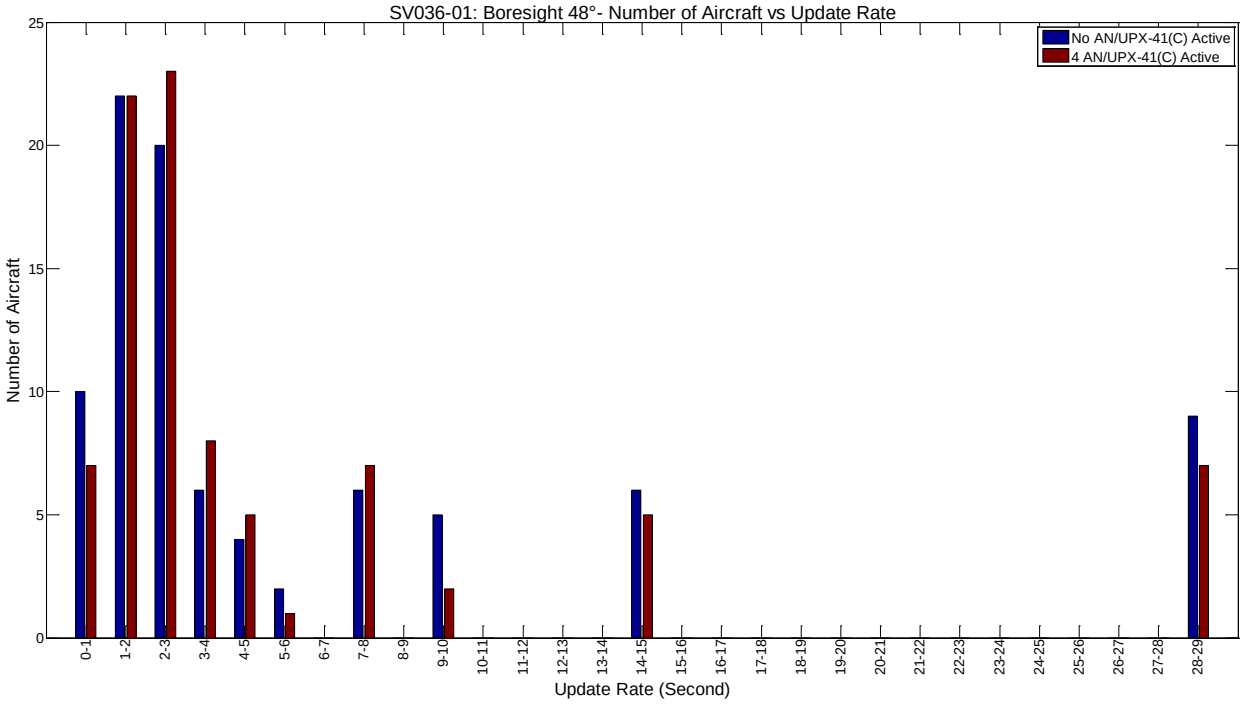


Figure 27. SV036-01 - Boresight 48° - Number of Aircraft vs. Update Rate

Similar to the analysis methodology for the recorded data, update rates for aircraft within twenty nautical miles of an ADS-B ground radio were compared for Active and Off cases and the results are contained in D.2.

Squitter received from aircraft within twenty nautical miles of a radio site is higher in power compared to overlapping FRUIT which is received from all ranges within LOS of a radio. This allowed for squitter overlapped by additional FRUIT elicited by simulated LBTS to not fail reception.

Since the rate of squitter failure increased by less than 2% and radio redundancy exponentially decreases the probability of failure at all radios within LOS, there was negligible impact to ADS-B ground radio performance due to the simulated LBTS.

3.3. Multilateration Analysis

3.3.1. Summary

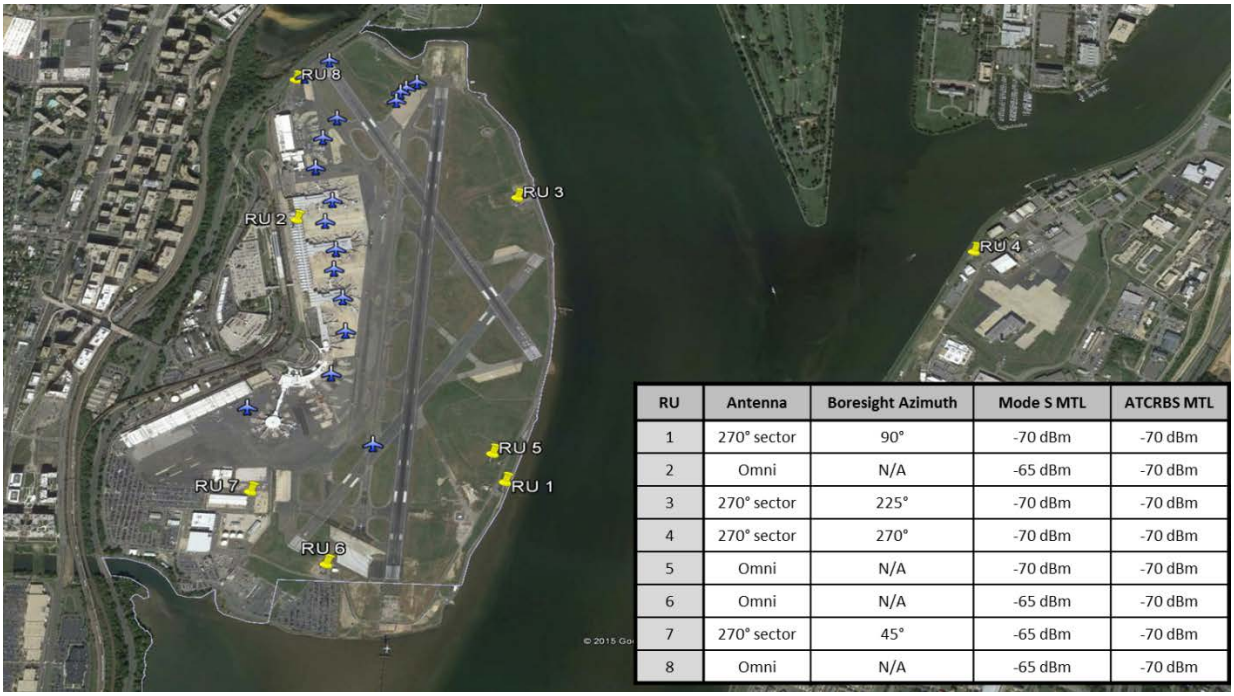
According to Section 5.5 of the Test Plan, it was infeasible to collect data at the DCA ASDE-X site using the available resources, and focus was instead put towards analyzing the impact from the proposed AN/UPX-41(C) Stage 4 configuration on MLAT systems using the Volpe Simulator (Section 4). The change in ATCRBS/Mode S FRUIT per second, aircraft detections per second and elicited replies per second were compared for scenarios with four simulated LBTS Active and Off. Minor changes in these parameters due to the addition of the four simulated LBTS were noticed, but had no major impact on MLAT system operation.

3.3.2. Background

MLAT systems interrogate and elicit signals from an aircraft's transponder to determine the aircraft’s location. A position determination can be made if a transponder correctly decodes, processes, and replies to an interrogation and the reply is received by a minimum of three remote units (RUs). MLAT systems determine position of an aircraft on the airport surface or approaching / departing within 5 nmi of an airport by using a Time Difference of Arrival (TDOA) measurement. Altitude is determined by Mode C code either in an ATCRBS reply or embedded in a Mode S reply data block.

3.3.3. MLAT Simulation Setup

A total of 18 Mode S aircraft and eight ASDE-X RUs were simulated on the surface of DCA to determine probability of position determination within the larger interference environment. See F.2 for additional simulation setup information. Figure 28 shows the location and properties of ADSE-X RUs and the position of aircraft present on the surface of DCA. ASDE-X RU locations and attributes were received from FAA system engineering. The simulation was run for 28.672 seconds – equal to seven rotations of the AN/UPX-41(C) – with the four simulated LBTS Off and then Active.



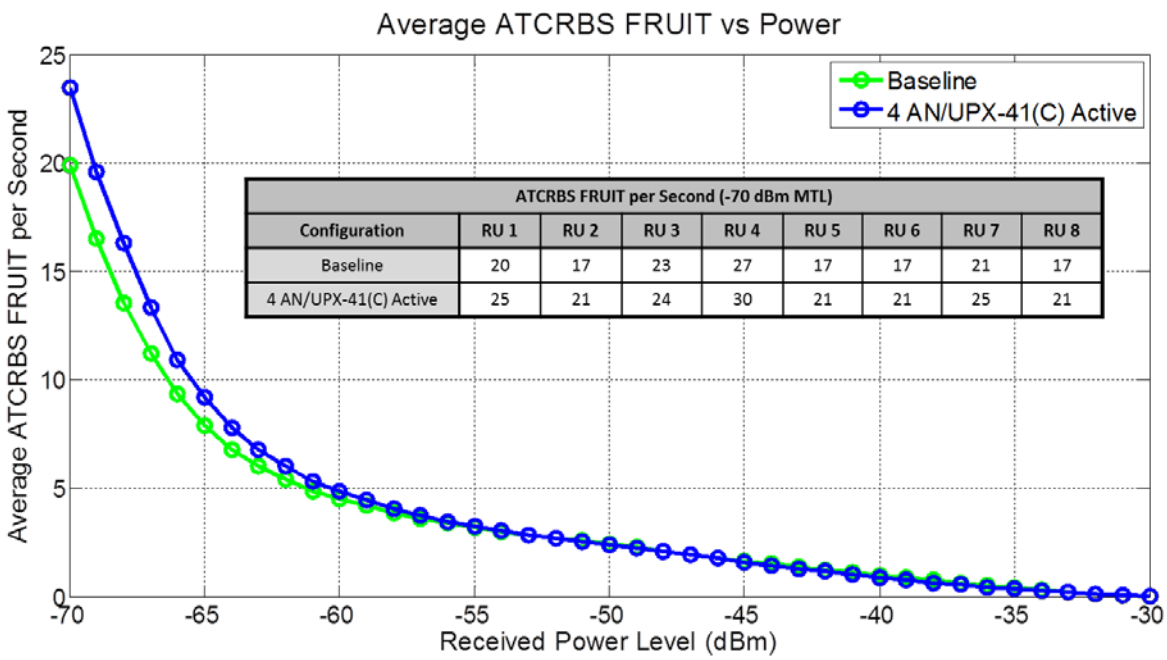
RU	Antenna	Boresight Azimuth	Mode S MTL	ATCRBS MTL
1	270° sector	90°	-70 dBm	-70 dBm
2	Omni	N/A	-65 dBm	-70 dBm
3	270° sector	225°	-70 dBm	-70 dBm
4	270° sector	270°	-70 dBm	-70 dBm
5	Omni	N/A	-70 dBm	-70 dBm
6	Omni	N/A	-65 dBm	-70 dBm
7	270° sector	45°	-65 dBm	-70 dBm
8	Omni	N/A	-65 dBm	-70 dBm

Figure 28. DCA ASDE-X MLAT Subsystem and Aircraft Locations

3.3.4. MLAT Simulation Analysis

The analysis examined changes in ATCRBS FRUIT/sec, Mode S FRUIT/sec, aircraft detections per second, and ASDE-X RU elicited replies per second.

Figure 29 compares ATCRBS FRUIT/sec averaged across all RUs for the Off and Active cases. At MTL, -70 dBm, from Off to Active, there was an increase of approximately four ATCRBS FRUIT/sec.

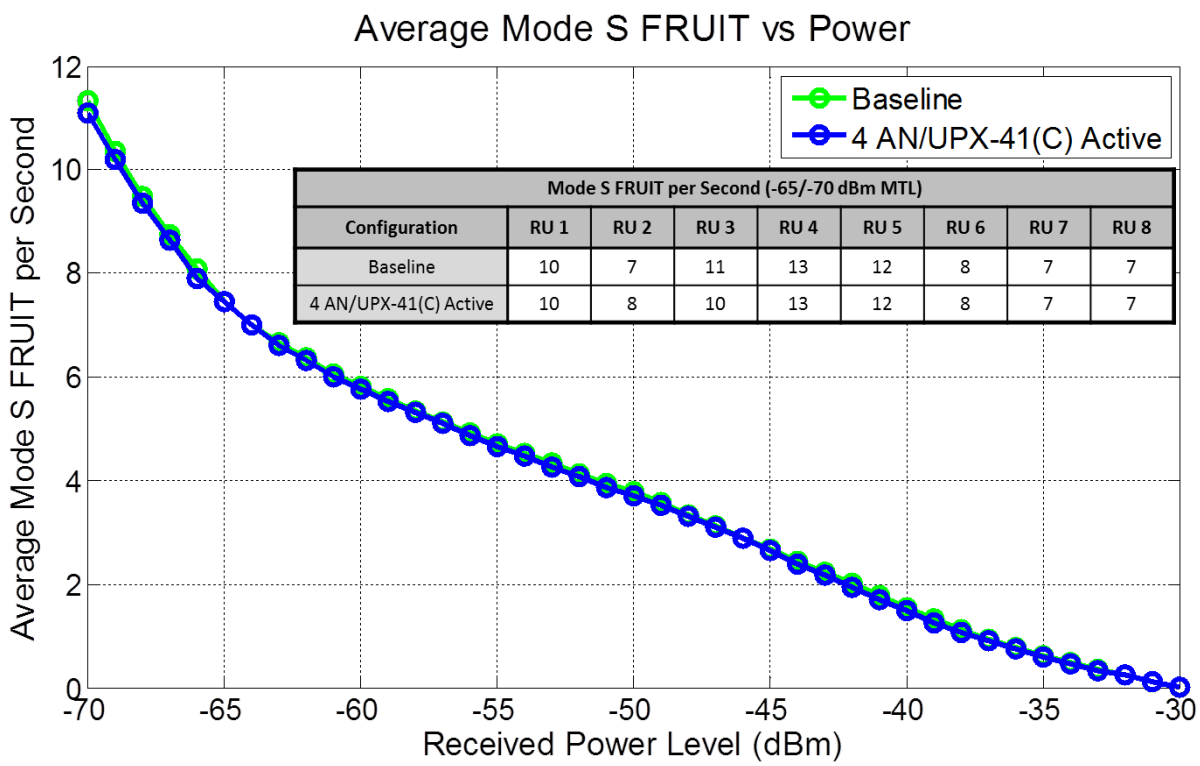


ATCRBS FRUIT per Second (-70 dBm MTL)								
Configuration	RU 1	RU 2	RU 3	RU 4	RU 5	RU 6	RU 7	RU 8
Baseline	20	17	23	27	17	17	21	17
4 AN/UPX-41(C) Active	25	21	24	30	21	21	25	21

Figure 29. DCA MLAT: Average ATCRBS FRUIT per Second

Figure 30 shows Mode S FRUIT/sec averaged across all RUs for both Active and Off cases. Since AN/UPX-41(C) systems only elicit ATCRBS replies, it was expected that Mode S FRUIT would stay the same or decrease due to transponder occupancy. However, the Mode S FRUIT/sec at RU 2 increased when the simulated LBTS were Active. The reason behind this phenomenon is that simulated aircraft are equipped with a realistic antenna that models phase interference and fuselage blockage resulting in peaks and nulls in the antenna pattern as opposed to the idealized omni-directional sphere. While the omni-directional antenna model fixes each aircraft's gain, this does not accurately reflect reality, and results in FRUIT levels that are inconsistent with measurements. When using the distorted antenna pattern, the simulator calculates a gain degradation factor to simulate variations in airborne antenna patterns. This results in small differences across the same simulation scenario that should not be attributed to any one interrogator while ensuring accurate reproduction of the signal environment.

ASDE-X procurement specifications[11], Section 3.7.4.1.3, requires the MLAT subsystem to meet all performance specifications when operating in a FRUIT environment consisting of 3000 ATCRBS FRUIT/sec and 225 Mode S FRUIT/sec. Considering that there was no average Mode S FRUIT/sec increase and the average ATCRBS FRUIT/sec increase changed the percent average ATCRBS FRUIT/sec against the requirement from 0.66% to 0.78%, the proposed AN/UPX-41(C) Stage 4 configuration's impact on the DCA ASDE-X's MLAT subsystem performance due to the 1090 MHz RF environment was negligible.



Mode S FRUIT per Second (-65/-70 dBm MTL)								
Configuration	RU 1	RU 2	RU 3	RU 4	RU 5	RU 6	RU 7	RU 8
Baseline	10	7	11	13	12	8	7	7
4 AN/UPX-41(C) Active	10	8	10	13	12	8	7	7

Figure 30, DCA MLAT: Average Mode S FRUIT per Second

Number of aircraft detections and ASDE-X RU elicited replies per second in the Off and Active cases are compared in Table 12. When the simulated LBTS were Active, aircraft detections and RU elicited replies decreased by 0.58% and 0.29%, respectively. This is a negligible change in performance.

Table 12. DCA MLAT: Aircraft Detection and RU Elicited Replies per Second

Configuration	Aircraft Detections per Second	RU Elicited Replies per Second
Baseline	41.12	169.05
Four AN/UPX-41(C) Active	40.88	168.56

According to LOS calculations, the furthest aircraft on the ground that would have received interrogations from the LBTS was approximately 30 nmi away. Since DCA is about 50 nmi away from the closest LBTS, the aircraft on the ground were not receiving interrogations from the LBTS. Therefore, the decrease in detections and replies in the simulation came from the additional ATCRBS FRUIT being generated when the simulated LBTS were Active and not from additional transponder occupancy.

4. Volpe 1030/1090 MHz Simulator Validation

Goal 2 of the Test was to provide data that could be used to validate the Volpe 1030/1090 MHz Simulator and its prediction of the impact of the proposed AN/UPX-41(C) Stage 4 configuration on the NAS. The intent was that, once validated, the Simulator could be used to predict the impact of other configurations of AN/UPX-41(C) systems for which live testing may not be feasible. The following summarizes the validation efforts and a more detailed discussion is given in Appendix F.

4.1. 1030 MHz Environment Validation

In general, the simulated transponder occupancy for the ATCRBS function of a Typical Mode A/C/S transponder from 1030 MHz interrogations differed by about 1% (i.e. 3% measured vs. 2% simulated) from measurements for all areas except Norfolk and Atlantic City (see Figure 31). Much of the discrepancy was due to differences in mutual suppression bus and P1-P2 suppression rates.

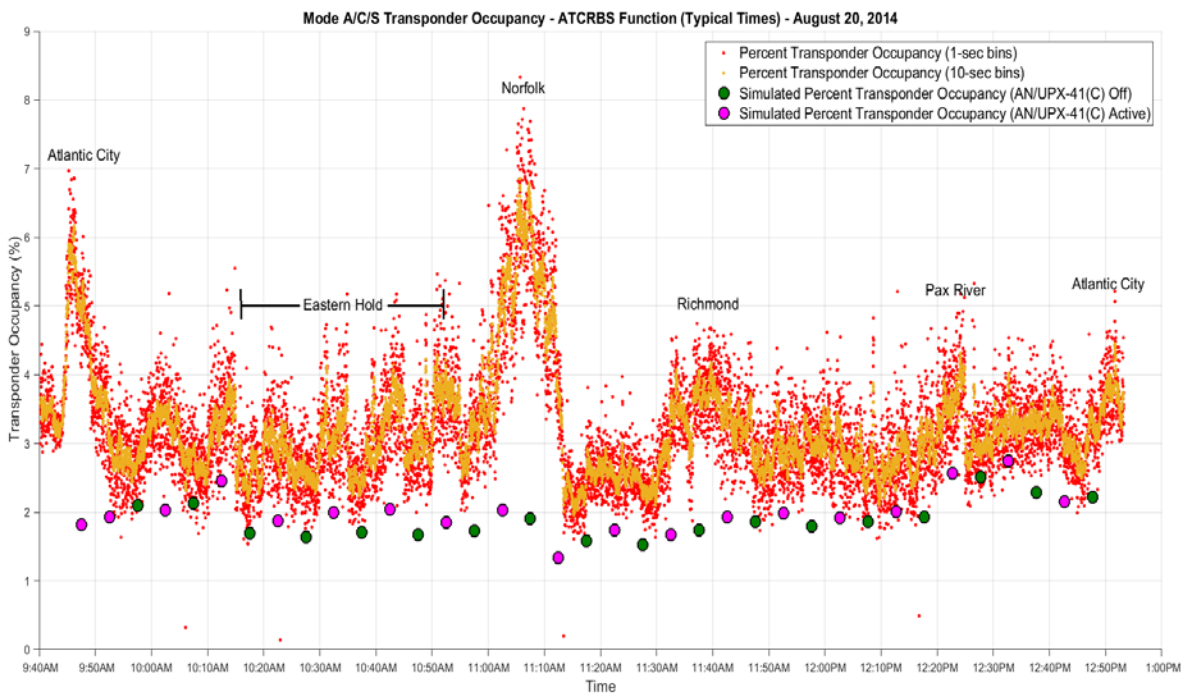


Figure 31. Mode A/C/S Transponder Occupancy for the ATCRBS Function using Typical Transponder Occupancy Times for Day 3

P1-P2-noP3 suppressions were measured near Atlantic City Airport (ACY) and RIC, indicating Improved Interrogator Sidelobe Suppression (IISLS) was operating and that ACY was not operating as a Mode S SSR. Discussions with FAA SMEs uncovered that ACY was using a BI-5. The observations from measurement can be corrected in the simulation by switching ACY from

a Mode S to a BI-5 interrogator and by turning on IISLS for both sites. Large differences between measured and simulated elicited ATCRBS replies and Mode 1 and Mode 4 suppressions created discrepancies around Norfolk that are currently irreconcilable. All interrogators within 250 nmi from Pax River were instructed to either stay on continuously from 0500-1700 or off depending on their specific needs. While this protected against a changing baseline environment that would have been detrimental to measurement analysis, it made validation more difficult since the Simulator does not model all land-based or any shipborne military interrogators. While there were some notable differences in Mode S reply and non-reply rates, their contributions to transponder occupancy were negligible. Still, consistently higher reply rates to uplink format (UF) 11 (Mode S All-call) interrogations in the simulation versus measurements warranted further investigation of FAA interrogator types. After correcting for a few small discrepancies, such as certain BI-6 long range radars operating in ATCRBS-only mode, the focus was turned to differences between real world and simulated transponder interpretation of low-level or near-MTL Mode S interrogations; however, this requires further investigation before conclusions can be made. Differences between the WJHTC TCAS unit's maximum number of allowed TCAS interrogations and that of the Simulator's TCAS unit showed simulated mutual suppression bus triggering rates 33% lower than measured. This highlights the variability in specifications of different TCAS units on the market and requires further study to understand the range of maximum interrogation rate restrictions in the TCAS population and the number of each type of TCAS unit that is employed in the NAS.

By removing the discrepancies highlighted in the previous paragraph that were known to not be simulated[1] or at least not simulated to the extent shown in the measurements, the simulated Mode A/C/S transponder ATCRBS function Typical occupancy average percent difference against the measurements is only 15%, reducing to 10% if Norfolk and Atlantic City are removed. This is a better assessment of how well the Simulator replicated what was known to be operating.

4.2. 1090 MHz Environment Validation

On the 1090 MHz side, measured ATCRBS FRUIT/sec was greater than simulated ATCRBS FRUIT/sec by a factor of two or less (see Figure 32) and measured ATCRBS reply rates that, on average, are 50/sec greater than simulated ATCRBS reply rates demonstrate why this difference has occurred. Reply rate differences can likely be attributed to differences between actual transponder operation and the Simulator transponder model, including the airborne antenna model, as well as unknown interrogators, especially around Norfolk; however, further investigation is required to confirm these theories. Unlike the ATCRBS FRUIT, simulated Mode

[1] Mode 1 and Mode 4 suppressions, P1-P2-P3-longP4 suppressions, P1-P2-noP3 suppressions, low-level Mode S-induced Mode A and C replies, Mode 4 ATCRBS replies, TCAS ownship interrogation occupancy rate difference

S FRUIT/sec was greater than measured Mode S FRUIT/sec by a factor of 1.5 to 2 (see Figure 33). While simulated Mode S reply rates that are greater than measured are negligible for transponder occupancy, they compound in their contribution to the Mode S FRUIT environment. The main culprit appears to be a simulated DF11 reply rate that is double the measurements, but investigation into the cause of this has been unsuccessful and further research is required.

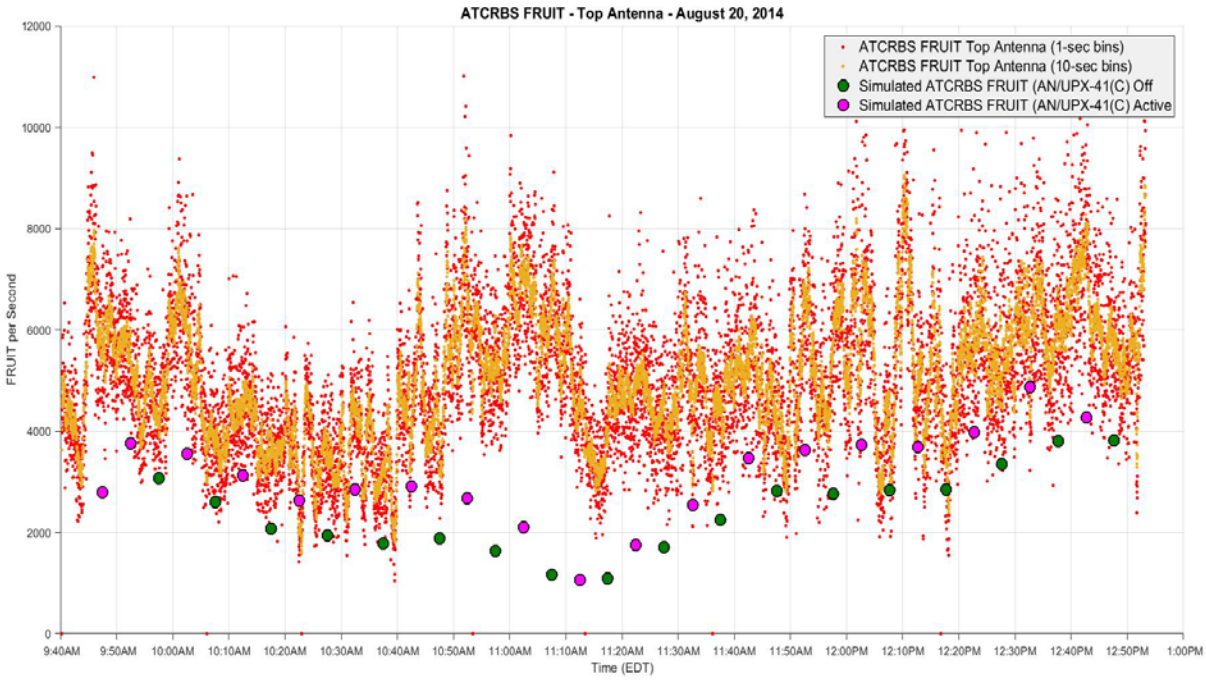


Figure 32. Measured (Top Antenna) and Simulated ATCRBS FRUIT ≥ -79 dBm for Day 3

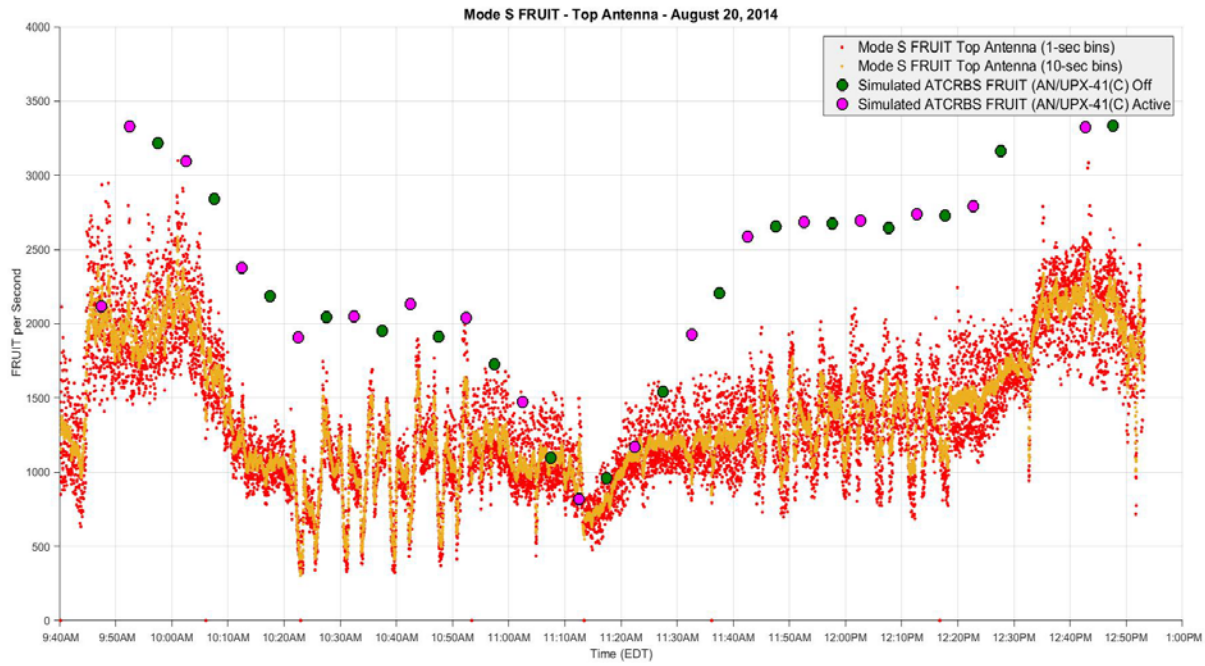


Figure 33. Measured (Top Antenna) and Simulated Mode S FRUIT ≥ -84 dBm for Day 3

4.3. Conclusions

To the extent that the Simulator replicates how the NAS would function for a specified set of signal sources based on an understanding of the way the NAS should operate, it is an effective tool in revealing the anomalies in how the NAS actually operates in terms of unexpected signal sources and/or effects. However, the validation effort has shown that there are caveats in using the simulation in its current form when assessing performance of ASCAS in a baseline environment or testing performance in an environment with new interrogators. Volpe can only account for the interrogators that are understood to be operating in a given area, and transponder models must be calibrated to replicate real world operation. The risk severity created by the discrepancies seen in the validation is dependent on the particular ASCAS in question as each system has a different sensitivity to changes in uplink or downlink interference. For each discrepancy, a general statement about the discrepancy's impact on the assessment of ASCAS performance can be made:

- Simulated ATCRBS and Mode S function transponder occupancy that is lower than measurements will result in optimistic performance of ASCAS, except those that operate only on 1090 MHz, versus what would be expected in the real world environment.
- Simulated ATCRBS FRUIT rates that are lower than measurements will result in optimistic performance of ASCAS versus what would be expected in the real world environment.

- Simulated Mode S FRUIT rates that are higher than measurements will result in conservative performance of ASCAS versus what would be expected in the real world environment.

Further validation and reconciliation is suggested to reduce error against measurements and increase confidence in simulation results. The main focus would be calibration of the transponder model and its handling of MTL+3dB and below power level interrogations. The current transponder model appears to underestimate ATCRBS replies and overestimate Mode S replies due to the transponder's idealized nature of only responding to MTL and above interrogations and lack of a probabilistic model to replicate real world transponder handling of low power level Mode S interrogations that can either generate ATCRBS replies or not be decoded entirely. Further suggestions for reconciliation can be found in the simulation validation discussion in Appendix F.

5. Conclusions and Recommendations

Goal 1 was successfully completed based on the live test, modeling, and post-test analysis. Stage 4 Certification (SPS 18778/1) criteria for the AN/UPX 41(C) were validated as sufficient to prevent degradation to NAS ASCAS.

Goal 2 was successfully completed in that usable data was collected for validation of the Volpe Center 1030/1090 MHz Interference Simulator. Under this test effort, the simulation validation has been taken as far as possible with the provided resources. Any further refinements to reduce discrepancies would require increased scope for additional work and resources. The validation effort revealed the following observations:

- The simulation underestimates the transponder occupancy for the ATCRBS function of a Typical Mode A/C/S transponder by about 1% (the average difference between measured and simulated occupancy). The simulation underestimates the transponder occupancy for the Mode S function of a Typical Mode A/C/S transponder by about 0.5% (the average difference between measured and simulated occupancy).
- The simulation overestimates total Mode S False Replies Unsynchronized in Time by a factor of 1.5 to 2 (measured approximately 1500 FRUIT/sec rate versus simulated 2500 FRUIT/sec rate).
- The simulation underestimates total ATCRBS FRUIT by a factor of 2 or less (measured approximately 5500 FRUIT/sec rate versus simulated 3000 FRUIT/sec rate).
- To the extent that the Simulator replicates how the NAS would function for a specified set of signal sources based on an understanding of the way the NAS should operate, it is an effective tool in revealing the anomalies in how the NAS actually operates in terms of unexpected signal sources and/or effects. However, the validation effort has shown that there are caveats in using the simulation in its current form when assessing performance of ASCAS in a baseline environment or testing performance in an environment with new interrogators. Volpe can only account for the interrogators that are understood to be operating in a given area, and transponder models must be calibrated to replicate real world operation. The risk severity created by the discrepancies seen in the validation is dependent on the particular ASCAS in question as each system has a different sensitivity to changes in uplink or downlink interference. For each discrepancy, a general statement about the discrepancy's impact on the assessment of ASCAS performance can be made:
    - Simulated ATCRBS and Mode S function transponder occupancy that is lower than measurements will result in optimistic performance of ASCAS, except those that operate only on 1090 MHz, versus what would be expected in the real world environment.
    - Simulated ATCRBS FRUIT rates that are lower than measurements will result in optimistic performance of ASCAS versus what would be expected in the real world environment.

    - Simulated Mode S FRUIT rates that are higher than measurements will result in conservative performance of ASCAS versus what would be expected in the real world environment.
- Further validation and reconciliation is suggested to reduce error against measurements and increase confidence in simulation results. The main focus would be calibration of the transponder model and its handling of MTL+3dB and below power level interrogations. The current transponder model appears to underestimate ATCRBS replies and overestimate Mode S replies due to the transponder's idealized nature of only responding to MTL and above interrogations and lack of a probabilistic model to replicate real world transponder handling of low power level Mode S interrogations that can either generate ATCRBS replies or not be decoded entirely. Further suggestions for reconciliation can be found in the simulation validation discussion in Appendix F.

Goal 3 was successfully completed and increased flexibility for AN/UPX-41(C) system operations can be supported. Details of the recommended relaxation can be found in "Proposed Interim Update to the AN/UPX-41(C) Spectrum Certification Conditions (SPS-18778/1)", document number DOT-VNTSC-NAVSEA-15-02. Data collected from the August 2014 flight tests, which provide actual measurements of 1030 and 1090 MHz spectrum activity due to operation of AN/UPX-41(C) interrogators, has substantiated performance estimates and provided confidence in the ability to estimate their spectrum impact.

While the test configuration of the LBTS showed a negligible impact on NAS ASCAS performance, there is not sufficient data and analysis to determine overall safe operating limits for transponder occupancy and 1090 MHz FRUIT rates in a given environment to support all Navy operations of the AN/UPX-41(C) and guarantee acceptable performance for NAS ASCAS. The proposed relaxations were developed through negotiations with the FAA utilizing the existing FAA process and methodology in concert with AN/UPX-41(C) test data. This process provides sufficient margins to ensure the safe operation of the NAS but still allows for relaxations as compared to the restrictions imposed on the AN/UPX-37 interrogator and proposed Stage 4 certification.

Ultimately, spectrum restrictions for operation of the AN/UPX-41(C) can be revisited as part of the IFF technical working group, which will develop a process that can be used as an overall spectrum allocation and management scheme.

Glossary

ACY	Atlantic City Airport
ADS-B	Automatic Dependent Surveillance – Broadcast
ADS-R	Automatic Dependent Surveillance – Rebroadcast
AIMS	Air Traffic Control Radar Beacon System, Identification Friend or Foe, Mark XII/Mark XIIA, Systems
ARC	Aviation Rulemaking Committee
ASCAS	Aeronautical Surveillance and Collision Avoidance Systems
ASDE-X	Airport Surface Detection Equipment, Model X
ASR	Airport Surveillance Radar
ASTERIX	All Purpose STructured Eurocontrol Radar Information EXchange
ATC	Air Traffic Control
ATCBI	Air Traffic Control Beacon Interrogator
ATCRBS	Air Traffic Control Radar Beacon System
ATO	Air Traffic Organization
BWI	Baltimore-Washington International Thurgood Marshall Airport
CAT033	CATegory 33 Messages
CATS	Civil Airspace 1090 MHz Extended Squitter
CD-2	Common Digitizer Model 2
CEC	Cooperative Engagement Capability
CG	Cruiser, Guided missile (*Ticonderoga* class)
CMS	Channel Management Statistics
CPR	Compact Position Reporting
CS	Combat System
CVN	Carrier Vessel Nuclear (*Ford* class and *Nimitz* class)
DCA	Ronald Reagan Washington National Airport
DDG	Destroyer, Guided missile (*Arleigh Burke* class)
DE	Data Extraction
DF	Downlink Format
deg	degree(s)
DME	Distance Measuring Equipment
DPSK	Differential Phase-Shift Keying
DoD	Department of Defense
ES	Extended Squitter

FAA	Federal Aviation Administration
FIS-B	Flight Information Services – Broadcast
FRUIT	False Replies Unsynchronized in Time
GUI	Graphical User Interface
IAD	Washington Dulles International Airport
ICAO	International Civil Aviation Organization
IFF	Identification Friend or Foe
II	Interrogator Identifier
IISLS/I^2SLS	Improved Interrogator Sidelobe Suppression
IWS	Integrated Warfare System
JHUAPL	Johns Hopkins University Applied Physics Laboratory
LBTS	Land-Based Test Sites
LHA	Landing Helicopter Assault (*Tarawa* class)
LHD	Landing Helicopter Deck (*Wasp* class)
LOS	Line of Sight
LPD	Landing Platform Dock (*San Antonio* class)
LSD	Landing Ship Dock (*Harpers Ferry* Class)
MASPS	Minimum Aviation System Performance Standards
MDAS	Mode S Data Analysis Software
MLAT	Multilateration
Mode S	Mode Select
MOPS	Minimum Operational Performance Standards
MTL	Minimum Trigger Level
MSAT	Mode S Analysis Tool
MSSR	Monopulse Secondary Surveillance Radar
N39	Convair 380
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NAVAIR	Naval Air Systems Command
NAVSEA	Naval Sea Systems Command
NAWCAD	Naval Air Warfare Center Aircraft Division
NCP	NAS Change Proposal
NHK	Trapnell Field, Patuxent River Naval Air Station
nmi/nm/NM	Nautical Miles

NTIA	National Telecommunications and Information Administration
ORF	Norfolk International Airport
QARS	Quick Analysis of Radar Sites
QPL	The Plains, Virginia, ATCBI-6 SSR
QVR	Oceana, Virginia, ATCBI-6M SSR
PEO	Program Executive Office
PEO T	Program Executive Office Tactical Aircraft Programs
P_d	Probability of Detection
PRM	Precision Runway Monitor
PRM-A	Precision Runway Monitor – Alternate
RBAT	Radar Beacon Analysis Tool
RFA	Radio Frequency Assignments
RIC	Richmond International Airport
RTADS	Real-Time Aircraft Display System
RTCA	RTCA, Inc. (formerly Radio Technical Commission for Aeronautics)
RU	Remote Unit
SAT	SBS Analysis Tool
SBS	Surveillance and Broadcast Services
SDP	Service Delivery Points
sec	second(s)
SIF	Selective Identification Feature
Simulator	Volpe 1030/1090 MHz Simulator
SLS	Sidelobe Suppression
SME	Subject Matter Expert
SPS	Spectrum Planning Subcommittee
SSDS	Ships Self Defense System
SSR	Secondary Surveillance Radar
SV	Service Volume
TACAN	TACtical Air Navigation
TCAS	Traffic Alert and Collision Avoidance System
TDOA	Time Difference of Arrival
TIS-B	Traffic Information Services – Broadcast

Typical	Typical parameters are a set of transponder occupancy times, in microseconds (µs), which have been determined to be average based on data from measurements from production transponders that operate in the airspace
UAT	Universal Access Transceiver
UF	Uplink Format
US&P	United States and Possessions
V-PAT	Volpe Performance Analysis Tool
WAM	Wide Area Multilateration
WJHTC	William J. Hughes Technical Center
Worst Case	Worst Case parameters are a set of transponder occupancy times, in microseconds (µs), which use the maximum transponder occupancy time allowable by the MOPS

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2. SPS-18778. *AN/UPX-41(C) Digital Interrogator System, S/W V5.5, with Mode 5 (Shipboard).* NTIA Certification. June 22, 2012.

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5. FAA. *1090 Spectrum Analysis Interim Report Version 1*. August 23, 2012.

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7. FAA. *Mode S Analysis Tool (MSAT)*, version 2.4 Interim, December 15, 2014. Available from: http://www.faa.gov/about/office_org/headquarters_offices/ang/offices/tc/about/campus/faa_host/tnes/ATCSurveillance/software/msat2/.

8. FAA Order JO 6100.1H. *Maintenance of NAS En Route Stage A - Air Traffic Control System*. En Route Services. February 09, 2009.

9. Bellman, Miles. Shah, Vaibhav. *AN-UPX-41(C) Test Data Analysis of Impacts to Secondary Surveillance Radars*. DOT-VNTSC-NAVSEA-15-04. February 2015.

10. NAS-IR-82530001, Version 3.5. *Surveillance and Broadcast Services (SBS) Service Delivery Point (SDP) to ATC Automation and Service Monitoring User Subsystems Interface Requirements Document (IRD).* February 23, 2012.

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Appendix A. Airborne-based Data Collection and System Analysis

A.1 Recording and Analysis Tools

The airborne test equipment is described in Section 9.5 of the Test Plan.

Typical and Worst Case Parameters:

Regarding transponder occupancy analysis, there are certain MOPS requirements that can vary within spec depending on the transponder design. ICAO has incorporated guidance for transponder occupancy parameter performance sets which include Typical and Worst Case. The Typical parameters are a set of transponder occupancy times, in microseconds (µs), which have been determined to be average based on data from measurements from production transponders that operate in the airspace. The Worst Case parameters use the maximum transponder occupancy time allowable by the MOPS. The post processing for the AN/UPX-41(C) system test flights was performed using both parameter sets. The following tables define the Typical and Worst Case parameters:

Table 13. ATCRBS Typical and Worst Case Parameters

ATCRBS Typical	ATCRBS Worst Case
Replies:	
Interrogation + Delay + Reply + Dead Time	
Mode A/C, ATCRBS Only, Intermode (A/C)	
8 + 3 + 21 + 56.7 = 88.7 µs	8 + 3 + 21 + 125 = 157 µs
21 + 3 + 21 + 56.7 = 101.7 µs	21 + 3 + 21 + 125 = 170 µs
Suppressions:	
Suppression Duration from P1 Lead Edge	
All Interrogations with P1-P2 including:	
Suppressed ATCRBS, Suppressed ATCRBS Only,	
Suppressed Intermode, Suppressed Mode 2,	
All Whisper-Shouts, Mode S,	
and Suppression Pairs	
41 µs	47 µs

Table 14. Mode S Typical and Worst Case Parameters

Mode S Typical	Mode S Worst Case
Replies:	
Interrogation + Delay + Reply + Dead Time	
Mode A/C, Intermode (S), Mode S Replied	
A) 8 + 3 + 21 + 16.5 = 48.5 µs	8 + 3 + 21 + 125 = 157 µs
C) 21 + 3 + 21 + 16.5 = 61.5 µs	21 + 3 + 21 + 125 = 170 µs
IMA) 10 + 128 + 64 + 16.5 = 218.5 µs	10 + 128+ 64 + 125 = 327 µs
IMC) 23 + 128 + 64 + 16.5 = 231.5 µs	23 + 128 + 64 + 125 = 340 µs
S short R) 4.8 + 128 + 64 + 16.5 = 213.3 µs	4.8 + 128 + 64 + 125 = 321.8 µs
S long R) 4.8 + 128 + 120 + 16.5 = 269.3 µs	4.8 + 128 + 120 + 125 = 377.8 µs
Recoveries:	
Recovery Period	
Mode S Wrong Address, Locked-Out All-Calls,	
Broadcast	
34.2 µs	45 µs
Suppression Bus:	
Defined Suppression Bus Duration for TOP and Bottom	
>-35 dBm: ATCRBS Only, Intermode (A/c)	
Whisper-Shout, Mode S	
70 µs Top, 90 µs Bottom	70 µs Top, 90 µs Bottom

A.2 1030 MHz – Sidelobe Suppression Characteristics – Day 2

The airborne test portion of Day 2 was dedicated to flying profiles designed to measure the sidelobe suppression (SLS) characteristics of the AN/UPX-41(C) systems. The sidelobe test was coordinated between the test pilots and the LBTS personnel to activate each of the four sites one at a time, while N39 flew from a distance of at least 40 nmi to directly over the active site and then to about 40 nmi past. With the Wallops Island sites (V-10 & V-24) the aircraft flew on a straight path from northeast to southwest past the sites. With the two LBTS located at Webster Field (8164 & 8225) the aircraft flew from east of the sites and turned around right over the site and flew back to the east. This was required due to airspace restrictions. Following the flight over the four individual sites, the aircraft flew two passes over the two co-located Wallops island sites while they were both Active. For all SLS tests the aircraft maintained an altitude of 6000 feet.

The 1030 MHz recorded data from the SLS tests was post-processed to examine transponder occupancy and detected suppression rates for the purpose of determining the range and

magnitude of the AN/UPX-41(C) system's suppression impact. It was expected that any impact on transponder occupancy from an aircraft flying in close range to an AN/UPX-41(C) system would be due to an increase in the number of sidelobe suppressions therefore it was not expected that a Mode S transponder would show significant effects. However the Mode S function of a Typical Mode A/C/S transponder's occupancy rates were examined and are presented here in order to perform a complete analysis of the AN/UPX-41(C) system.

A.2.1 1030 MHz – Sidelobe Suppression Characteristics, Test Site V-10

After departing the WJH FAA Technical Center at approximately 14:33:00 (UTC) on Day 2, N39 flew south at an altitude of 6,000 feet towards the Wallops Island temporary installation of AN/UPX-41(C) systems. The first site to be tested was the one designated as V-10. For this portion of the test, the V-10 was to be the only one of the LBTS that was Active and interrogating. Figure 34 shows a map of the N39's flight path and the location of the LBTS.

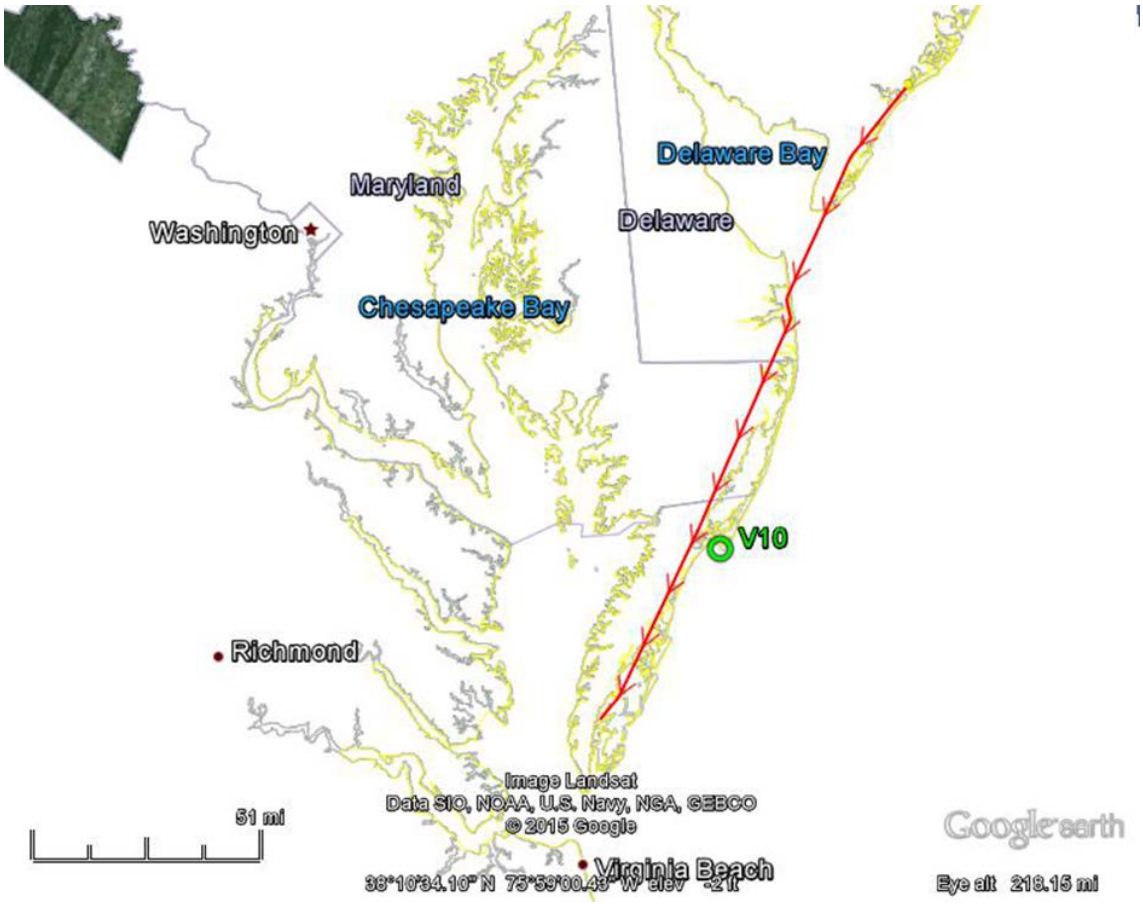


Figure 34. Day 2 - N39 Flight Path of Site V-10

The measured occupancy for the ATCRBS function of a Typical Mode A/C/S transponder from the test flight over site V-10 is shown in Figure 35. The graph is a scatter plot of the measured

occupancy percentage per second with the darker bands as a 10-second average. The blue data points are prior to the V-10 being turned Active and the red area is when it is Active and transmitting. The green data points are during the transition. The distance between N39 and the site is shown on the gold line with the right side Y-axis. The same general format is used for all of the occupancy plots.

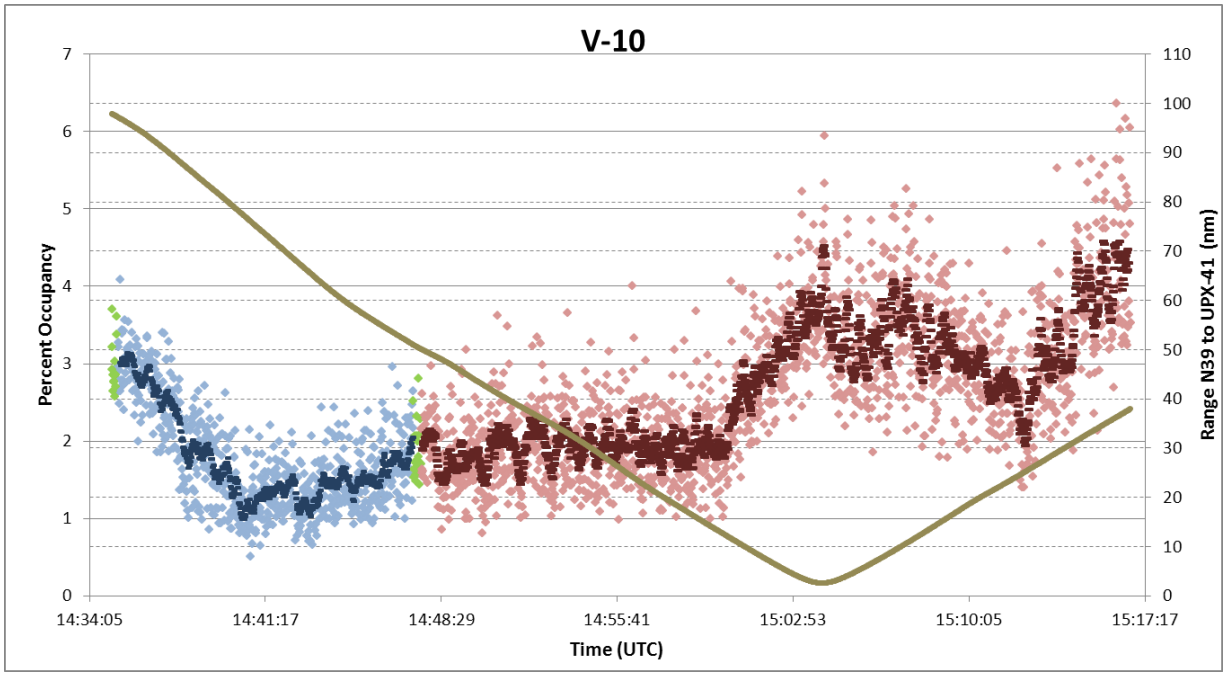


Figure 35. ATCRBS Transponder Occupancy, SLS Test of Site V-10

In Figure 35 there is an obvious increase in the average occupancy when the aircraft is approaching the site from the north beginning at a range of about 12 nmi. Prior to this, the average occupancy was about 2% and it increases to about a 4% average at the closest range. After the aircraft passes the site to the south the occupancy decreases but not as evenly as the approach and then actually increases again further south. Deeper analysis of the increased and varying occupancy to the south revealed that there was at least one other interrogator (not AN/UPX-41(C) system) present that caused this additional occupancy.

The expected increase in ATCRBS function's transponder occupancy can be calculated using the documented interrogation sequence and PRF of the AN/UPX-41(C) system along with assumptions of typical transponder dead time and suppression duration. Analysis of interrogation and reply data from N39's transponder shows that at the closest range to the LBTS the beam dwell is about 40 total unsuppressed interrogations (non-Mode 4 scan). Two of the interrogation modes will elicit replies from the transponder, Mode 3/A and Mode C (Modes 1 & 2 will not). Therefore there will be about 10 Mode 3/A and 10 Mode C replies per scan. The typical transponder occupancy for Mode 3/A and Mode C are 88.7 and 101.7 microseconds, respectively. This is including interrogation acceptance, reply delay and transmission dead time.

The 10 Mode 1 and 10 Mode 2 interrogations will desensitize the receiver some, but for this calculation they are not a factor for transponder occupancy. For the peak occupancy calculation, it is assumed that the receiving transponder is completely in the interrogator sidelobes, therefore, the remaining 960 interrogations will trigger suppressions. The typical transponder will be occupied for 41 microseconds per suppression. The following summarizes the occupancy for the ATCRBS function of a Typical Mode A/C/S transponder calculation:

Each 4 second scan:

10 x 88.7 (Mode 3/A interrogation, delay and dead time) = 887 microseconds

10 x 101.7 (Mode C interrogation, delay and dead time) = 1017 microseconds

960 x 41 (typical suppression duration) = 39,360 microseconds

887 + 1017 + 39,360 = 41,264 microseconds

Average per second:

41,264 / 4 = 10.316 milliseconds or about **1%**

Thus, according to the above calculation, a single operational AN/UPX-41(C) system using only the 360-degree scan mode should increase an ATCRBS function of a Typical Mode A/C/S transponder by **one percent**. The extra occupancy rates measured from the test of the V-10 site was most likely due to additional interrogators in the same area and multipath effects.

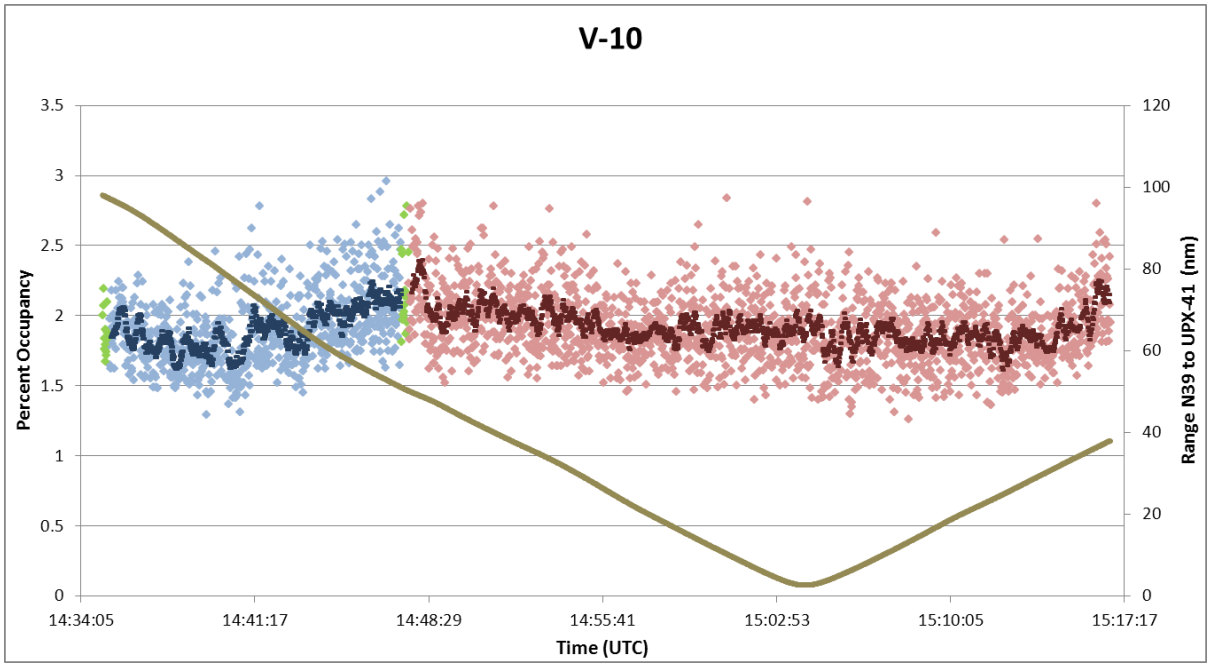


Figure 36. Mode S Transponder Occupancy, SLS Test of Site V-10

Figure 36 shows the occupancy for the Mode S function of a Typical Mode A/C/S transponder from the same part of the flight test. The Mode S function's occupancy measured from the flight over site V-10 shows no noticeable effect related to the aircraft's distance from the LBTS.

In addition to transponder occupancy, the 1030 MHz data was post-processed to analyze the detected rate of sidelobe suppressions as N39 flew over the sites being tested. Figure 37 shows a bar graph color coded to show the rate of the various detected suppressed interrogations.

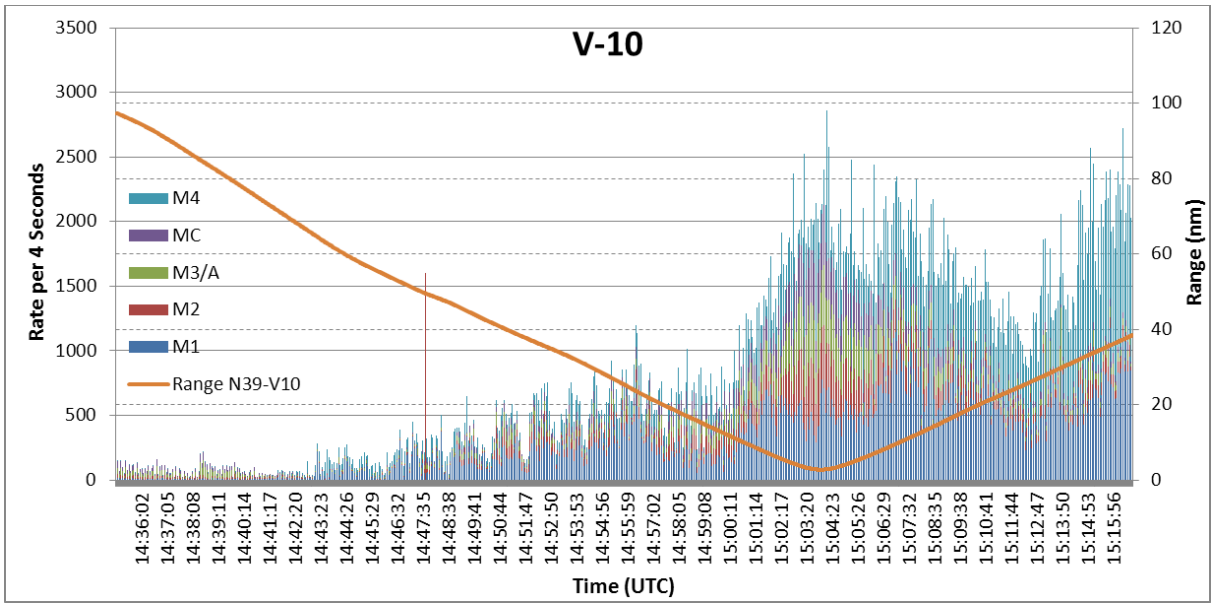


Figure 37. Detected Suppressed Interrogation Rates from the SLS Test of Site V-10

Each vertical bar in the figure is the count of suppressions over 4 seconds thus providing a count for approximately each complete antenna rotation. There were a significant number of suppressions detected that do not correlate to the aircraft's proximity to the V-10 LBTS, especially Mode 1 and Mode 4. Deeper analysis determined that the extra suppressions are from another non-AN/UPX-41(C) system. The extra suppressions interfere with the goal of measuring the V-10 SLS characteristics. Figure 38 is a similar graph with suppressed Mode 1 and Mode 4 removed to perhaps provide a clearer indication of the SLS characteristics of the V-10 interrogator. (Note that the red vertical line near time mark 14:48 in both graphs is not a suppression count but a mark to indicate when the V-10 Site was turned Active)

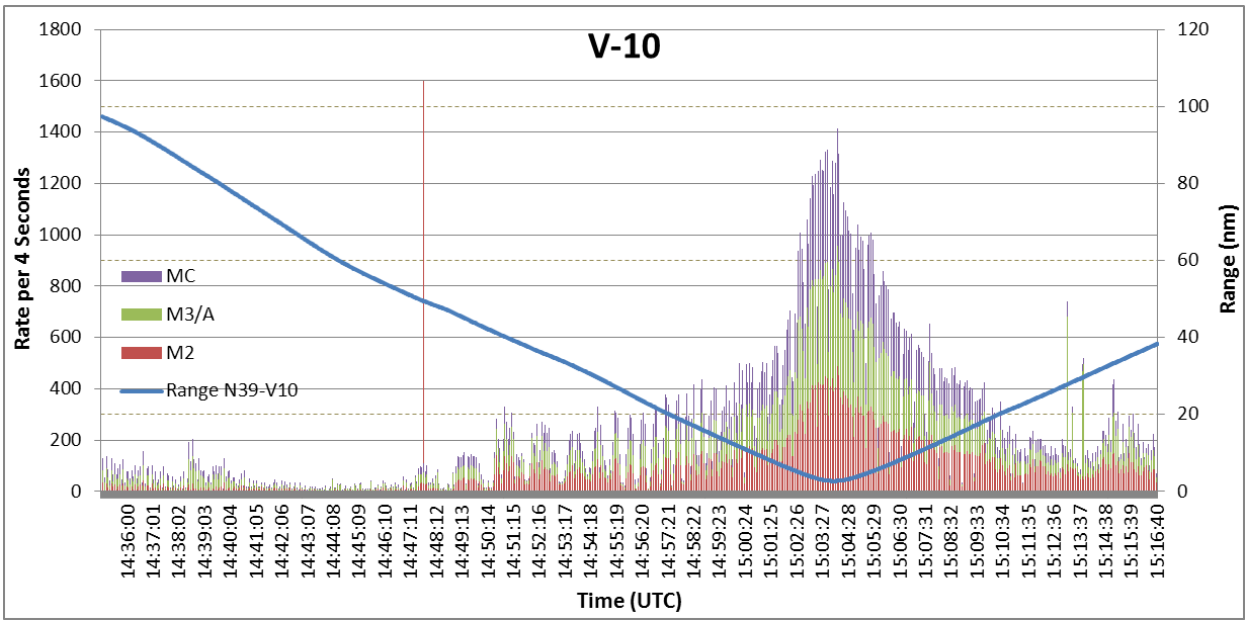


Figure 38. Mode 2, 3/A and C Suppression Rates from the Test Flight of Site V-10

The Mode 2, 3/A and C suppression rates shown in Figure 38 generally correlate to the aircraft's proximity to the interrogator with the highest rate measured when closest to the site. However, there are some apparent extra suppressions especially when the aircraft has passed the site. Also, since the AN/UPX-41(C) system has a 250 PRF, the highest rate of suppressions of each type in four seconds is expected to be 250 or less. The graph shows a contribution of about 400 from each of the suppression types at the peak.

Another measure of the AN/UPX-41(C) system's SLS characteristics is an analysis of the unsuppressed interrogations that trigger replies as N39 flies over the site. With a properly working SLS, there should only be mainbeam replies solicited at all ranges, so the expected reply rate should be fairly constant. An increase in Mode 3/A or Mode C replies that are associated with the AN/UPX-41(C) system could be an indication of improperly working SLS. However, there are other interrogators in the live test environment that may cause some variations. Figure 39 shows the Mode 3/A reply rate and Figure 40 shows the Mode C reply rate from the flight over the V-10 site.

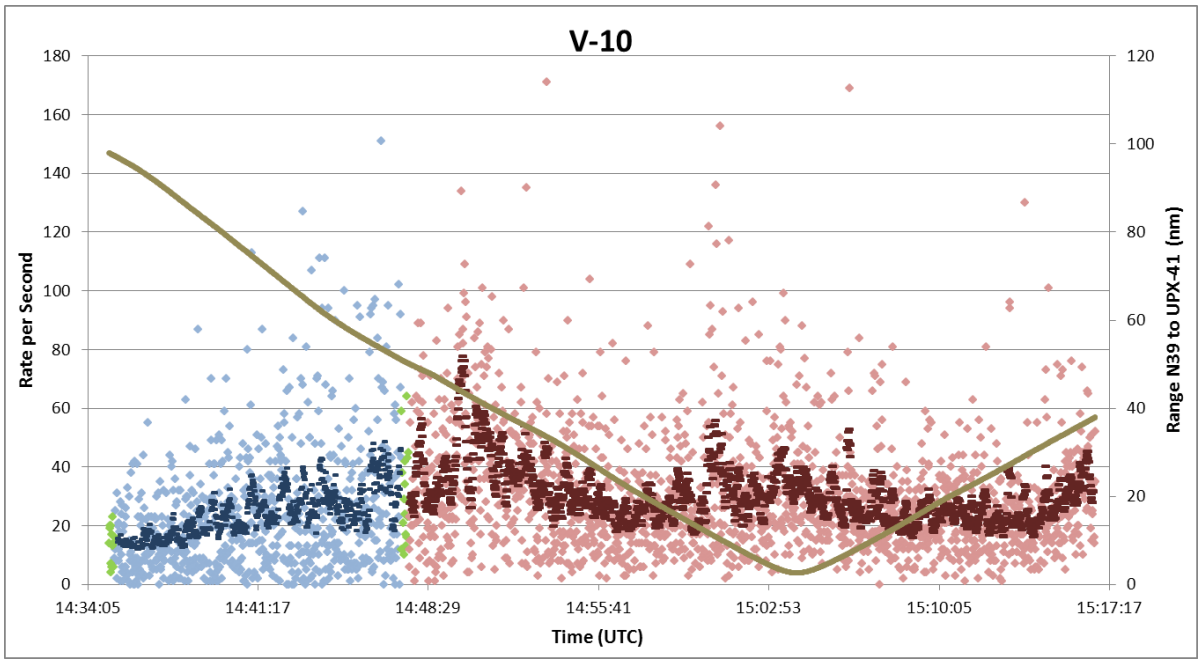


Figure 39. Mode 3/A Reply Rate from SLS Test Flight of site V-10

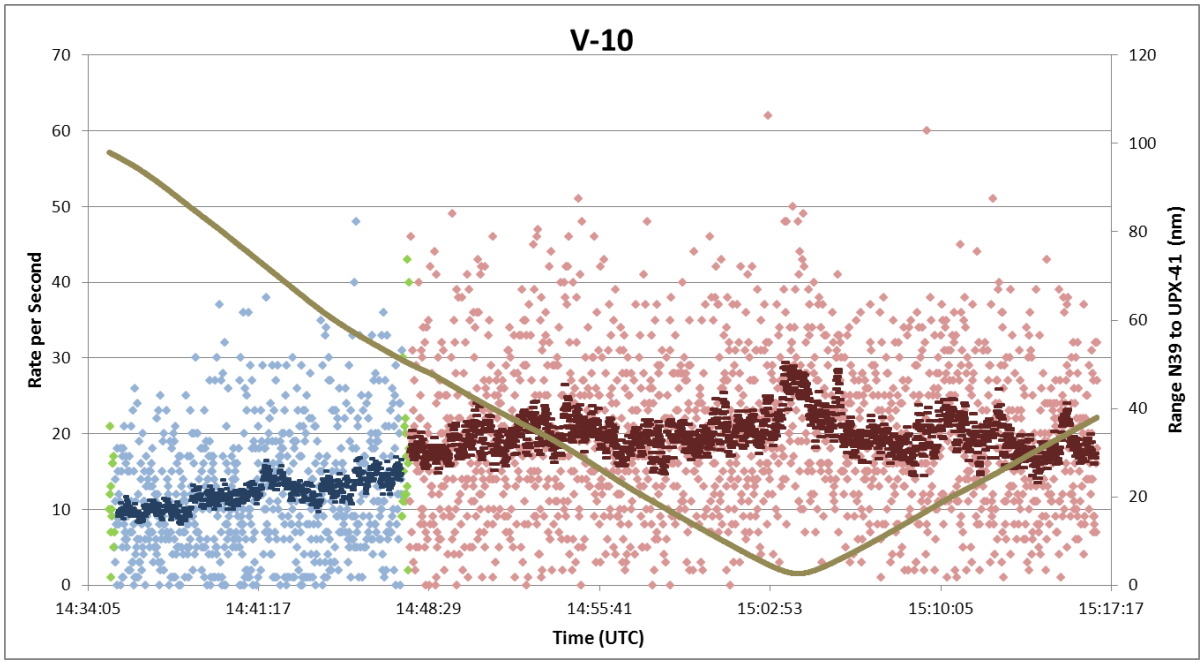


Figure 40. Mode C Reply Rate from SLS Test Flight of site V-10

A.2.2 1030 MHz – Sidelobe Suppression Characteristics, Test Site V-24

After the test of site V-10, N39 turned around to the south and flew back north with site V-24 now Active. Figure 41 shows a map of N39's flight path and the location of the test site. Note that as with the flight over V-10, N39 did not fly directly over the interrogator.

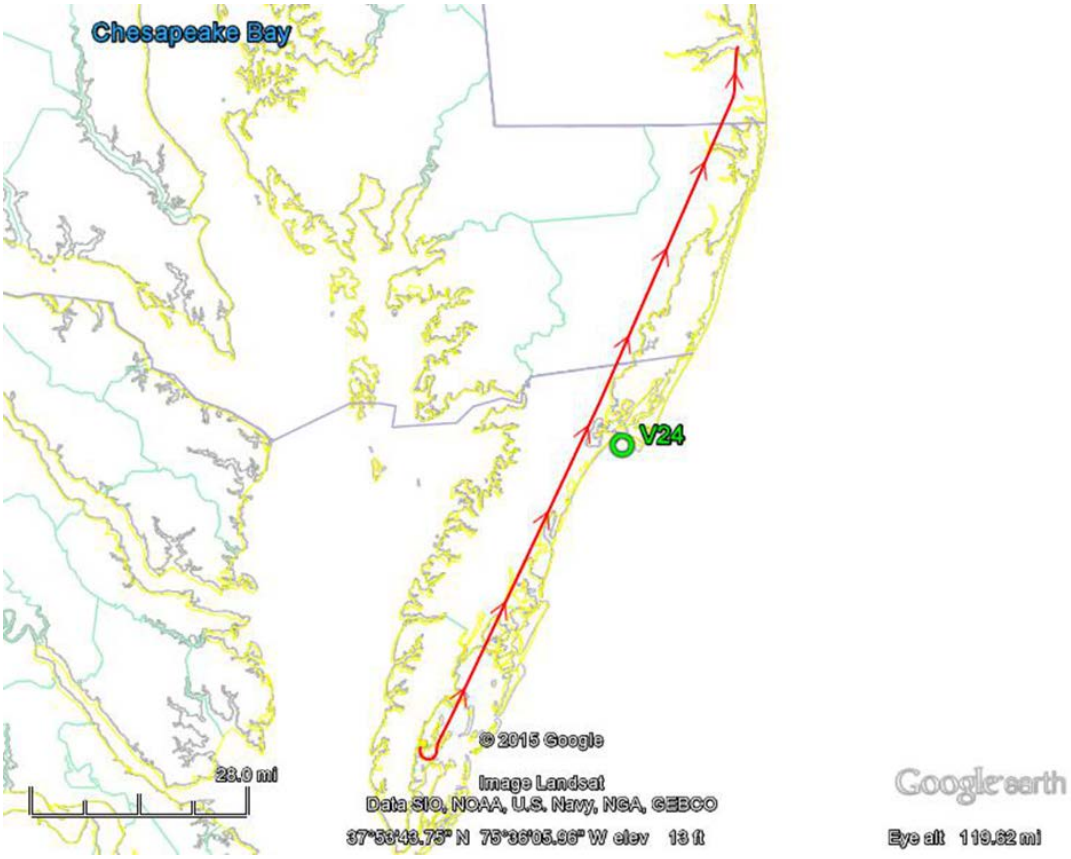


Figure 41. Day 2 – N39 Flight Path of Site V-24

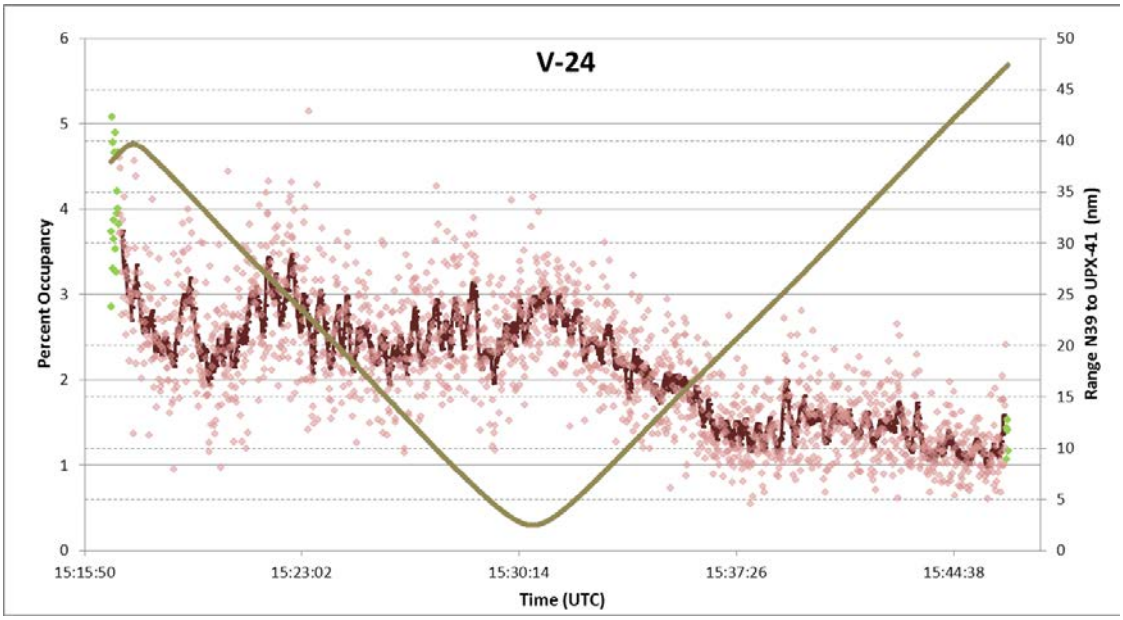


Figure 42. ATCRBS Transponder Occupancy, SLS Test of Site V-24

The measured transponder occupancy for the ATCRBS function from the test flight over site V-24 is shown in Figure 42. Similar to the flight test of site V-10, there was additional increased occupancy to the south of the site (left side of the graph) that was determined to be from sources other than V-24. The measured occupancy from closest to the site and to the north is more like what is expected with heightened occupancy at close range with a decreased percentage farther out in range. However, the rate is about 1 ½ percent higher over the site than it is 20 or more nmi to the north. The higher than expected occupancy near the site and to the north may still be affected by the other sources and multipath.

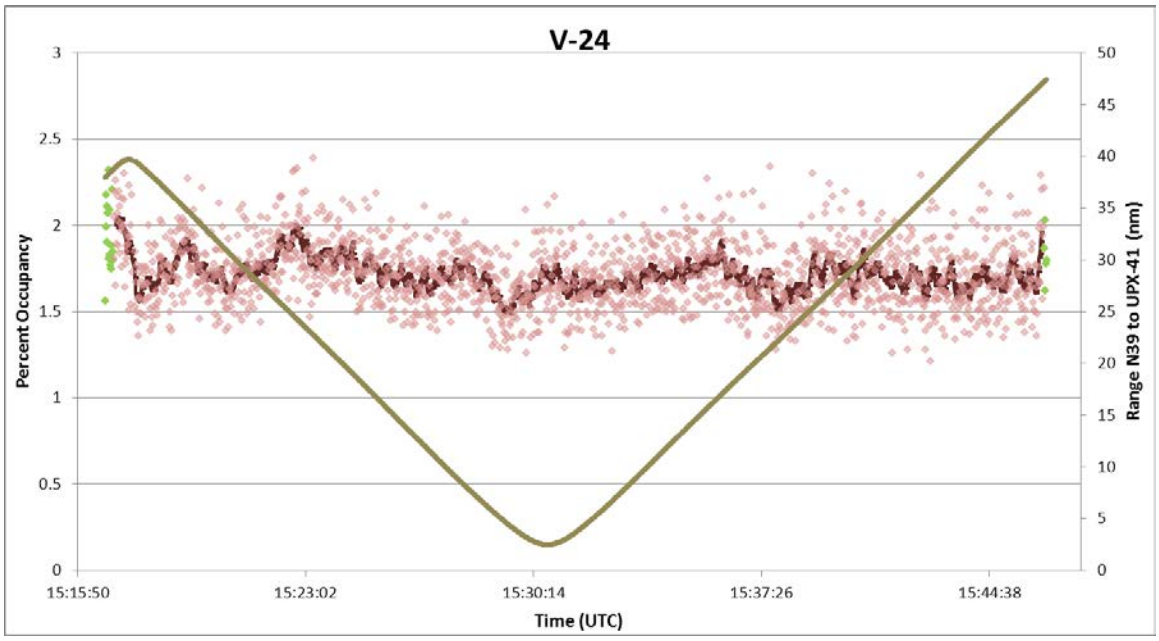


Figure 43. Mode S Transponder Occupancy, SLS Test of Site V-24

Figure 43 shows the transponder occupancy for the Mode S function of a Typical Mode A/C/S transponder from the SLS test flight over the V-24 site. As expected there was no significant impact from the AN/UPX-41(C) system on Mode S function's occupancy.

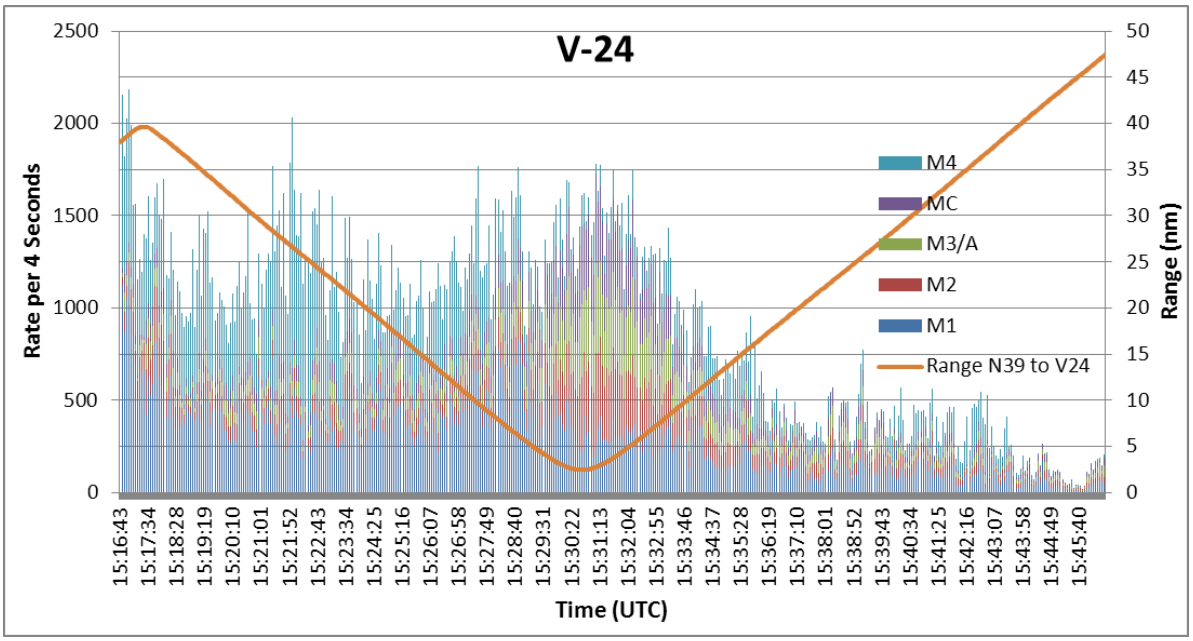


Figure 44. Detected Suppressed Interrogation Rates from the SLS Test of Site V-24

Figure 44 shows a count of various suppressed interrogation types from the SLS flight test of V-24. Each vertical bar in the figure is the count of suppressions over 4 seconds thus providing a count for each complete antenna rotation. Similar to the test of site V-10, there were a significant number of suppressions detected that do not correlate to the aircraft's proximity to V-24, especially Mode 1 and Mode 4. This is from the same source of extra suppressions that affected the V-10 test. The extra suppressions interfere with the goal of measuring V-24's SLS characteristics especially on the southern end. Figure 45 is a similar graph with suppressed Mode 1 and Mode 4 removed to perhaps provide a clearer indication of the SLS characteristics.

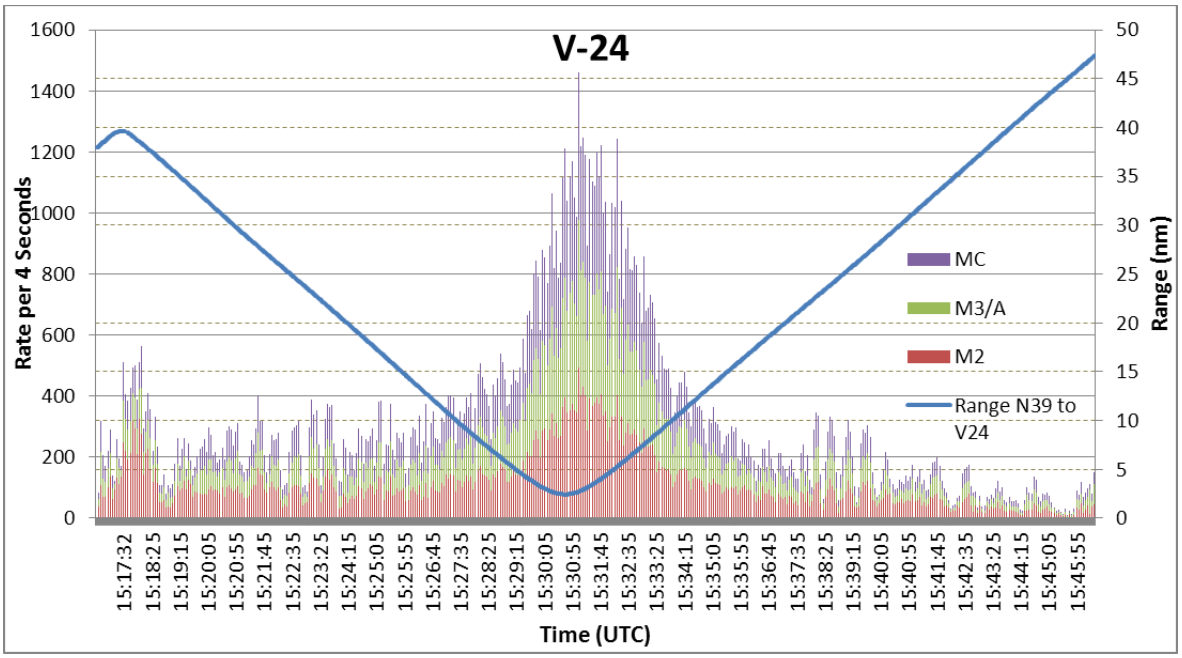


Figure 45. Mode 2, 3/A and C Suppression Rates from the Test Flight of Site V-24

The Mode 2, 3/A and C suppression rates shown in Figure 45 generally correlate to the aircraft's proximity to the interrogator with the highest rate measured when closest to the site. However, there are some apparent extra suppressions especially when the aircraft is south of the site. Also, since the AN/UPX-41(C) system has a 250 PRF, the highest rate of suppressions of each type in four seconds is expected to be 250 or less. The graph shows a contribution of about 400 from each of the suppression types at the peak. This data is similar to the data from the V-10 site test.

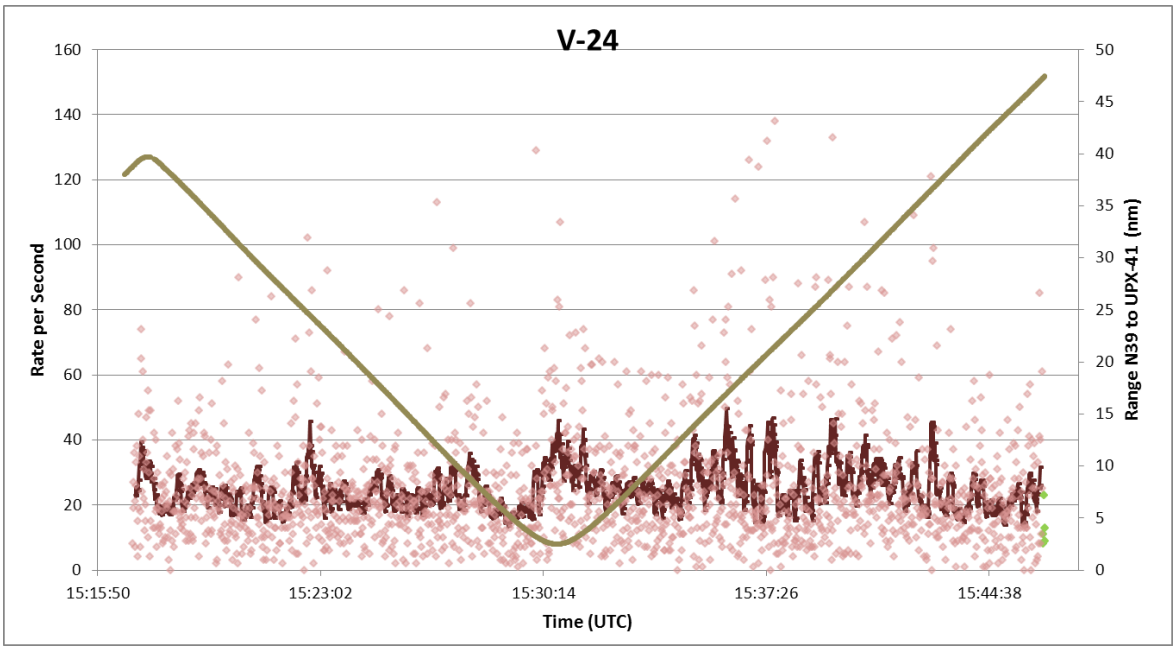


Figure 46. Mode 3/A Reply Rate from SLS Test Flight of site V-24

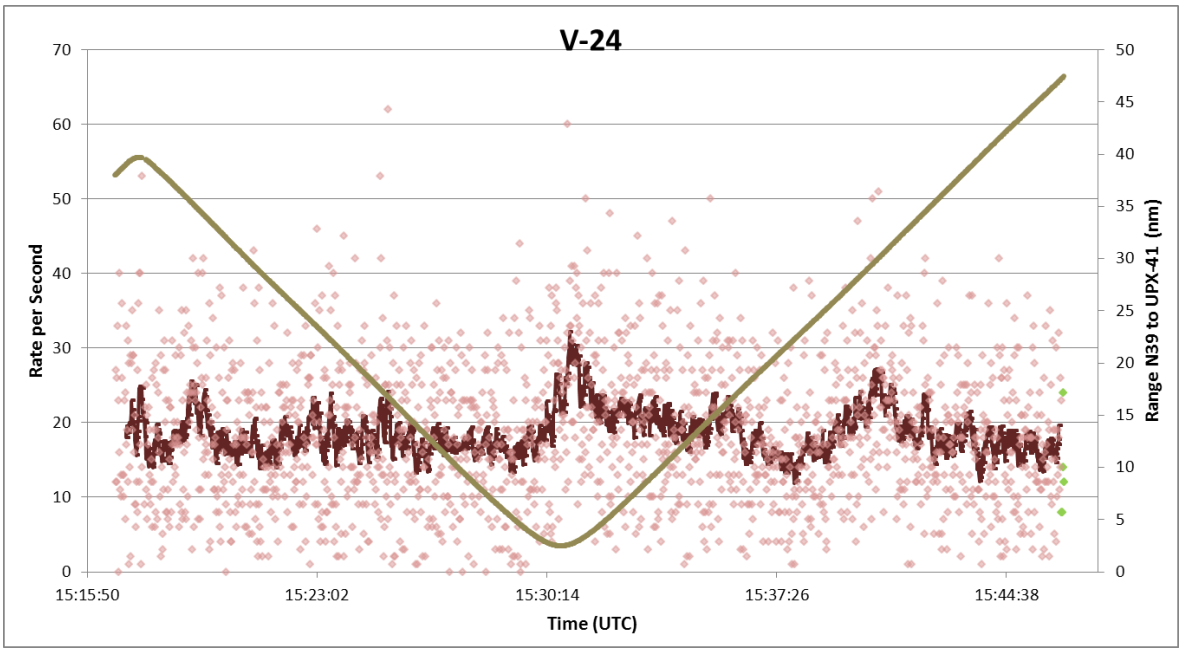


Figure 47. Mode C Reply Rate from SLS Test Flight of site V-24

The Mode 3/A and Mode C reply rates are shown in Figure 46 and Figure 47 respectively. The ten second average reply rates for both modes are generally the same for the duration of the test, about 20 per second for Mode C and slightly higher for Mode 3/A but for both modes there is a lot of variation. There is an indication, especially in the Mode C plot that there was a brief increase in replies when nearest to the interrogator. When considering the Y-axis scale, the Mode 3/A reply rate may have a similar rate increase. This may be an indication that the P1 to P2 ratio is somewhat affected by vertical antenna pattern when nearly right above the site.

A.2.3 1030 MHz – Sidelobe Suppression Characteristics, Test Site 8225

After the test of site V-24, N39 turned around to the south and when east of the Webster Field sites turned west to fly over the site designated as 8225. For this test, the 8225 site was the only site operating. Figure 48 shows a map of N39's flight path and the location of the test site. N39 was not permitted to fly past the site to the west, so both the approach and departure from the site is to the east.

Figure 48. Day 2 – N39 Flight Path Over Site 8225

Figure 49 shows the transponder occupancy for the ATCRBS function of a Typical Mode A/C/S transponder measured from the test flight over site 8225. There is a distinct increase in occupancy within 20 nmi of the AN/UPX-41(C) system and peaking right over the site. There does not appear to be any significant interference from another interrogator. The ATCRBS function's occupancy beyond the 20 nmi range is about 1.25% average and it peaks to about 3.5% average when right over the site. This occupancy increase (2.25%) is more than expected for a Typical transponder based on the specifications of the AN/UPX-41(C) system.

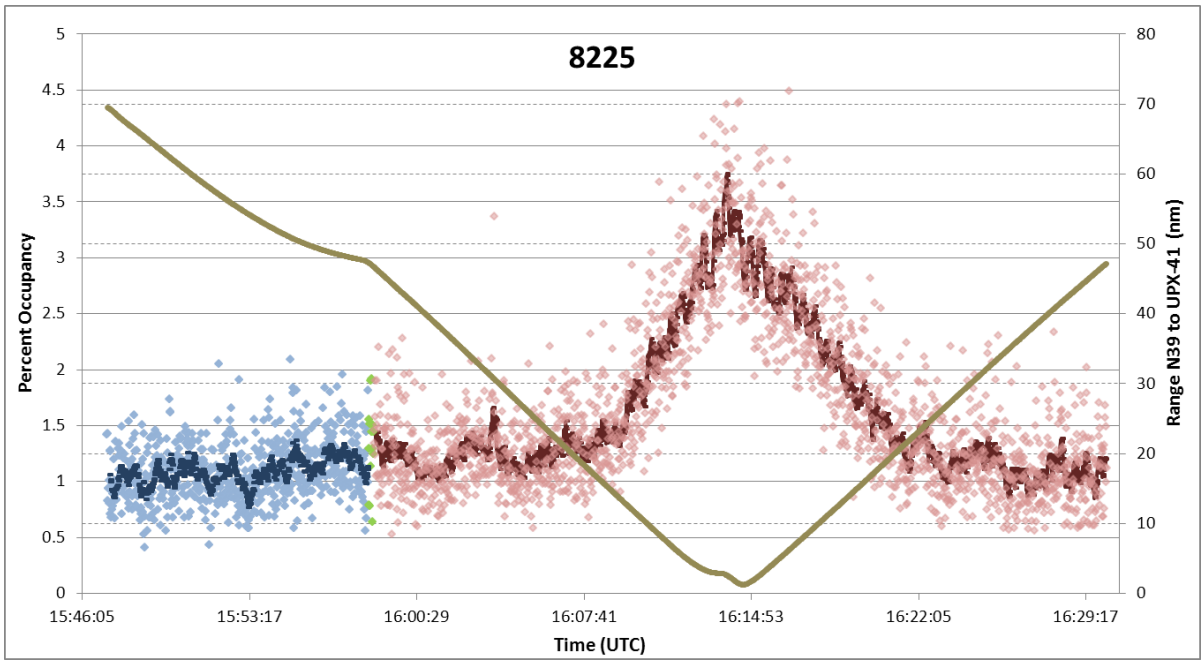


Figure 49. ATCRBS Transponder Occupancy, SLS Test of Site 8225

The transponder occupancy for the Mode S function of a Typical Mode A/C/S transponder is shown in Figure 50. This is definitely not as expected since it is showing an apparent occupancy effect to the Mode S function's transponder occupancy from site 8225.

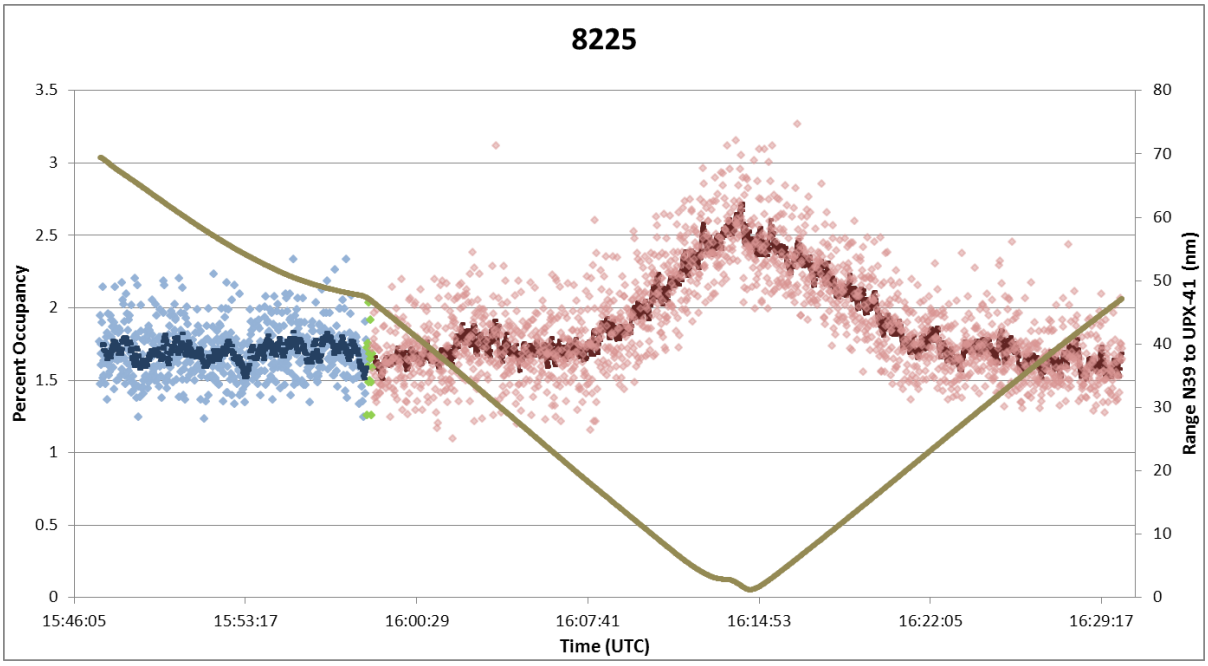


Figure 50. Mode S Transponder Occupancy, SLS Test of Site 8225

The Mode S function's occupancy data from the test of site 8225 shows an increase of almost one percent right over the site as compared to the rate at 18 or more nautical miles away. Since Mode S is not occupied by P1-P2 suppression pairs, this is an indication that there is additional occupancy due to the reception of interrogations that trigger replies (unsuppressed). If there is a problem with the SLS at this interrogator, the measured rate of suppressions will be lower than expected, and the Mode 3/A and Mode C reply rates will be higher than expected. Figure 51 shows the measured rate of the various suppression types from the test of site 8225.

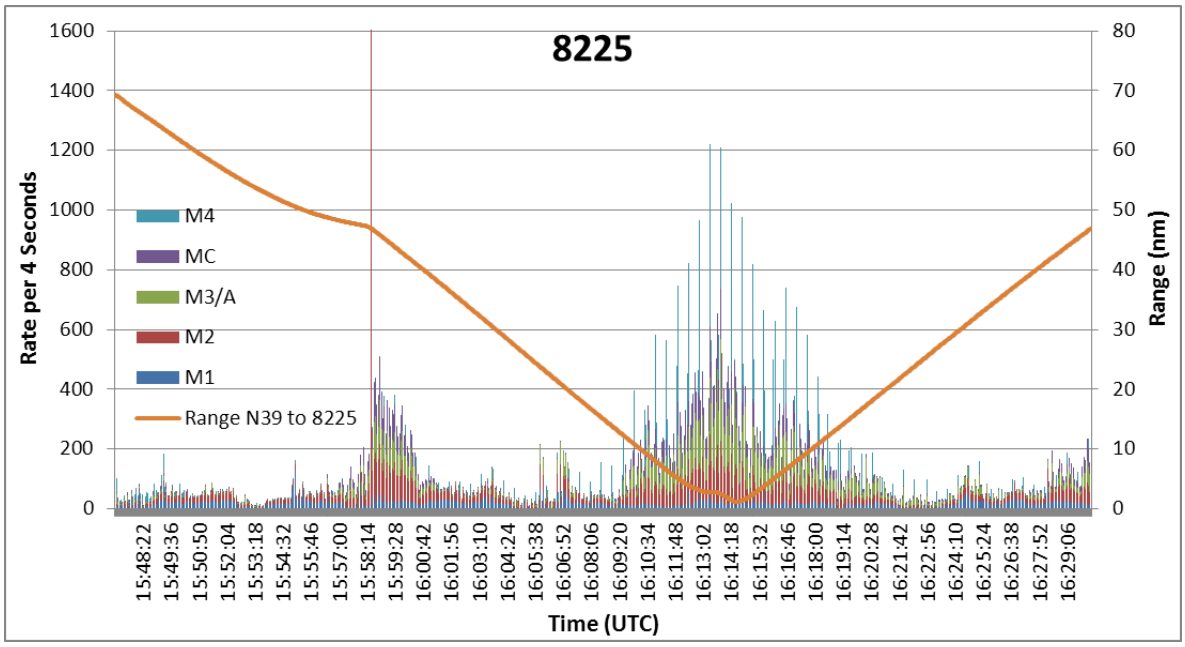


Figure 51. Detected Suppressed Interrogation Rates from the SLS Test of Site 8225

In Figure 51 the rate of the various suppressed interrogation modes is much lower than the rate measured at all other LBTS. If the aircraft is completely within the radiated sidelobes, which it is expected to be at the close range tested, each interrogation type is expected to contribute almost 250 per scan (each colored vertical bar represents a 4-second interval). Note that the vertical red line at about 15:58:14 is just a mark of when site 8225 was turned Active and the cluster of suppressions around that time were determined to be another interrogator.

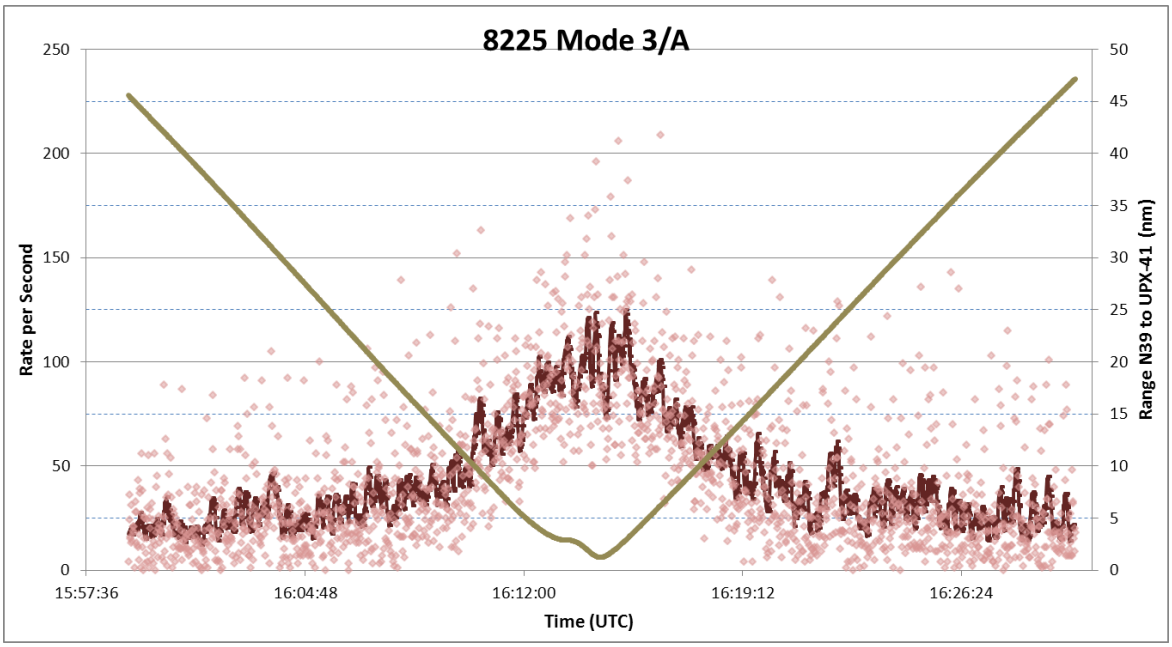


Figure 52. Mode 3/A Reply Rate from SLS Test Flight of Site 8225

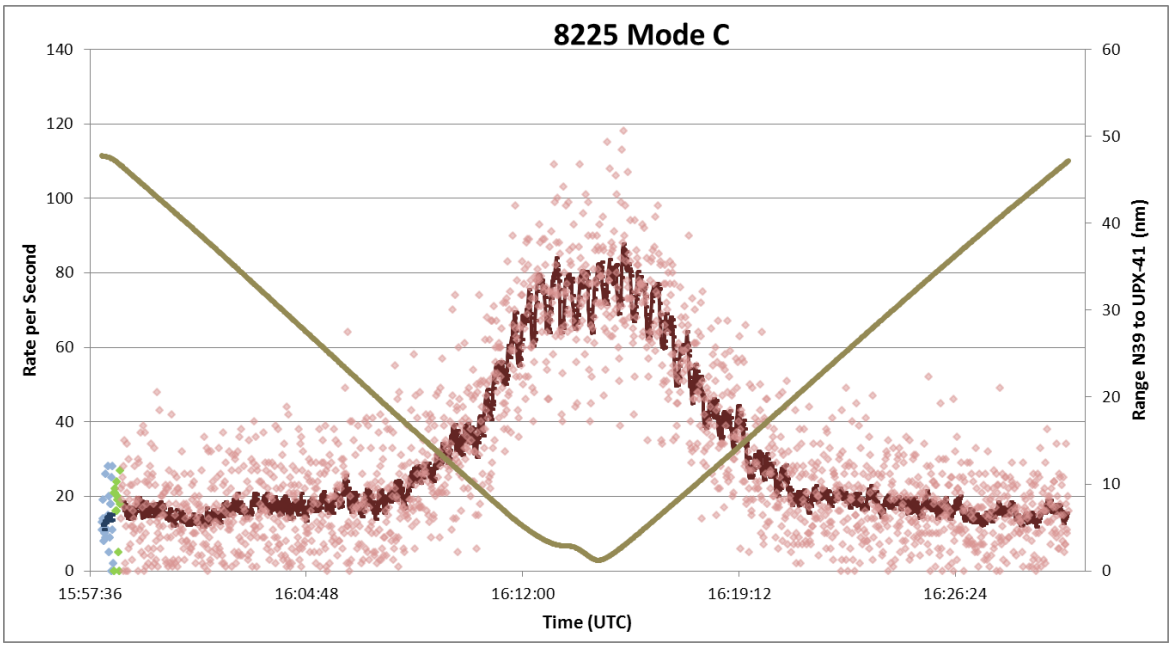


Figure 53. Mode C Reply Rate from SLS Test Flight of Site 8225

Figure 52 and Figure 53 show the Mode 3/A reply rate and the Mode C reply rate respectively from the test flight over site 8225. Unlike the data from the other sites, and contrary to what is expected, the reply rate for both modes show a significant increase that peaks when at the closest range from the interrogator. This is an indication of a lack of sidelobe suppression. The improperly working SLS may be the cause of the higher than expected rate of transponder occupancy.

1090 Reply Correlation with Site 8225 interrogations – Day 2

Figure 54 shows the received power of the interrogations that resulted in a reply from. N39 was about 45 nmi from the site at both edges of this plot. The processing also puts out summary data about the interrogations/replies from this data. Part of that data for the start of this plot is shown on Table 15.

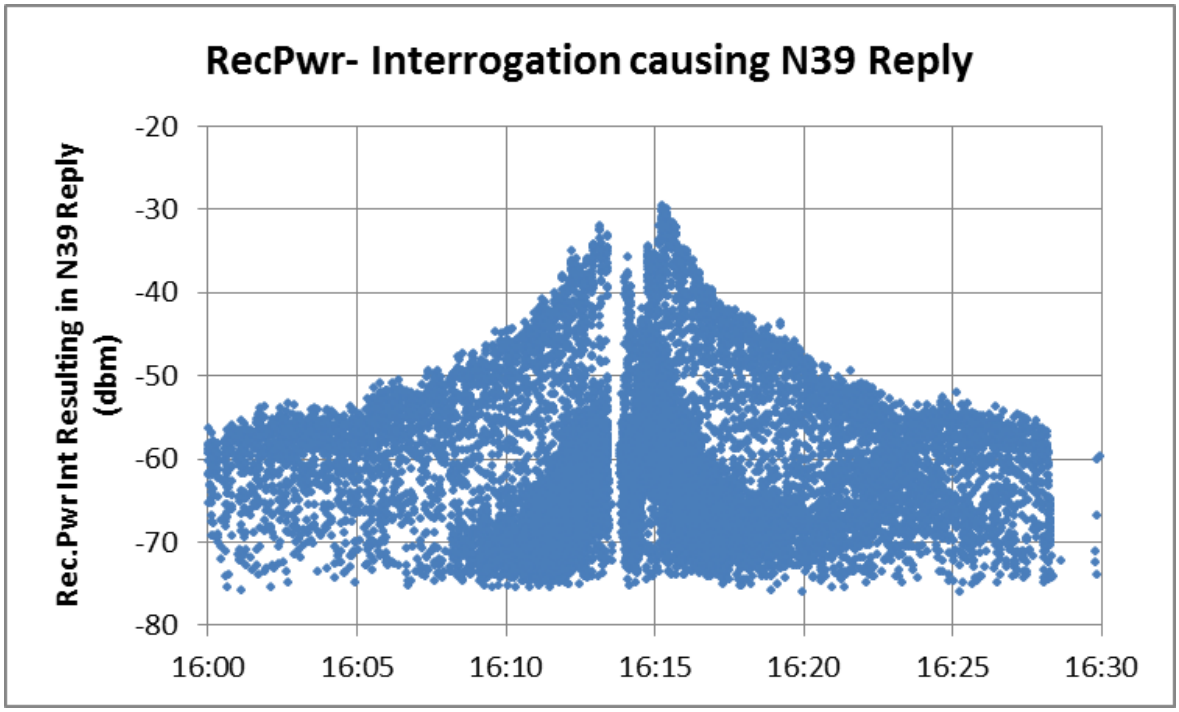


Figure 54. Received power of interrogations causing a reply from N39 – Day 2

The Tdiff column of the table is merely to verify that the reply is correlated to the interrogation (31 is 3.1µs delay).

The Int/Reply 8225 Tdiff column is the time difference between consecutive replies. A number of about 40000 represents consecutive PRT's from 8225. A number of about 80000 indicates that one PRT was missed, 120000 indicates that 2 PRT's were missed and 160000 indicates that 3 PRT's were missed. The blank cells in this row indicate a N39 reply that was not in the list of interrogations that fit the requirements to be assigned to site 8225. These are replies to other interrogators. Time differences were not calculated for these interrogations

Table 15. Summary data of interrogations/replies from N39 near 8225 – Day 2

Time	TimStrtSec	TodaySync Ref 1st File	TOA Sync Ref 1st File	Tdiff Rep_Int	Int/Reply 8225, Tdiff	RXx Pwr Int causing Reply
16:00:03	5169.055	5169054604.9	51690546049	31		
16:00:03	5169.07	5169070397.4	51690703974	31	157925	-65.2571
16:00:03	5169.075	5169074631.5	51690746315	31		
16:00:03	5169.087	5169086651.0	51690866510	31	120195	-61.9986
16:00:03	5169.091	5169090715.5	51690907155	31	40645	-61.7787
16:00:03	5169.103	5169102964.0	51691029640	31	122485	-60.2393
16:00:03	5169.107	5169107080.7	51691070807	31	41167	-58.48
16:00:03	5169.119	5169118881.2	51691188812	31	118005	-59.2497
16:00:03	5169.123	5169123039.9	51691230399	31	41587	-59.3597
16:00:03	5169.135	5169134824.5	51691348245	31	117846	-58.8099
16:00:03	5169.139	5169138665.6	51691386656	30	38411	-58.1495
16:00:03	1569.151	5169150737.3	51691507373	31	120717	-56.3648
16:00:03	1569.155	5169154678.5	51691546785	31	39412	-59.0298
16:00:04	5169.167	5169166537.0	51691665370	31	118585	-63.3141
16:00:04	5169.171	5169170775.5	51691707755	31	42385	-61.6688
16:00:04	5169.183	5169182873.2	51691828732	31	120977	-63.0955
16:00:04	5169.187	5169187011.6	51691870116	31		
16:00:04	5169.199	5169198773.0	51691987730	31		
16:00:04	5169.203	5169202744.7	51692027447	32		
16:00:07	5173.152	5173151575.0	51731515750	31		
16:00:08	5173.164	5173163870.0	51731638700	32	122950	-64.8253
16:00:08	5173.168	5173167895.2	51731678952	30	40252	-65.2571
16:00:08	5173.18	5173180185.9	51731801859	31	122907	-61.8887

The correlation of replies from N39 to detected unsuppressed Mode A and C interrogations was higher than 90% in all areas we checked.

Our time for this data is referenced to the start time of 1st file of the day. Another column (not shown here) was added to use time referenced to midnight, which is used by the Navy data.

The only data available from the Navy was target reports which appeared to correlate within about 2 seconds with our data. A sample of that output is shown on the next page.

The data below was taken when N39 was 42 nmi from site 8225.

Table 16. Summary of detected beams that resulted in replies from N39 – Day 2

Tdiff Rep_Int	Int/Reply 8225, Tdiff	Rx Pwr Int causing Reply	Rep Time Leaving N39	Tdiff Sec		TGTAZ	TGTRNG	ModeC	Mode2	Mode1	Mode3	TIME	ToDay	Tdiff(Sec)
						96.68	42.97	6100	0	0	5375	57599.993	16:00:00	4.09
						96.15	42.75	6100	0	0	5375	57604.073	16:00:04	4.08
31			57606.527		1	96.15	42.56	6100	0	0	5375	57608.166	16:00:08	4.09
31	157925	-65.26	57606.543	0.015793	2									
31			57606.547	0.004234	3									
31	120195	-62.00	57606.559	0.012019	4									
31	40645	-61.78	57606.563	0.004065	5									
31	122485	-60.24	57606.575	0.012248	6									
31	41167	-58.48	57606.580	0.004117	7									
31	118005	-59.25	57606.591	0.011800	8									
31	41587	-59.36	57606.595	0.004159	9									
31	117846	-58.81	57606.607	0.011785	10									
30	38411	-58.15	57606.611	0.003841	11									
31	120717	-56.36	57606.623	0.012072	12									
31	39412	-59.03	57606.627	0.003941	13									
31	118585	-63.31	57606.639	0.011858	14									
31	42385	-61.67	57606.643	0.004239	15									
31	120977	-63.10	57606.655	0.012098	16									
31			57606.659	0.004138	17									
31			57606.671	0.011761	18									
32			57606.675	0.003972	19									
31			57610.624	3.948830	1	96.15	42.34	6100	0	0	5375	57612.269	16:00:12	4.10
32	122950	-64.83	57610.636	0.012295	2									
30	40252	-65.26	57610.640	0.004025	3									
31	122907	-61.89	57610.653	0.012291	4									
31	40935	-60.79	57610.657	0.004093	5									
31	116134	-59.25	57610.668	0.011613	6									
31	40007	-59.80	57610.672	0.004001	7									
31			57610.684	0.011819	8									
31	42138	-56.81	57610.688	0.004214	9									
31	119180	-58.92	57610.700	0.011918	10									
31			57610.720	0.019887	11									
31			57610.732	0.011776	12									
31	42284	-60.90	57610.736	0.004228	13									
31	120977	-66.77	57610.748	0.012098	14									
31	38282	-63.96	57610.752	0.003828	15									
31	121658	-67.63	57610.764	0.012166	16									
31	40979	-69.18	57610.768	0.004098	17									
31			57614.722		1	96.33	42.13	6100	0	0	5375	57616.359	16:00:16	4.09
31			57614.726		2									
31			57614.742		3									
31			57614.755		4									
31	38629	-60.79	57614.758		5									
31	120021	-60.57	57614.770		6									
31	42080	-57.82	57614.775		7									
31	119542	-60.13	57614.787		8									
31	37832	-61.01	57614.790		9									
31			57614.807		10									
31			57614.819		11									
32	39050	-58.81	57614.823		12									
31	120600	-63.64	57614.835		13									
31	37832	-61.34	57614.838		14									
31			57614.850		15									
31	42008	-64.39	57614.854		16									
31	119890	-67.85	57614.866		17									
31	38455	-69.29	57614.870		18									
30			57618.814			96.33	41.91	6100	0	0	5375	57620.450	16:00:20	4.09

This is only the Mode A and Mode C interrogation data. You can tell from the Tdiff column of our data that every scan is detected (the differences of 120000 are the missing Mode 1 and 2 interrogations. The blanks are replies that do not fit the 8225 criteria. This beam has 14 MA and MC hits

This beam has 14 MA and MC hits

This beam has 11 MA and MC hits

Figure 55 shows the received power of interrogations comprising the longest continuous beam detected during the approach to site 8225 on Day 2. This sample occurred at 16:12:53 when N39 was approximately 3.3 nmi from site 8225. The hit count was 788 for this beam. The beam lasted for approximately 3.4 seconds. All interrogations were detected as 'unsuppressed' as no P2 pulse

was detected. Only 1 or 2 PRT's were missed in most cases, before another mainbeam was detected when in this area closer than 5 nmi of the site.

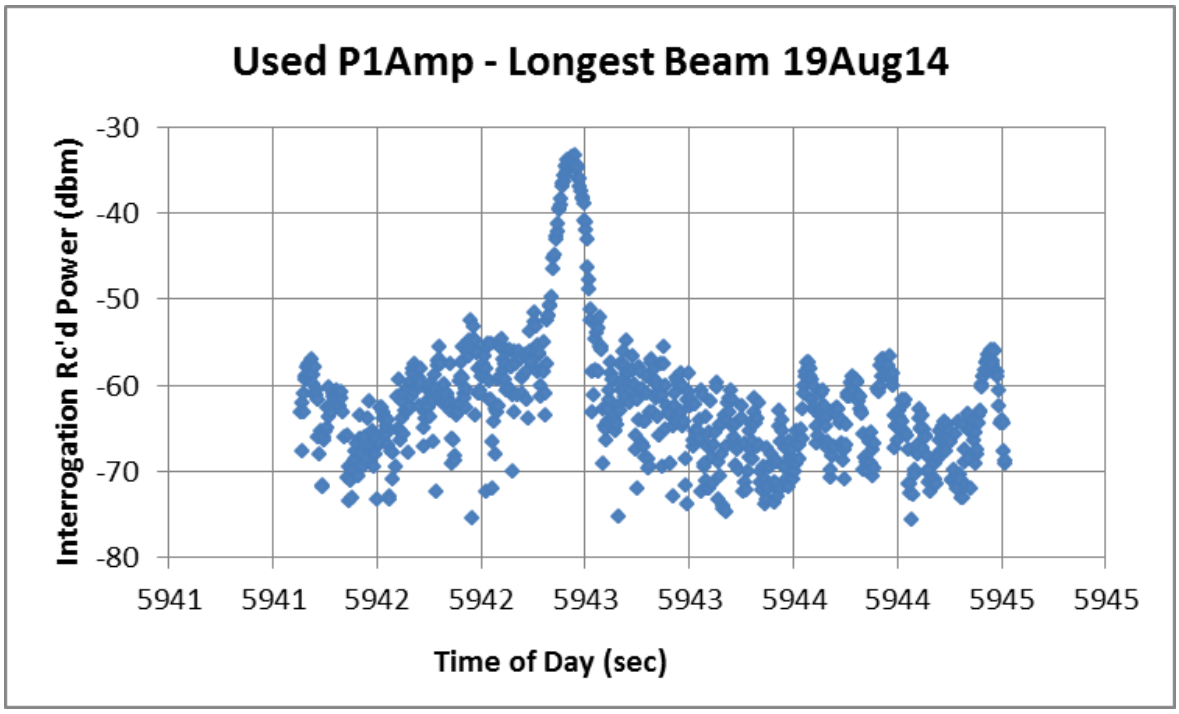
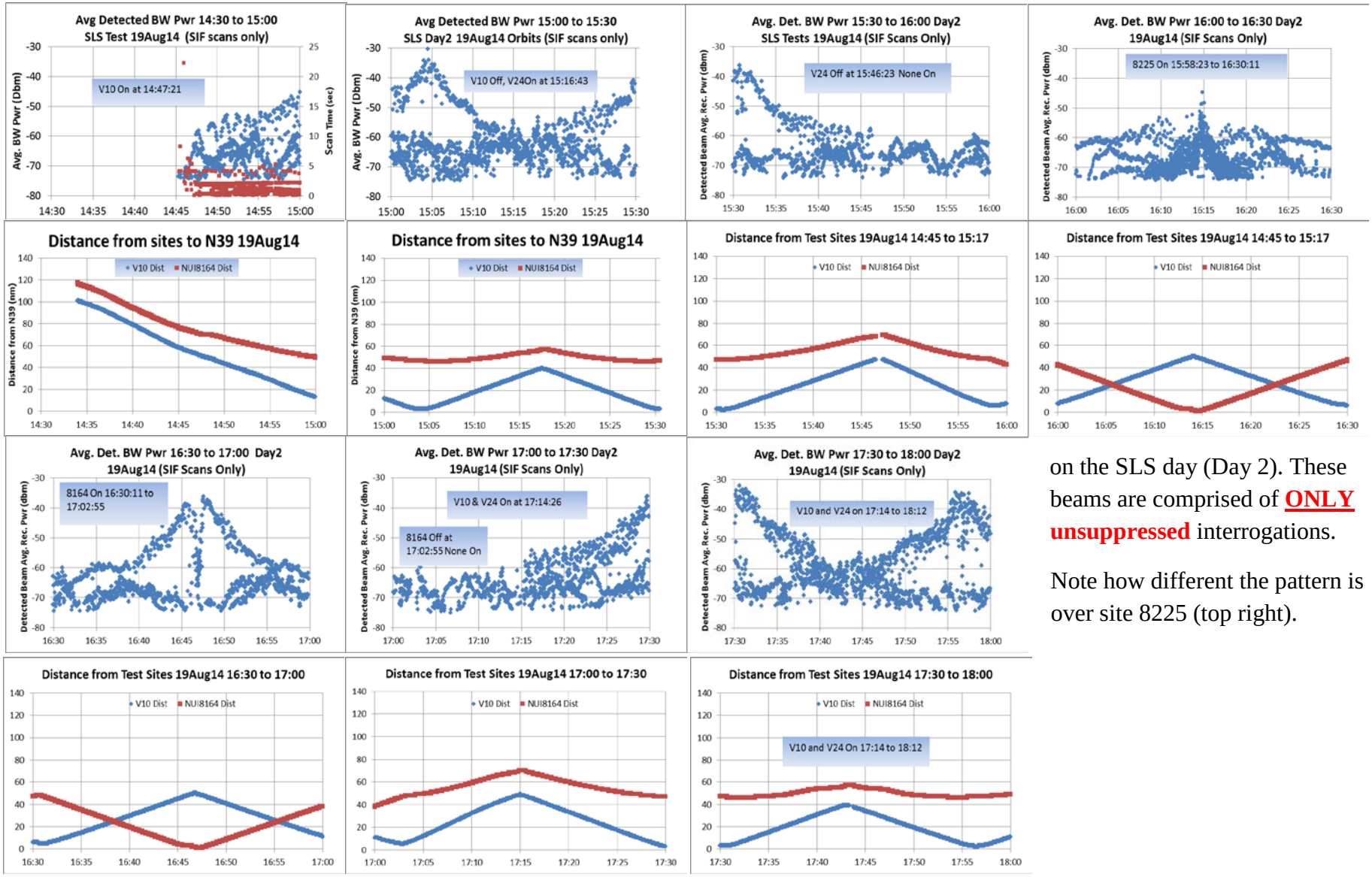


Figure 55. Used P1 Amplitude – Longest Beam from 8225 – Day 2

Plots from Day 2 (SLS Test Flight) These plots show the average power of mainbeams detected while passing over the respective sites



on the SLS day (Day 2). These beams are comprised of **ONLY unsuppressed** interrogations.

Note how different the pattern is over site 8225 (top right).

A.2.4 1030 MHz – Sidelobe Suppression Characteristics, Test Site 8164

After the test of site 8225, N39 turned around to the east to fly west over the site designated as 8164. For this test, 8164 was the only site operating. Figure 56 shows a map of N39's flight path and the location of the test site. N39 was not permitted to fly past the site to the west, so both the approach and departure from the site is to the east.

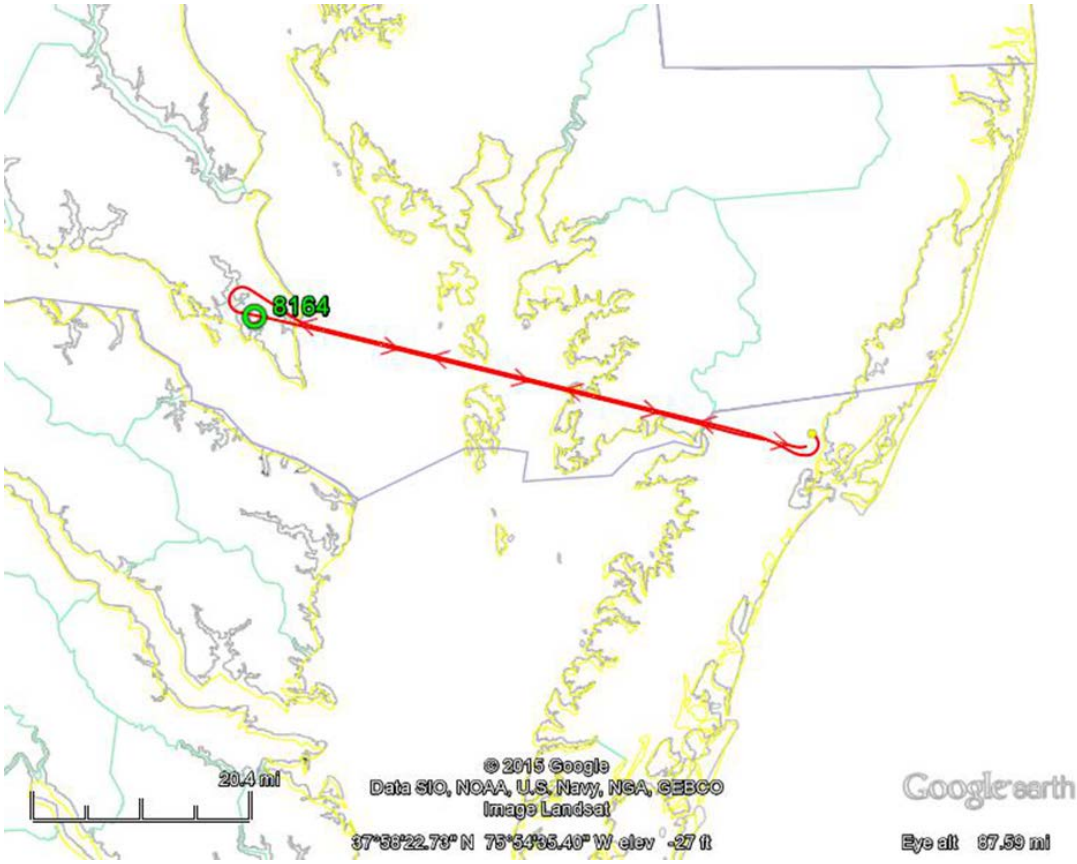


Figure 56. Day 2 – N39 Flight Path Over Site 8164

Figure 57 shows the transponder occupancy for the ATCRBS function of a Typical Mode A/C/S transponder measured from the test flight over site 8164. There is a distinct increase in occupancy within 15 nmi of site 8164 and peaking right over the site. The ATCRBS function's occupancy beyond the 20 nmi range is about 1.5% average and it peaks to about 3.5% average when right over the site. This occupancy increase (2%) is more than expected for a typical transponder based on the specifications of the AN/UPX-41(C) system.

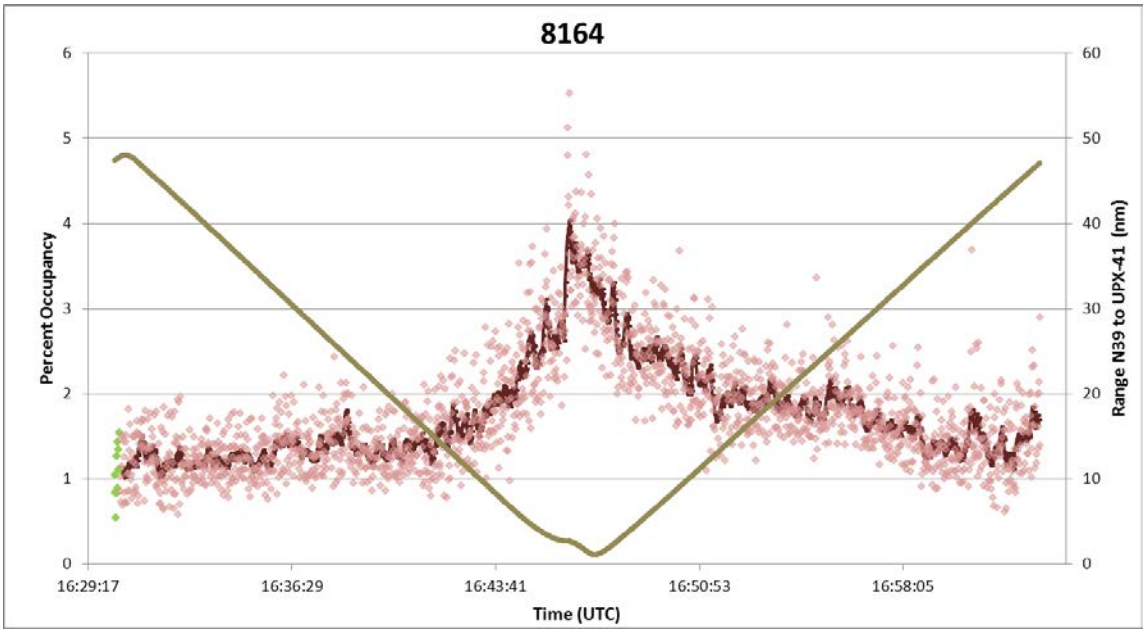


Figure 57. ATCRBS Transponder Occupancy, SLS Test of Site 8164

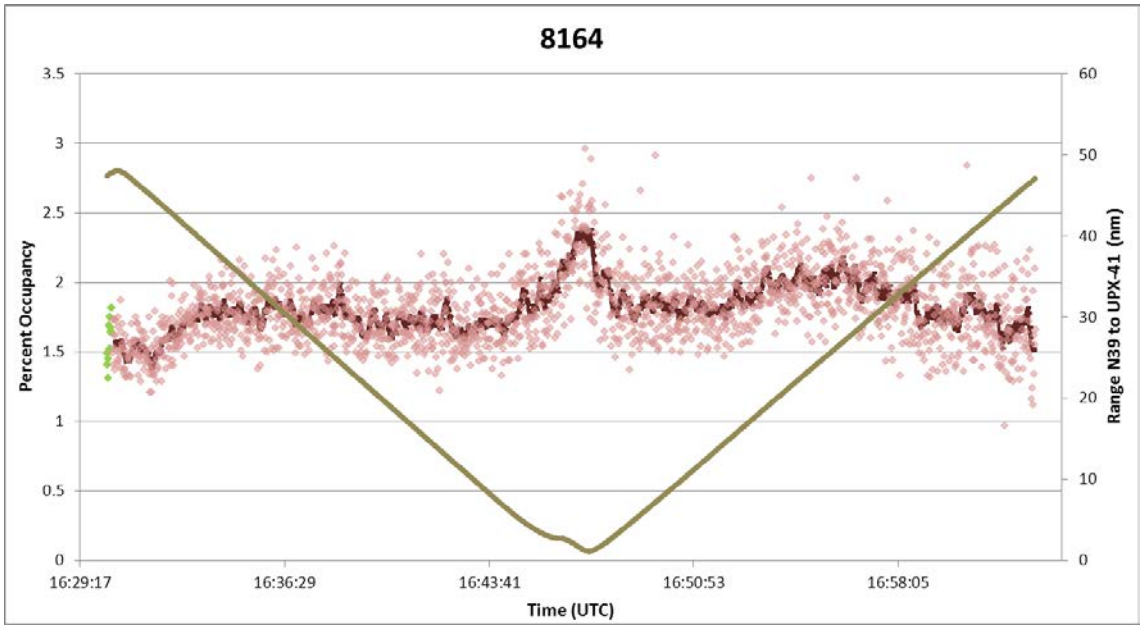


Figure 58. Mode S Transponder Occupancy, SLS Test of site 8164

Figure 58 shows the transponder occupancy for the Mode S function of a Typical Mode A/C/S transponder measured from the test flight over site 8164. The occupancy is mostly constant but there is brief approximate .5 % average increase right over the site. This is most likely from an increase in ATCRBS replies that may be due to the vertical proximity to the site affecting SLS or some other cause. ATCRBS replies are examined after the SLS rate analysis.

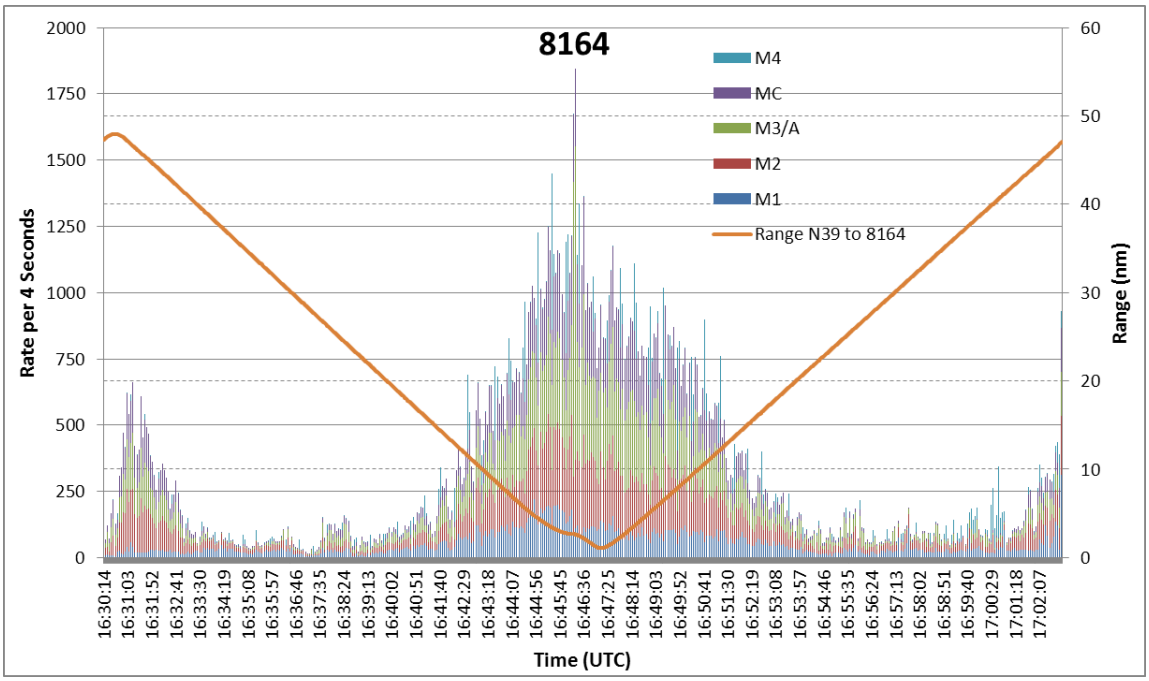


Figure 59. Detected Suppressed Interrogation Rates from the SLS Test of Site 8164

Figure 59 shows a stacked color-coded graph showing the detected rate of the various types of suppressed interrogations. These are the total received that were detected per 4-seconds when the aircraft's on-board transponder receiver wasn't otherwise occupied. If an aircraft is near enough to an interrogator to be completely in a sidelobe pattern with the 250 PRF, there could be as many as 250 suppressions per second for each type, although likely fewer as some interrogations will be from the mainbeam and trigger replies. With site 8164, this generally looks to be the case since the Mode 1 (blue) color band approaches 250, the Mode 2 (red) approaches 500, the Mode 3/A (green) approaches 750 and the Mode C (purple) approaches 1000. However there is a brief period of time just prior to the bottom of the range curve where the suppressions total more than 1750. The reason for this spike in suppression rate is discussed in the following paragraphs.

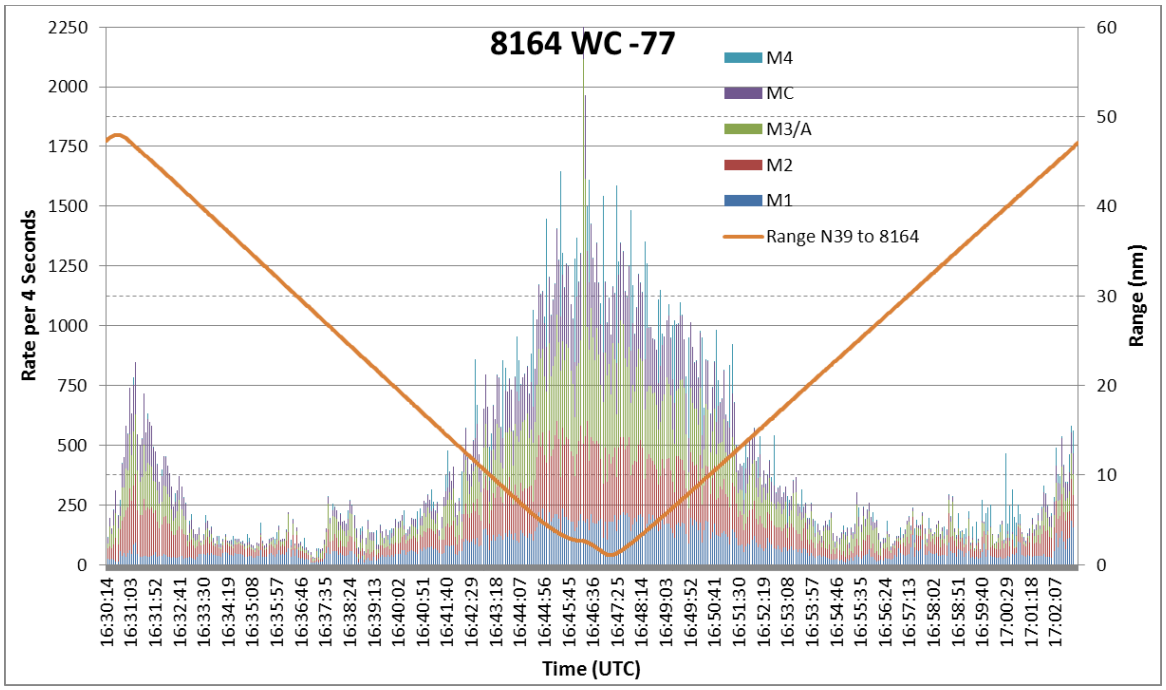


Figure 60. Detected Suppressed Interrogation Rates from the SLS Test of Site 8164 Worst Case

Figure 60 shows another stacked bar graph of suppressed interrogations. In this case, the detection process was modified to potentially expand the suppression range by maximizing the receiver SLS pulse acceptance characteristics. The intent was to show the potential worst-case impact of the AN/UPX-41(C) system's SLS. For this test, the receiver sensitivity was reduce by 1 dB to -77 dBm and the P1 to P2 pulse ratio was lowered to accept a P2 suppression when the power is -8 dB or greater relative to P1. Normally this is set to -4dB or greater. This test did not appear to expand the SLS range of the site. It just increased the number of suppressions detected within the same range of about less than 20 nmi. This "worst-case" test was applied to the data from the 8164 site because it had the best test conditions of the four individual LBTS tested.

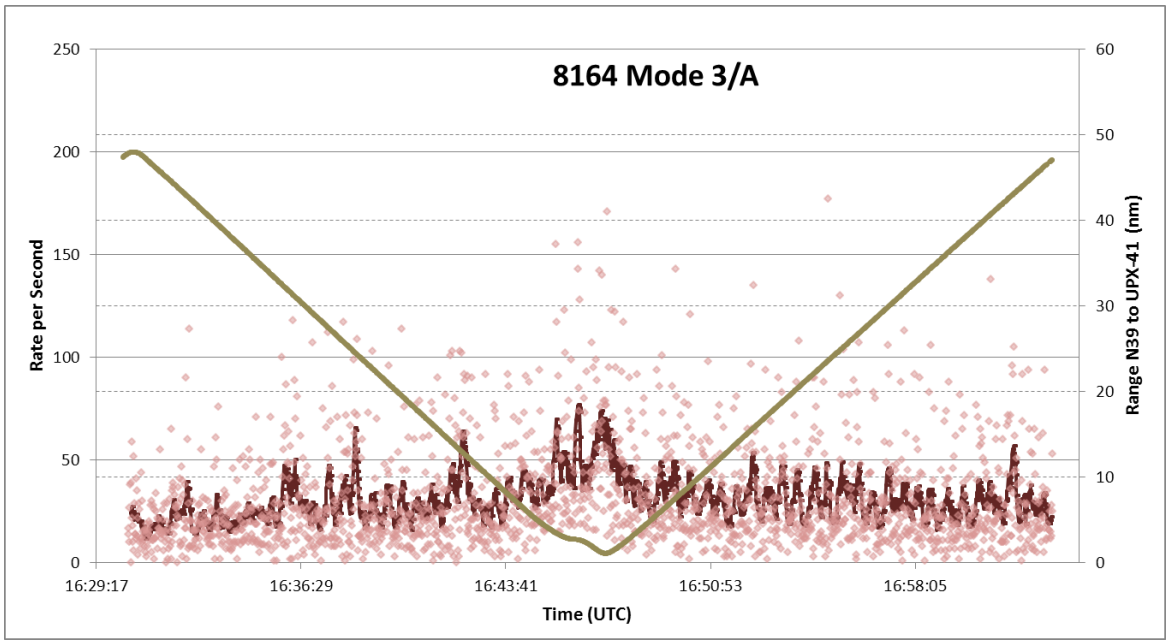


Figure 61. Mode 3/A Reply Rate from SLS Test Flight of Site 8164

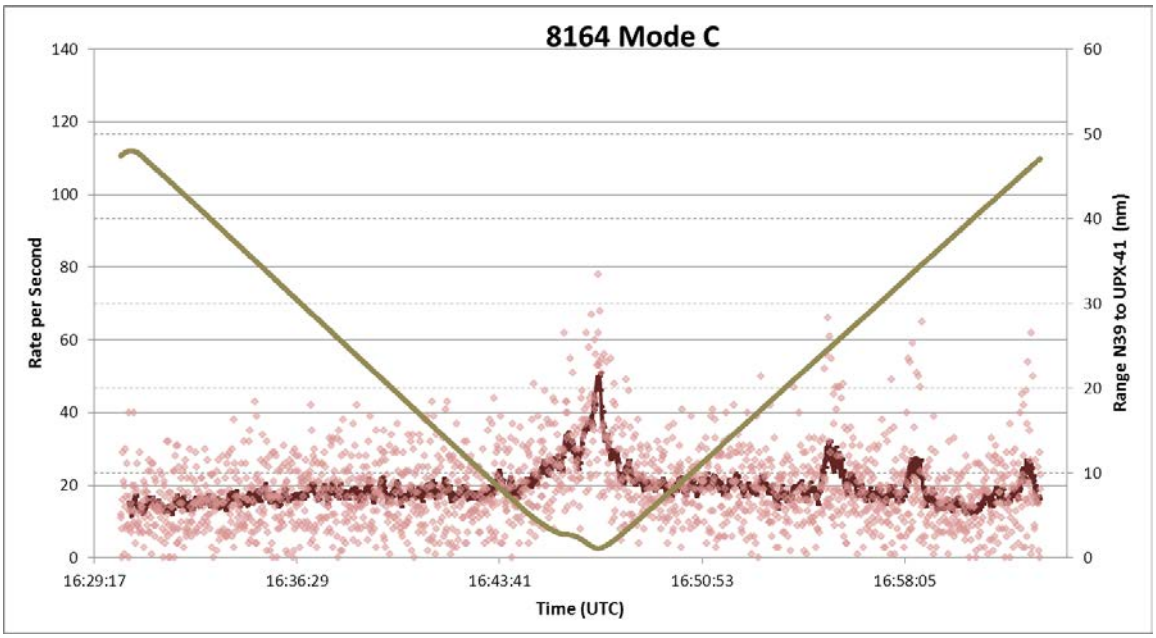


Figure 62. Mode C Reply Rate from SLS Test Flight of Site 8164

The Mode 3/A and Mode C reply rates are shown in Figure 61 and Figure 62, respectively. The ten second average reply rates for both modes are generally the same for the duration of the test, about 20 per second for Mode C and slightly higher for Mode 3/A, but for both modes there is a lot of variation. There is an indication, especially in the Mode C plot, that there was a brief increase in replies when nearest to the interrogator. When considering the Y-axis scale, the Mode 3/A reply rate may have even a greater rate increase. This may be an indication that the P1 to P2

ratio is somewhat affected by vertical antenna pattern when nearly right above the site. There may also be some mainbeam activity from some other interrogator, as the next series of plots show significant burst of Mode 3/A suppressions measured from this test.

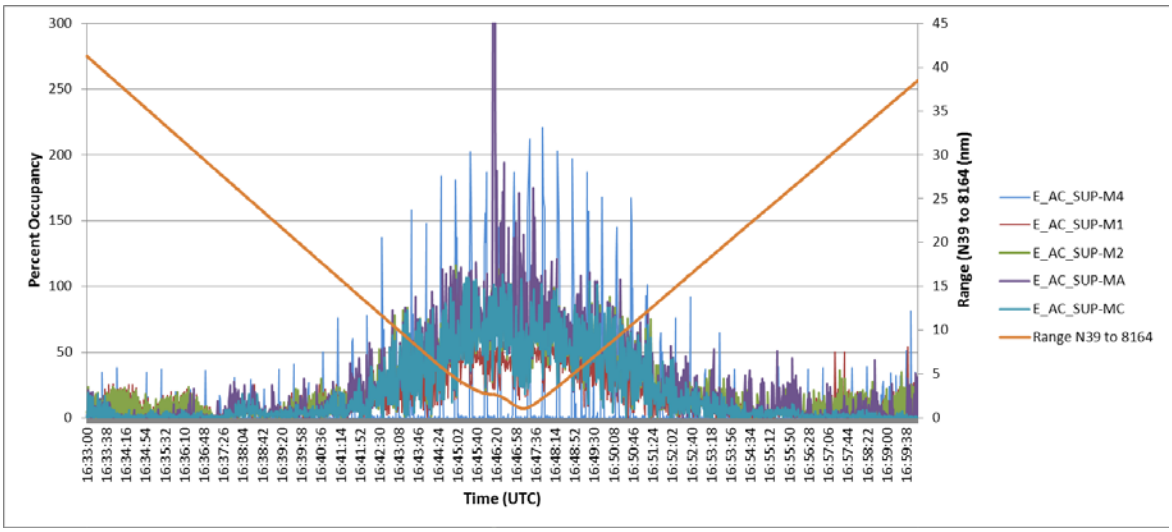


Figure 63. Detected Suppressed Interrogation Rates from the SLS Test of Site 8164, Line Graph

Figure 63 shows an alternative view of the rate of various types of suppressions detected with the test of site 8164. This type of plot was chosen while investigating the extra high spike in suppressions detected when near the interrogator. This view shows that the source of the spike in suppressions is predominantly suppressed Mode 3/A interrogations. In one second of the data, at 16:43:13, there were 350 detected suppressed Mode 3/A interrogations. The following graphs examine these suppressions further.

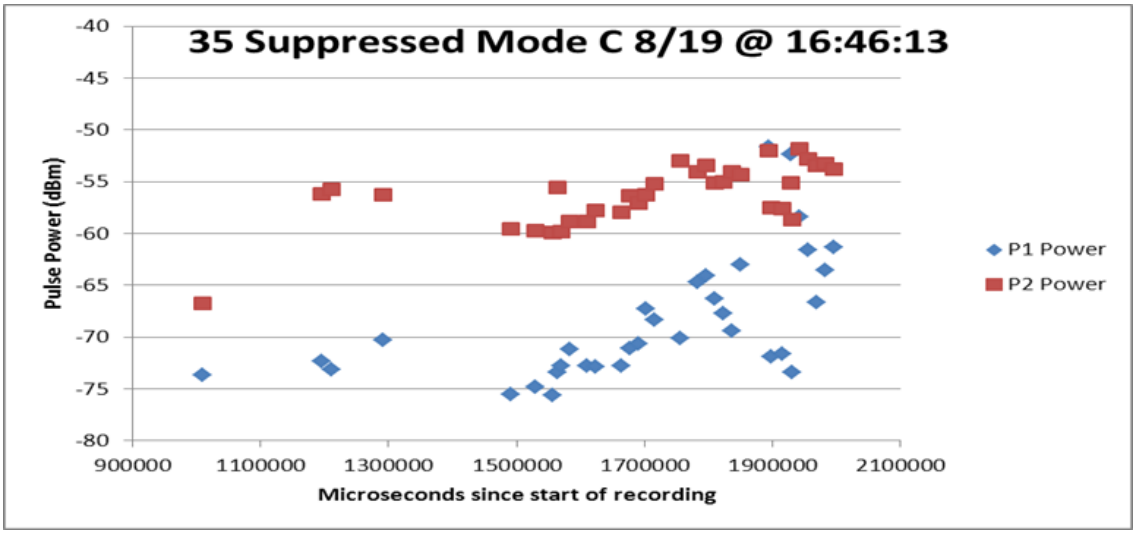


Figure 64. Distribution of Suppressed Mode C Interrogations at 16:46:13 UTC

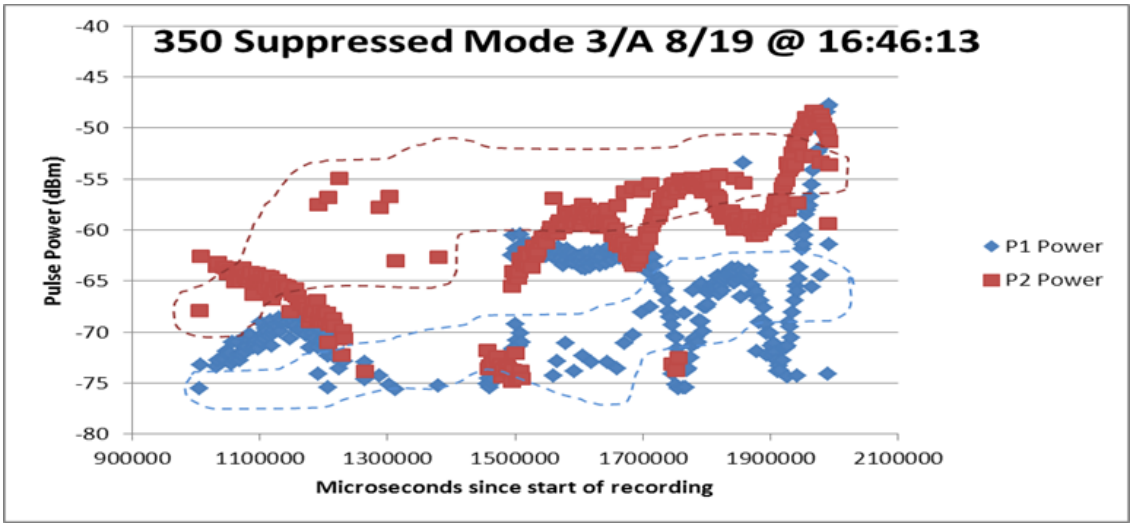


Figure 65. Distribution of Suppressed Mode 3/A Interrogations at 16:46:13 UTC

Figure 64 and Figure 65 show the distribution of suppressed Mode C interrogations and suppressed Mode 3/A interrogations from the test of site 8164 during the one second interval at 16:46:13. The P1 power (blue) and P2 power (red) are plotted. In the one-second interval there were 350 Mode 3/A suppressions and only 35 Mode C suppressions. The Mode C suppressions were determined to be from site 8164 and some of the Mode 3/A suppressions appear to be as well. They are circled with the dashed lines and have a similar pattern as the Mode C suppressions. The additional Mode 3/A suppressions are received at a much higher rate.

In reference to Figure 57 there was a higher than expected increase in transponder occupancy of about 2% average measured flying over site 8164. The additional suppressions from the unknown source contributed to the additional occupancy rate. For the one-second interval examined above, the 350 Mode 3/A suppressions caused over 1.4% transponder occupancy.

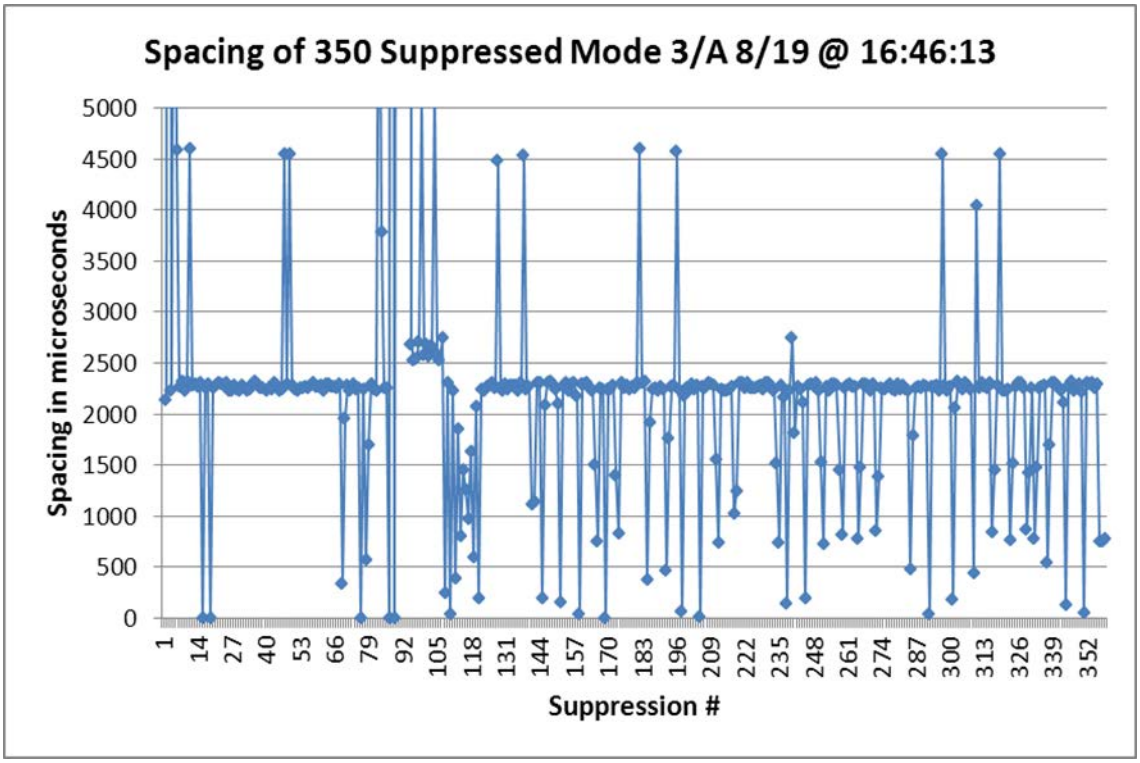


Figure 66. Mode 3/A Suppression Spacing from 16:46:13

Figure 66 shows the spacing in microseconds of the 350 Mode 3/A suppressions detected at 16:46:13. Most of the 350 Mode 3/A suppressions are spaced at about 2.25 milliseconds which equates to 444 PRF. The AN/UPX-41(C) system was built to interrogate at 250 PRF.

Investigation of the interrogations during 1 second (16:46:13) on SLS Day 2

Refer to Figure 64, Figure 65, and Figure 66 for the analysis that prompted this investigation. They showed that there were 350 suppressed Mode A interrogations in a single second. The investigation started by processing the time period from 16:30 to 17:00 on Day 2 with all known interrogators that used only Mode A interrogations. The earlier analysis had already shown that there was not an increase in Mode C interrogations during this second. Figure 67 shows the received amplitudes of several interrogators overlaid.

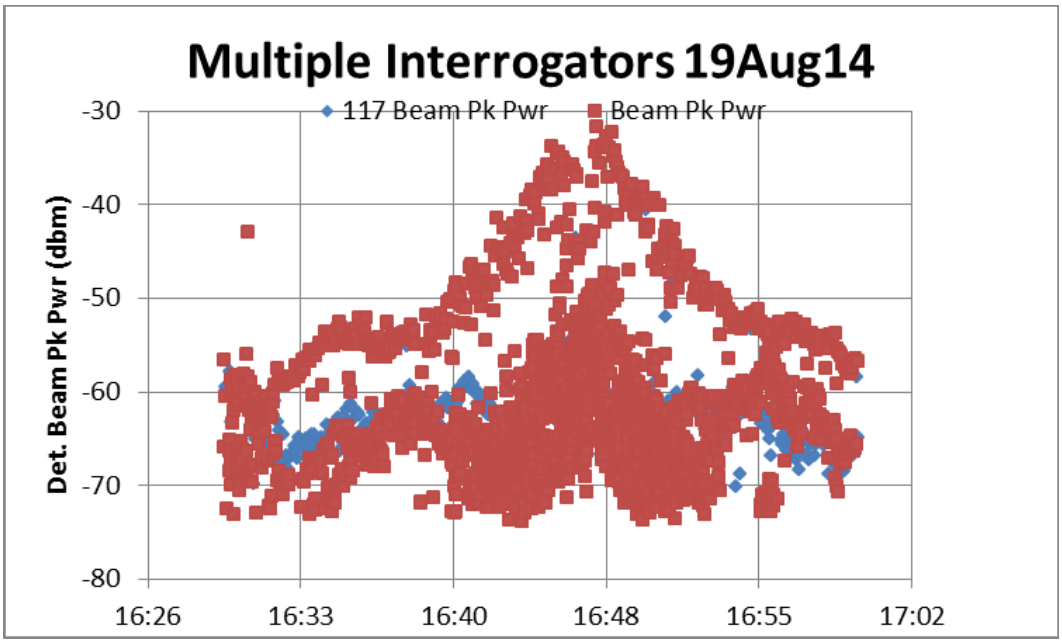


Figure 67. Multiple Interrogators detected beams overlaid – Day 2

The interrogators shown are (red) site 8164, (blue) Radar 117, and Radar 70. Site 8164 is the AN/UPX-41(C) system, so, its PRF is 250 and interlace pattern is 1,2,A,C. Radar 117 is a radar with a PRF of 298.5 and an interlace pattern of 2,A,C. Radar 70 has a PRF of 383.9 and has only Mode A interrogations. This process was going nowhere, so we started over. Table 17 gives the count of all interrogation types in the entire file as well as the single second.

Table 17. Interrogation count by type – Day 2 16:30-17:00

Interrogation type	Count in file 16:30 to 17:00	Count in second 16:46:13
Mode 1 with P2 Unsuppressed	4578	0
Mode 2 with P2 Unsuppressed	4468	0
Mode A with P2 Unsuppressed	4186	82
Mode C with P2 Unsuppressed	2841	9
Mode 1 with P2 Suppressed	24356	36
Mode 2 with P2 Suppressed	31687	36
Mode A with P2 Suppressed	39573	334
Mode C with P2 Suppressed	34091	32

The data was searched for another possible interrogator that used an all Mode A interlace. The results were assigned to Radar 72 in our PRT database. This interrogator has an average PRF of 449.4 interrogations per second (all Mode A). Processing the entire 30 minute period for this interrogator yielded the data shown on Figure 68.

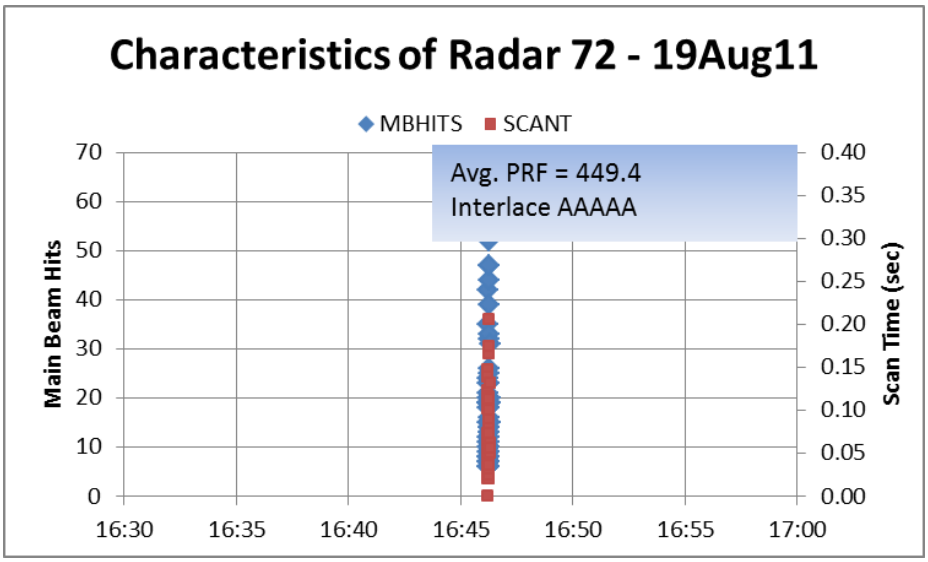
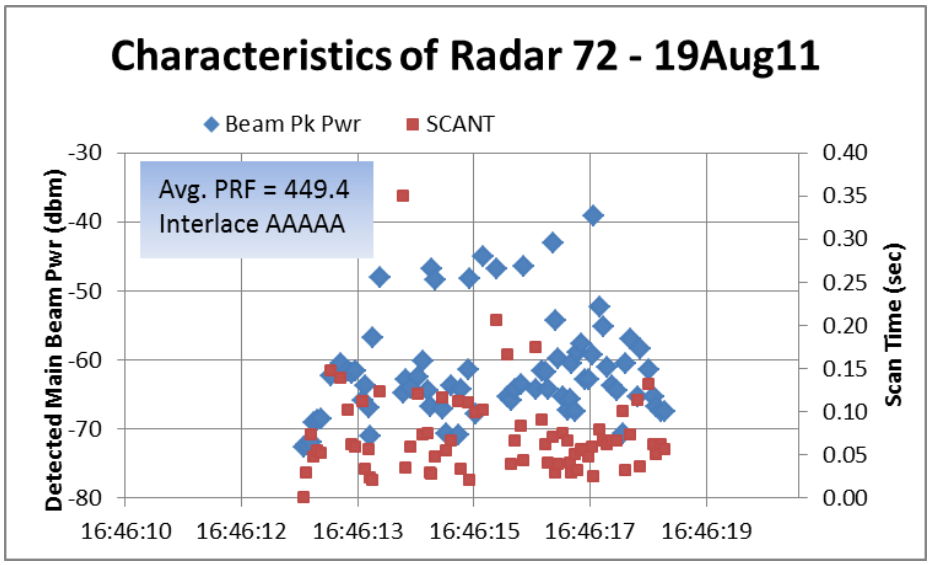


Figure 68. Detection of Radar 72 during 16:30 to 17:00 – Day 2

Figure 69 shows an expanded view of the detection of Radar 72. It is only detected for about 6 seconds. The peak amplitudes are very much like those of site 8164. It seems likely that site 8164 is the source of these interrogations in some other mode.



Int Type	Count
M1_	0
M1p2_	0
MA_	14
MAp2_	48
MC_	0
MCp2_	0
M1P2S	0
M2P2S	0
MAP2S	183
MCP2S	0

Figure 69. Expanded Detection of Radar 72 during 16:30 to 17:00 – Day 2

The table to the right shows the count of the various interrogation types from Radar 72 during it detection period. A total of 183 Mode A suppressions accompanied 62 interrogations that would have produced Mode A replies during the six seconds that Radar 72 was detected, it provided an average of 202 suppressions per second.

A.2.5 1030 MHz – Sidelobe Suppression Characteristics, Test Site Combination V-10 & V-24

After the test of site 8164, N39 turned to fly two passes over sites V-10 and V-24 while both were operating. Figure 70 shows a map of N39's flight path and the location of the LBTS.

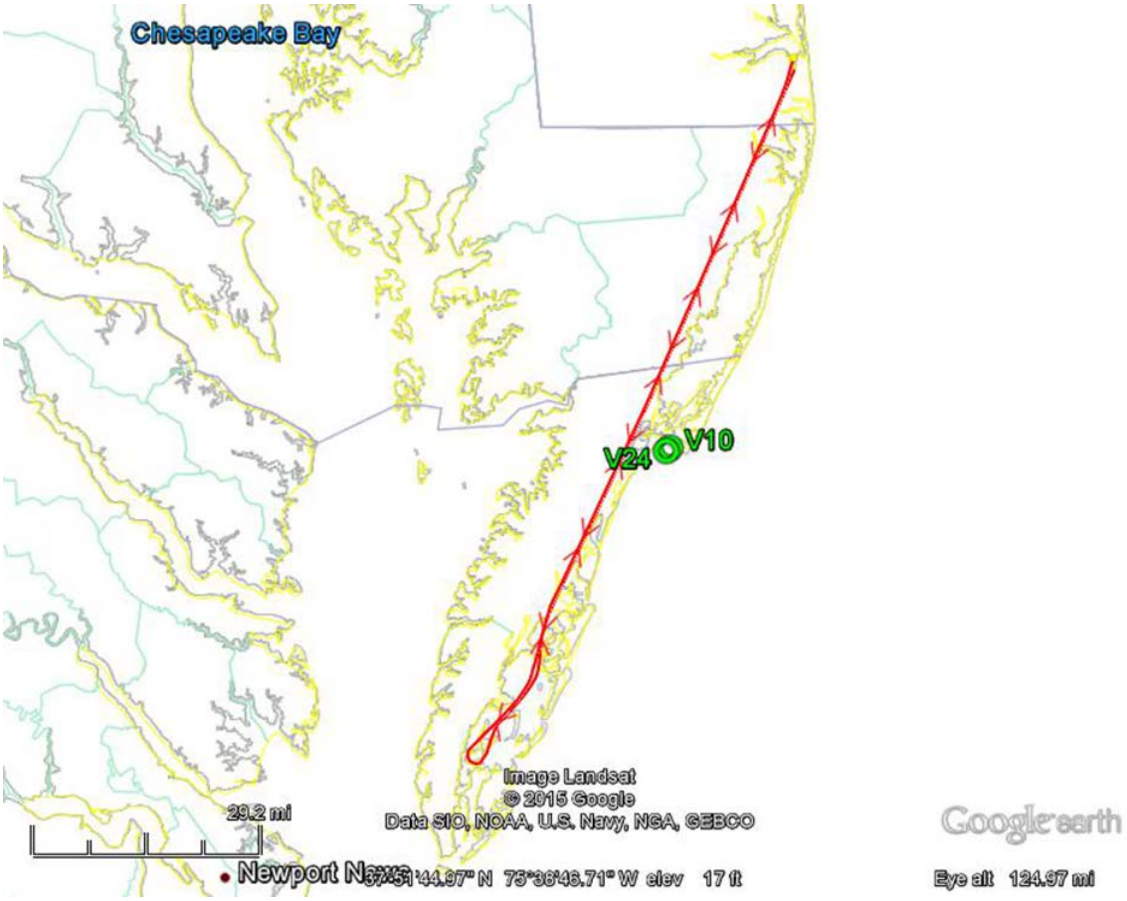


Figure 70. Day 2 – N39 Flight Path Over Sites V-10 and V-24

Figure 71 shows the transponder occupancy for the ATCRBS function of a Typical Mode A/C/S transponder measured from the test flight over sites V-10 and V-24. There is a distinct increase in occupancy within about 20 nmi of the LBTS and peaking right over the sites. The ATCRBS function's occupancy beyond the 20 nmi range is about 1.5% average and it peaks to about 3.5% to 4% average when right over the sites. This occupancy increase (2%+) is about what is expected for two AN/UPX-41(C) systems.

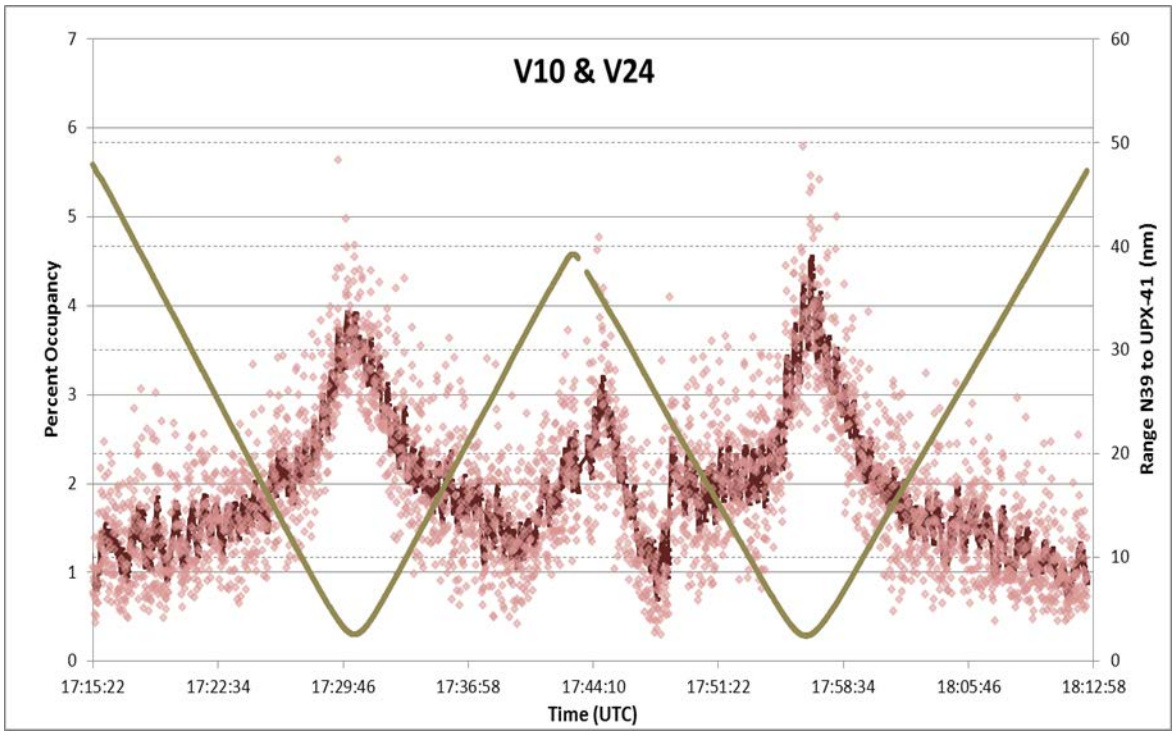


Figure 71. ATCRBS Transponder Occupancy, SLS Test of Sites V-10 and V-24

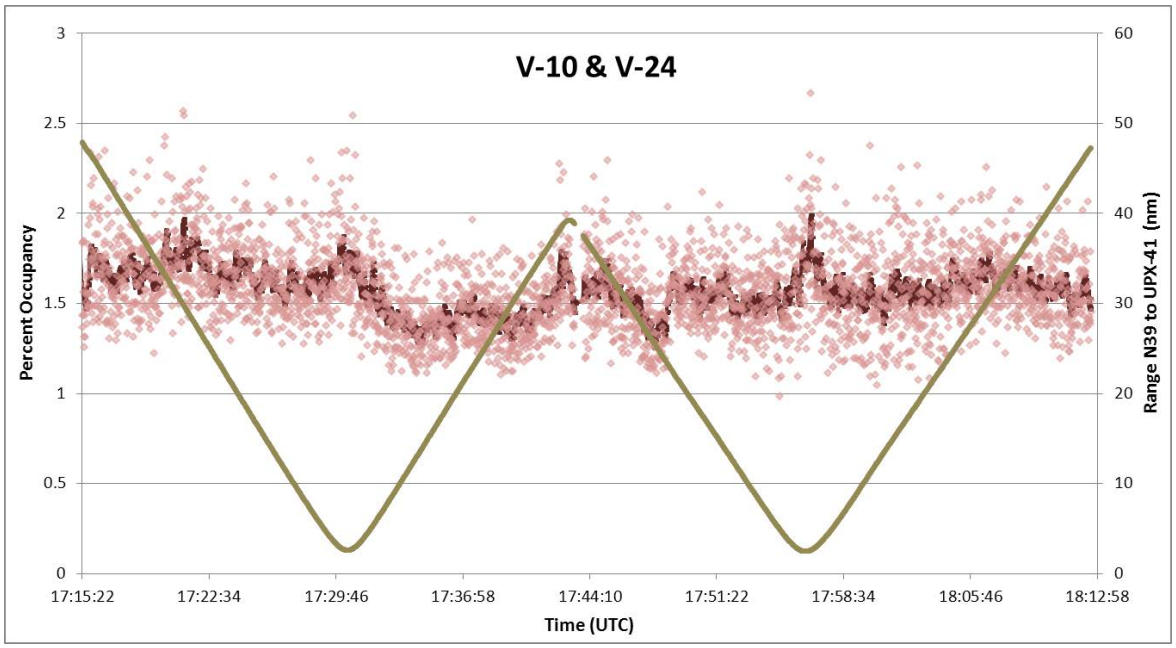


Figure 72. Mode S Transponder Occupancy, SLS Test of Sites V-10 and V-24

Figure 72 shows the transponder occupancy for the Mode S function of a Typical Mode A/C/S transponder measured from the test flight over sites V-10 and V-24. The occupancy is mostly constant but there is some increase right over the sites similar to that recorded over the individual site tests.

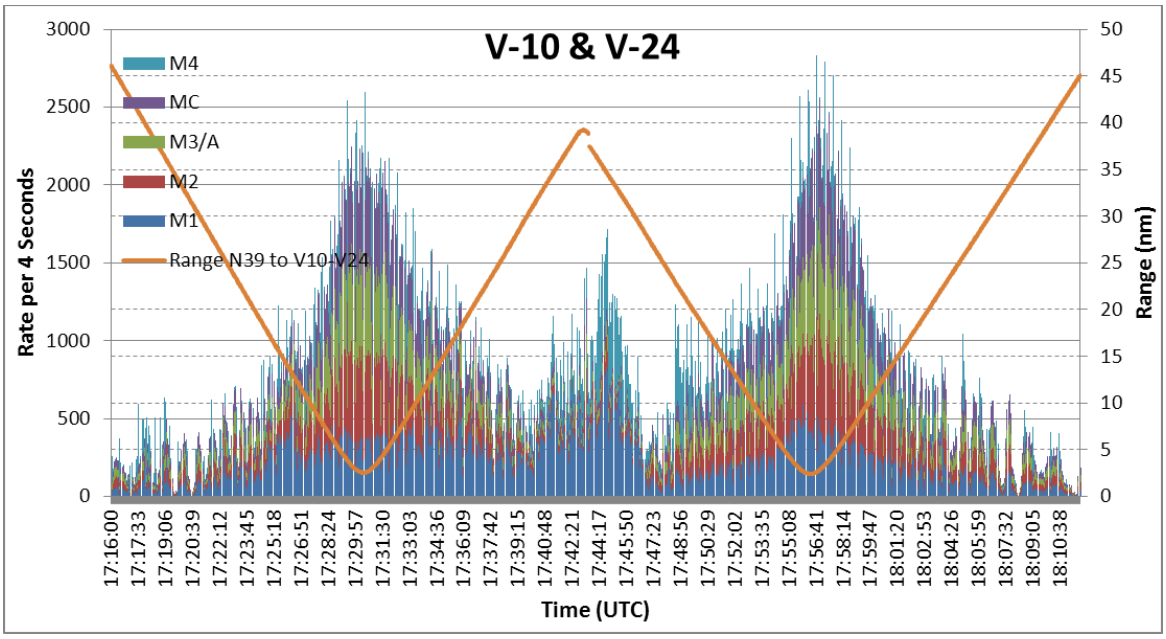


Figure 73. Detected Suppressed Interrogation Rates from the SLS Test of Sites V-10 and V-24

Figure 73 shows a stacked color-coded graph showing the detected rate of the various types of suppressed interrogations. These are the total received that were detected per 4-seconds when the aircraft's on-board transponder receiver wasn't otherwise occupied. When N39 is near enough to the LBTS to be completely in a sidelobe pattern with the 250 PRF each, there could be as many as 500 suppressions per second for each type. With the test of the combined V-10 and V-24 sites, this generally looks to be the case since the Mode 1 (blue) color band approaches 500, the Mode 2 (red) approaches 1000, the Mode 3/A (green) approaches 1500 and the Mode C (purple) approaches 2000. The extra suppressions that were detected when these two sites were tested individually appear to be gone. That is evident in the fact that the measured suppression rates with both sites operating are as expected.

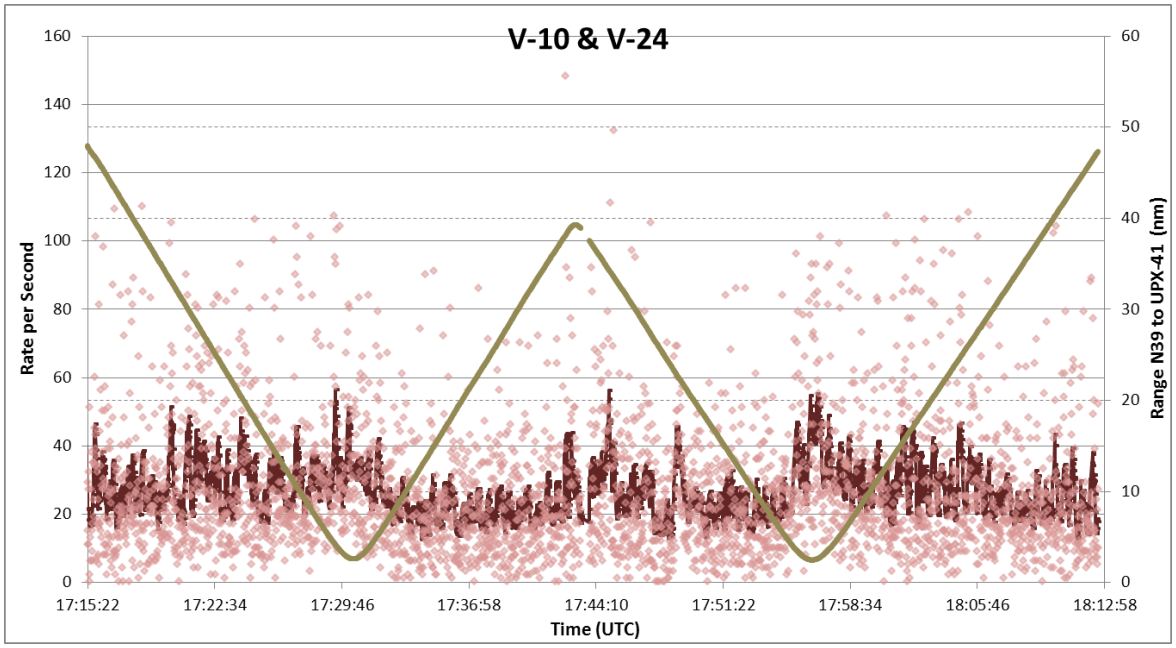


Figure 74. Mode 3/A Reply Rate from SLS Test Flight of Sites V-10 and V-24

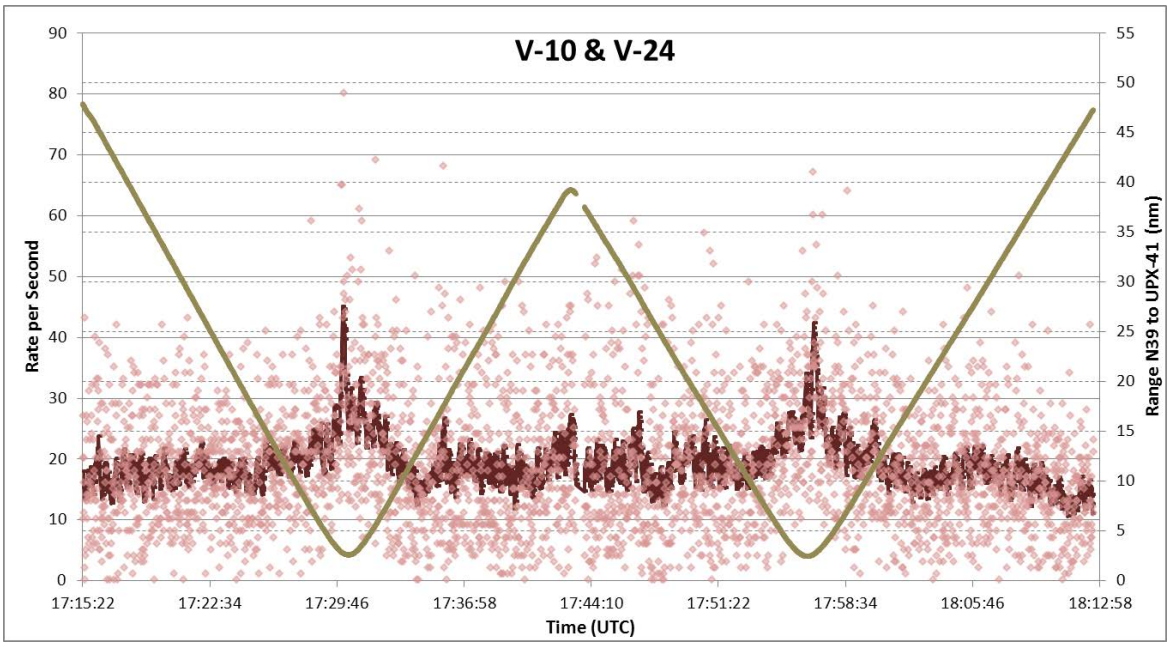


Figure 75. Mode C Reply Rate from SLS Test Flight of Sites V-10 and V-24

The Mode 3/A and Mode C reply rates are shown in Figure 74 and Figure 75, respectively. The ten second average reply rates for both modes are generally the same for the duration of the test, about 20 per second for Mode C and slightly higher for Mode 3/A but for both modes there is a lot of variation. There is an indication, especially in the Mode C plot that there was a brief increase in replies when nearest to the interrogators. Like the individual site tests, this may be an

indication that the P1 to P2 ratio is somewhat affected by vertical antenna pattern when nearly right above the sites.

Investigation of Suppression Counts of V-10 and V-24 Alone and Together

One of the first new interrogators seen in the AN/UPX-41(C) system data was a fixed PRT of 4017.1µs. This interrogator was added to the existing PRT database as Radar 43. The plots below show the characteristics. Figure 76 shows the peak beam received power and scan time. Figure 77 shows the number of hits in the detected beams and the number of suppressions in those mainbeams as a function of time. All plots shown here for Radar 43 were developed using all interrogations (unsuppressed and suppressed). This interrogator has a fixed PRT of 4017.1µs and an interlace pattern of 2,2,A,A,C,C.

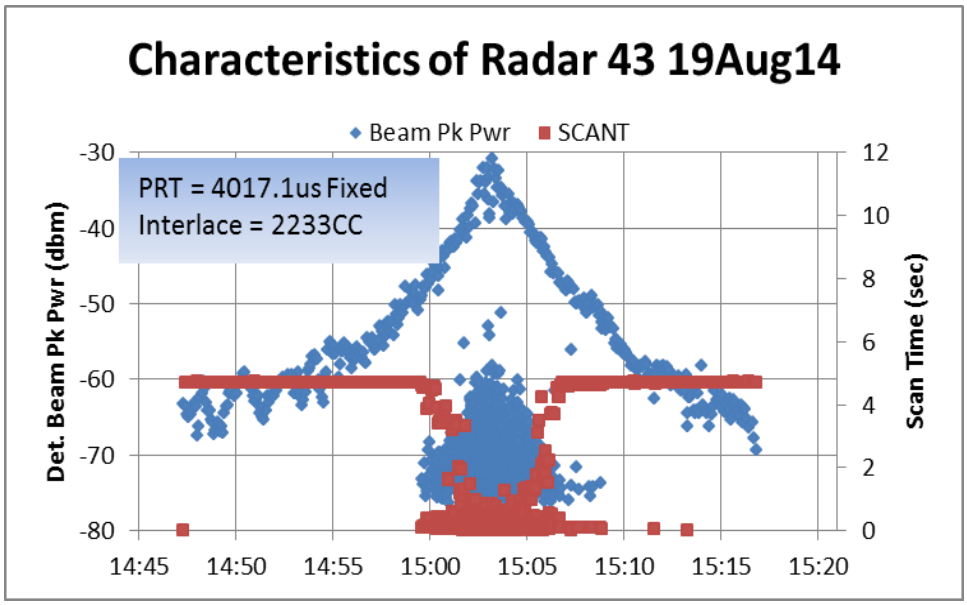


Figure 76. Detected Peak Beam Power and Scan time

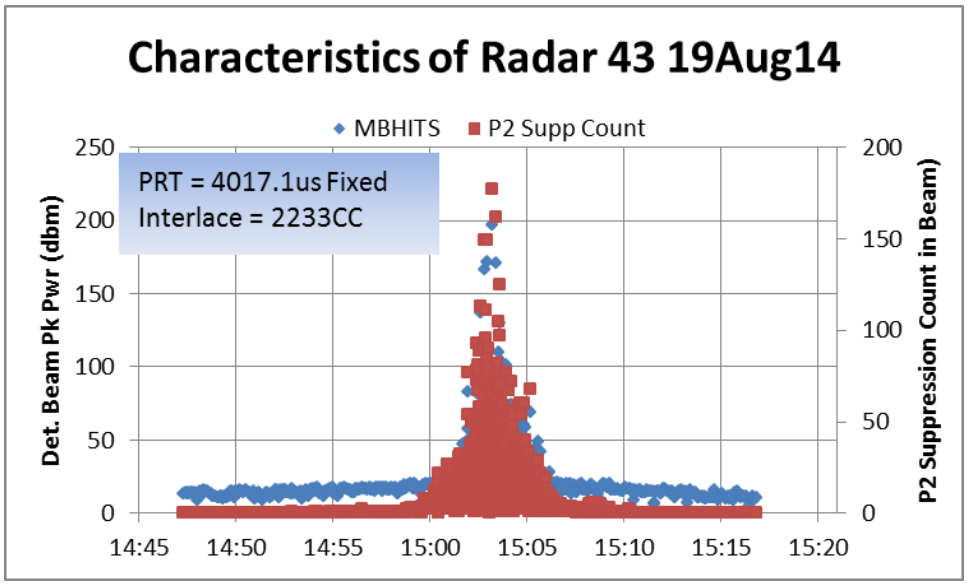


Figure 77. Detected Beam Power Suppressions per beam – 15:03

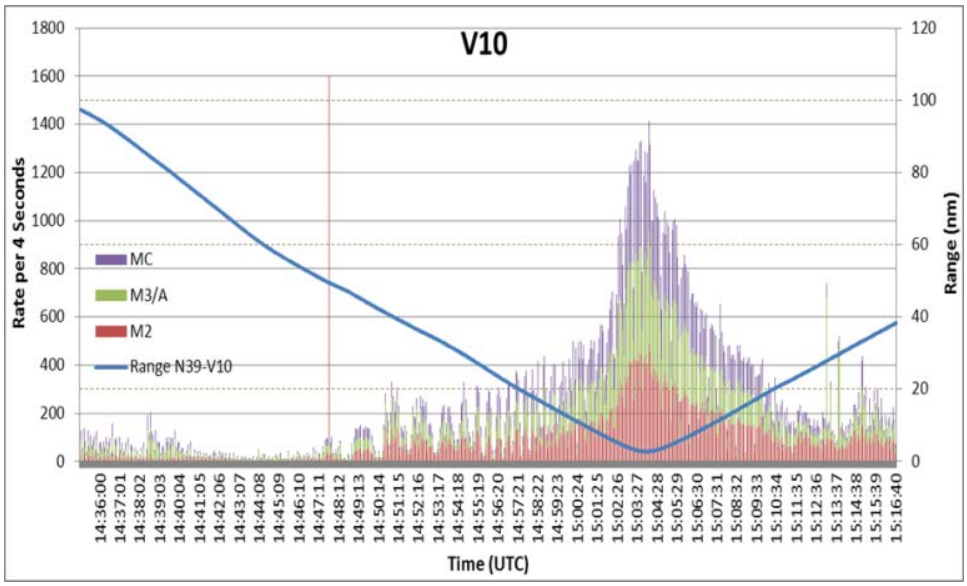


Figure 78. Mode 2, 3/A and C Suppression Rates from the Test Flight of Site V-10

Figure 78 shows the counts of suppressions as a function of Mode 2, A and C. Modes 1 and 4 were removed because there were so many that they obscured these modes. The source of them will be addressed below.

Figure 79 shows the average detected power of beams detected while flying over site V-10. The proximity of Radar 43 and its suppressions will definitely affect the counts when N39 flew over V-10.

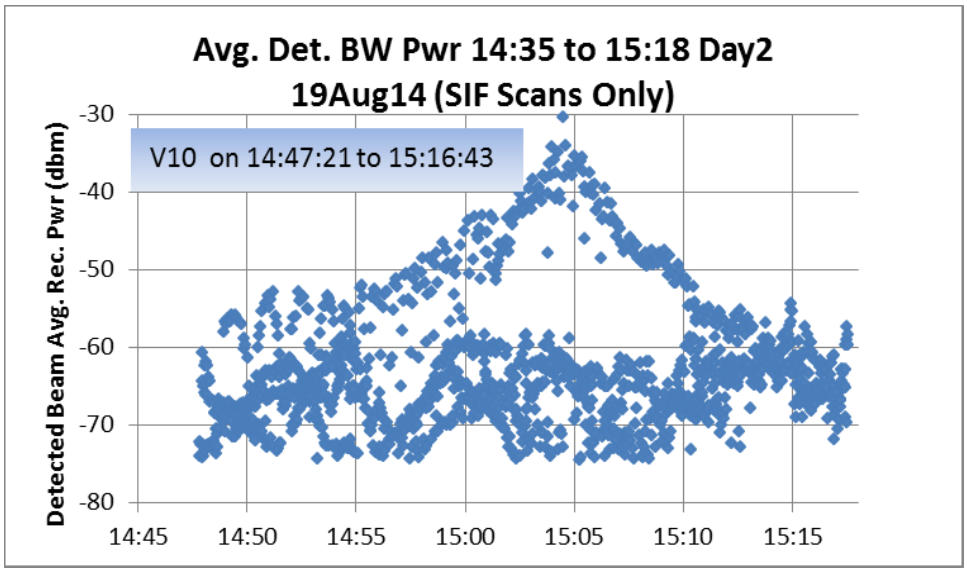


Figure 79. Average Detected Beam Width Power – Site V-10

Figure 80 shows the beam characteristics of Radar 43 when N39 flew directly over V-24 when it was transmitting alone. The data from Radar 43 looks almost identical to the pass at 15:03.

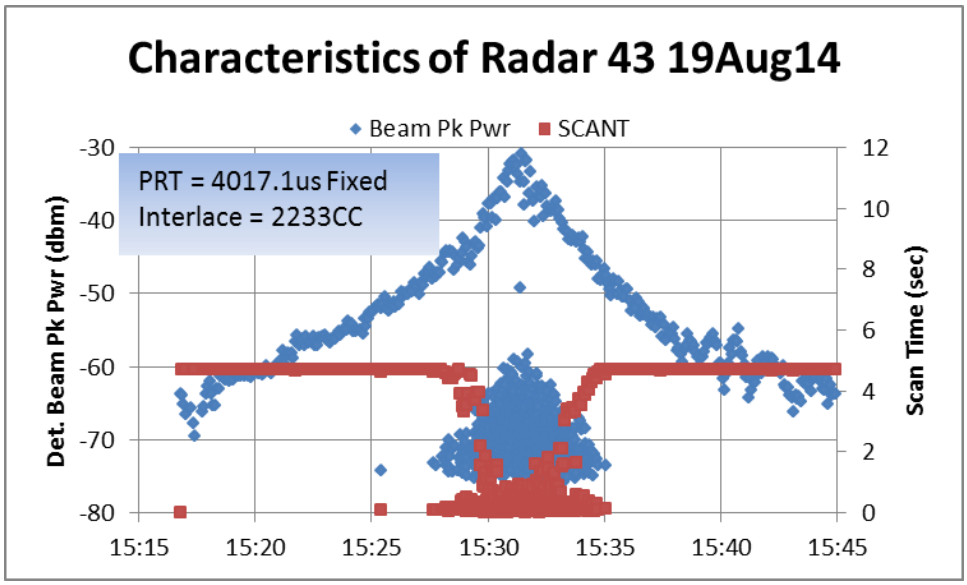


Figure 80. Detected Beam Power Suppressions per beam – 15:30

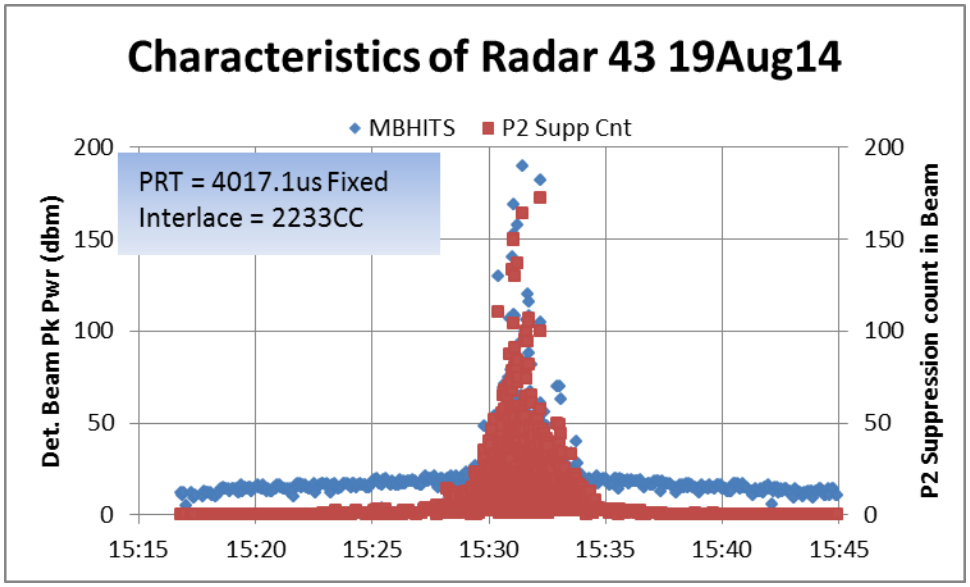


Figure 81. Detected Beam Power Suppressions per beam – 15:30

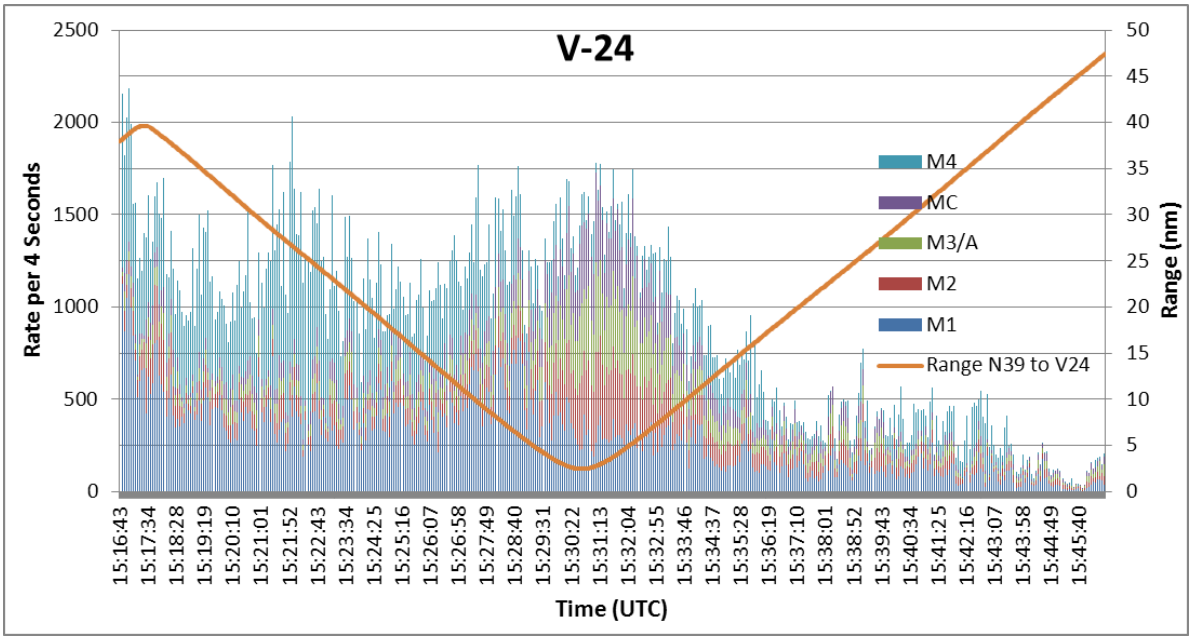


Figure 82. Detected Suppressed Interrogation Rates from the SLS Test of Site V-24

The Mode 1 and Mode 4 interrogations were left in for Figure 82. The Mode 1 interrogations were contributed by Radar 115. Figure 83 shows the detected beam power and scan time for this interrogator. This interrogator has at least two mode sequence patterns. One is all Mode 1's as shown here and the other is a pattern of 1,2,A,C. It only used 1,2,A,C for about 6 seconds starting at 15:16:43. It switched back to 1,1,1,1,1 after a beam of 151 hits.

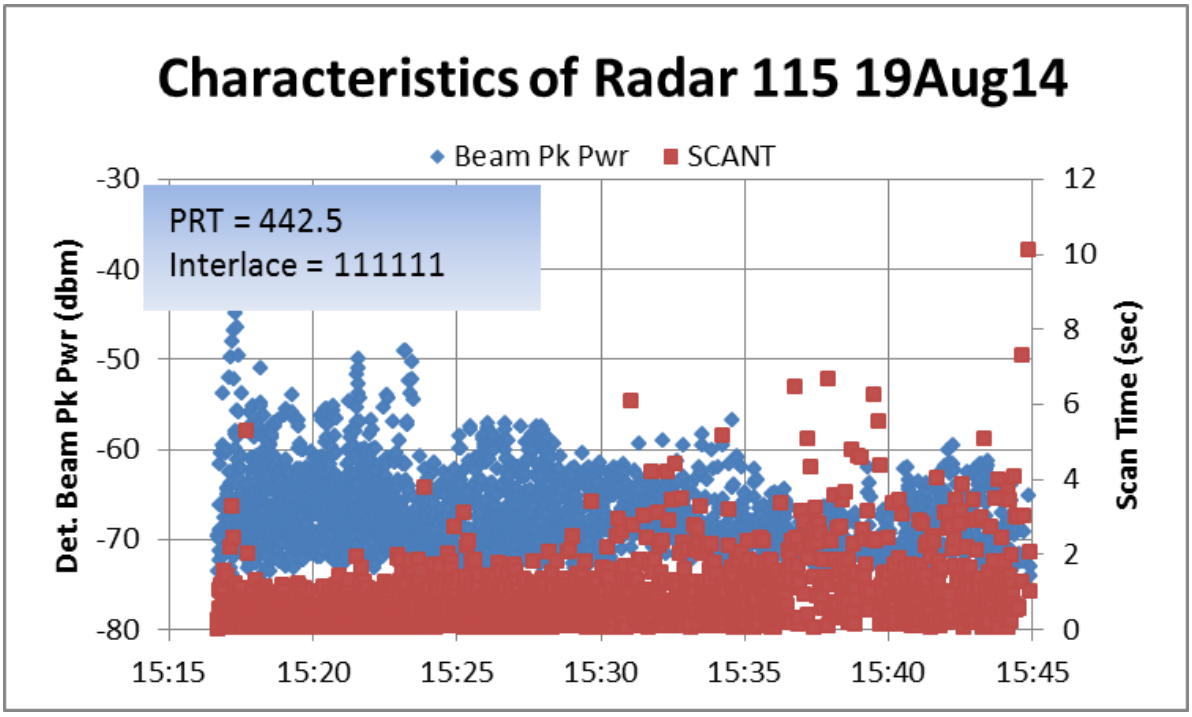


Figure 83. Detected Beams and scan time for Radar 115 – All Mode 1's

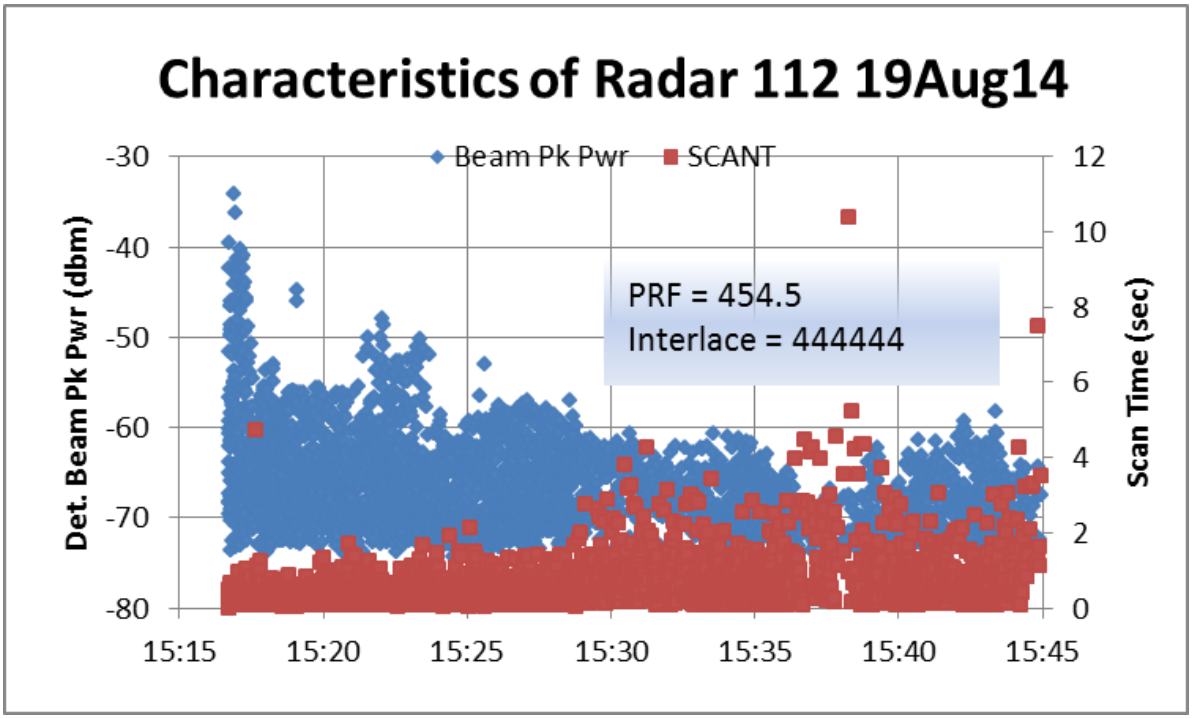


Figure 84. Detected Beams and scan time for Radar 112- All Mode 4

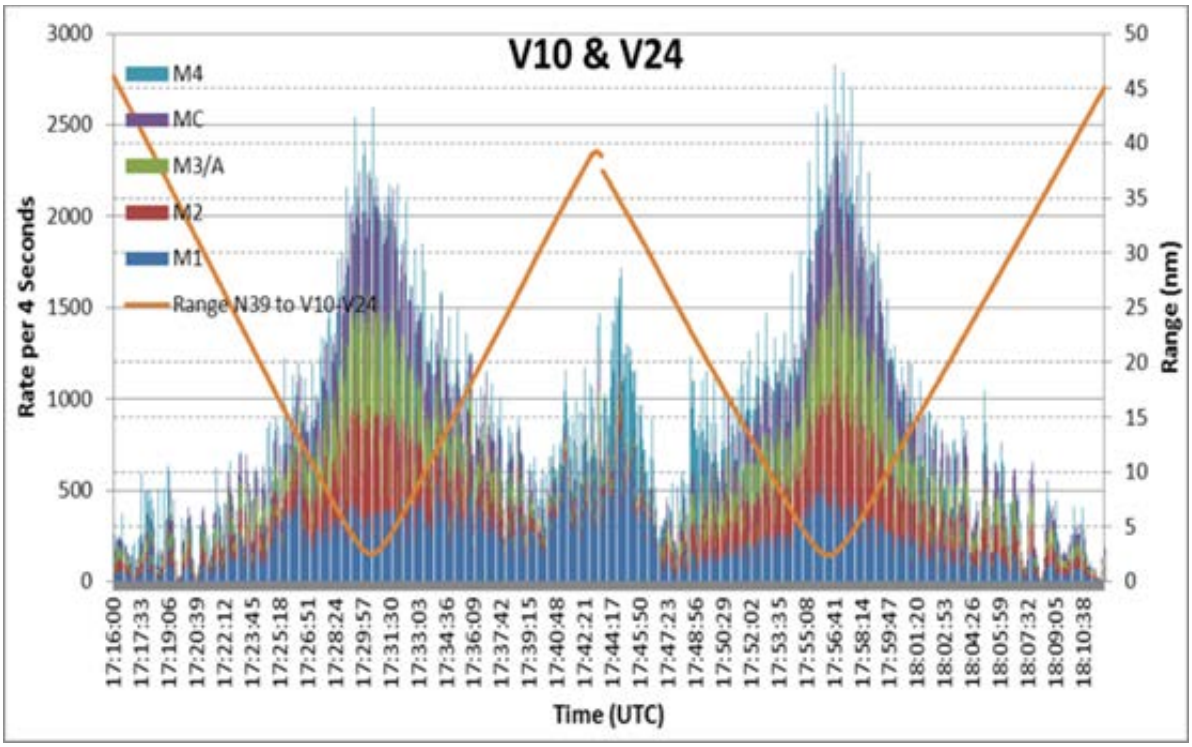


Figure 85. Detected Suppressed Interrogation Rates from the SLS Test of Sites V-10 and V-24

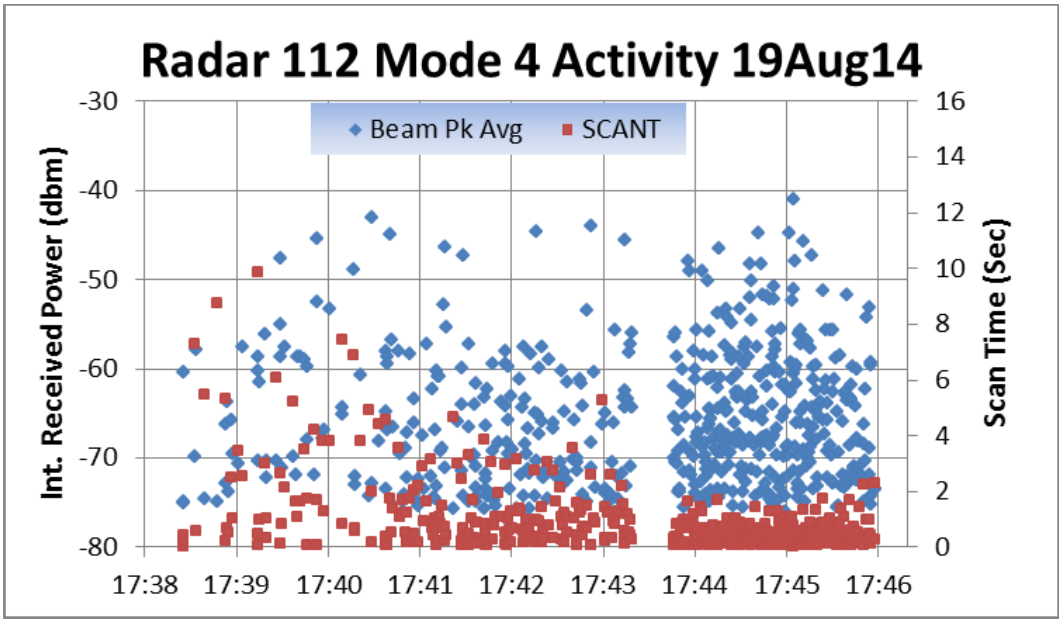


Figure 86. Mode 4 Activity when between V-10 and 24 when both are transmitting

There is similar activity from Radar 115 (All Mode 1 mode).

In order to see if Radar 43 is the source of the extra suppressions when V-10 and V-24 were transmitting alone, we need to determine if this interrogator was transmitting when N39 went

over both interrogators later in the flight when the combined suppression counts were much closer to the theoretical.

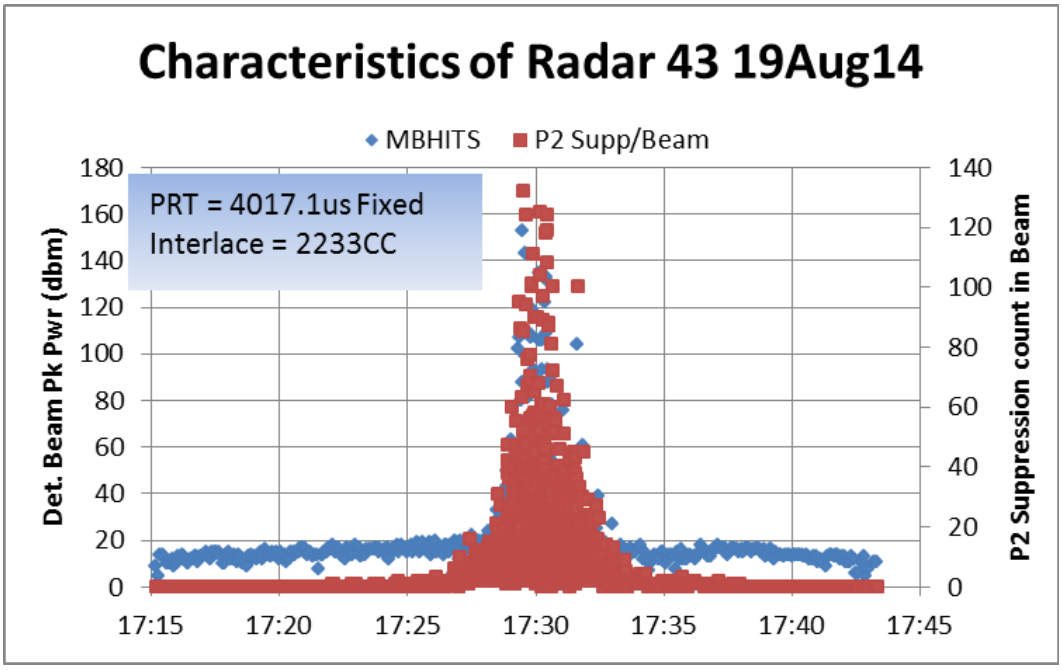


Figure 87. Detected Beam power and suppression counts – Radar 43 – 17:30

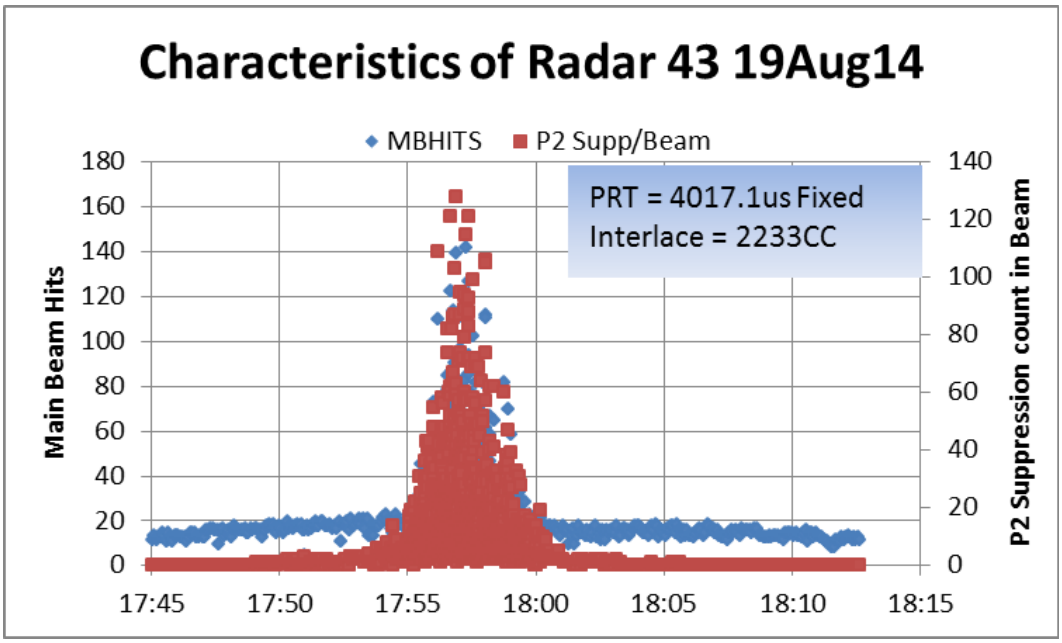


Figure 88. Detected Beam power and suppression counts – Radar 43 – 17:57

The suppression data in Figure 87 and Figure 88 indicate that this interrogator also contributed suppressions to those from V-10 and V-24 when both were transmitting.

Table 18 shows the timing of the peak amplitude distribution of interrogations from Radar 43 and the corresponding time when the distance from the LBTS involved is at a minimum. This will show how well the peaks of the two systems align for each pass over the sites.

Table 18. Time and Distance between peaks of LBTS and Radar 43

Peak Time of Radar 43	Distance from V-10/V-24 at Peak time (nm)	True Min Dist from V-10/V-24	Time of Min Dist V-10/V-24	Time Diff Min Dist (sec)	Est Dist Diff Pks
15:03:47	2.65	2.50	15:04:04	17	6.0
15:31:26	3.30	2.45	15:30:40	-46	-16.2
17:30:10	2.69	2.55	17:30:27	17	6.0
17:57:30	3.86	2.41	17:56:26	-64	-22.5

The first row is the pass when V-10 was Active alone. The peak of the amplitude distribution of the interrogations seen from Radar 43 occurred at 15:03:47. The minimum distance from V-10 occurred 17 seconds later (an estimated distance of about 6 nmi). On the next pass (V-24 alone), the peak of the Radar 43 distribution occurred 46 seconds after the minimum distance from V-24. At the first pass with both V-10 and V-24 transmitting, the peak of Radar 43 occurred 17 seconds earlier than the minimum distance from V-24. On the last pass with both transmitting, the peak of Radar 43 occurred 64 seconds after the minimum distance. This equates to approximately 22.5 nmi, so the interference from Radar 43 is the least of the four runs.

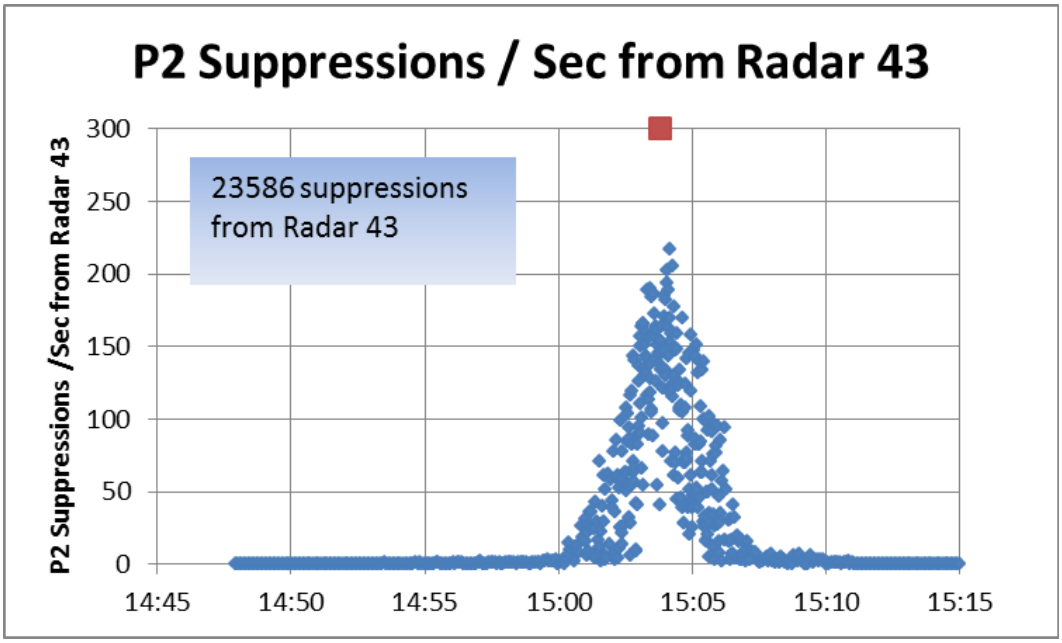


Figure 89. P2 Suppression counts – Radar 43 – 15:03

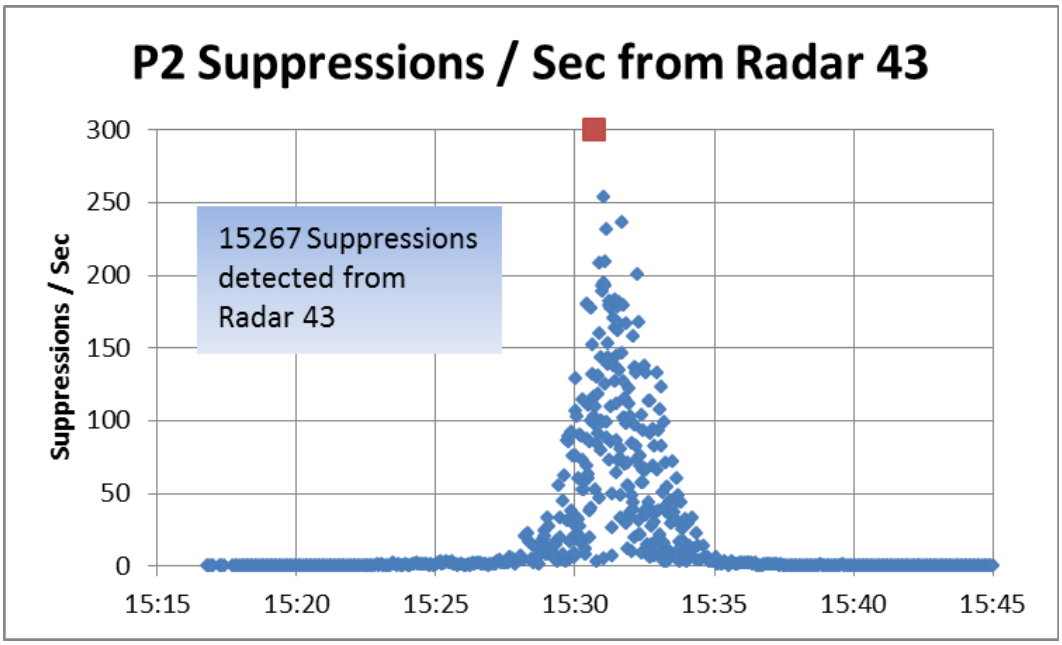


Figure 90. P2 Suppression counts – Radar 43 – 15:30

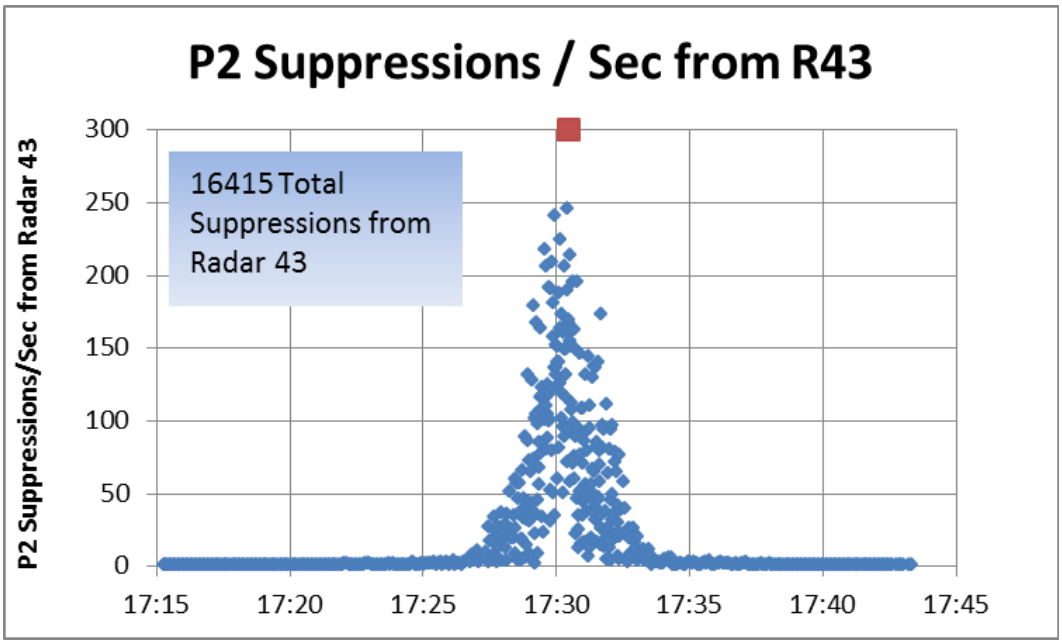


Figure 91. P2 Suppression counts – Radar 43 – 17:30

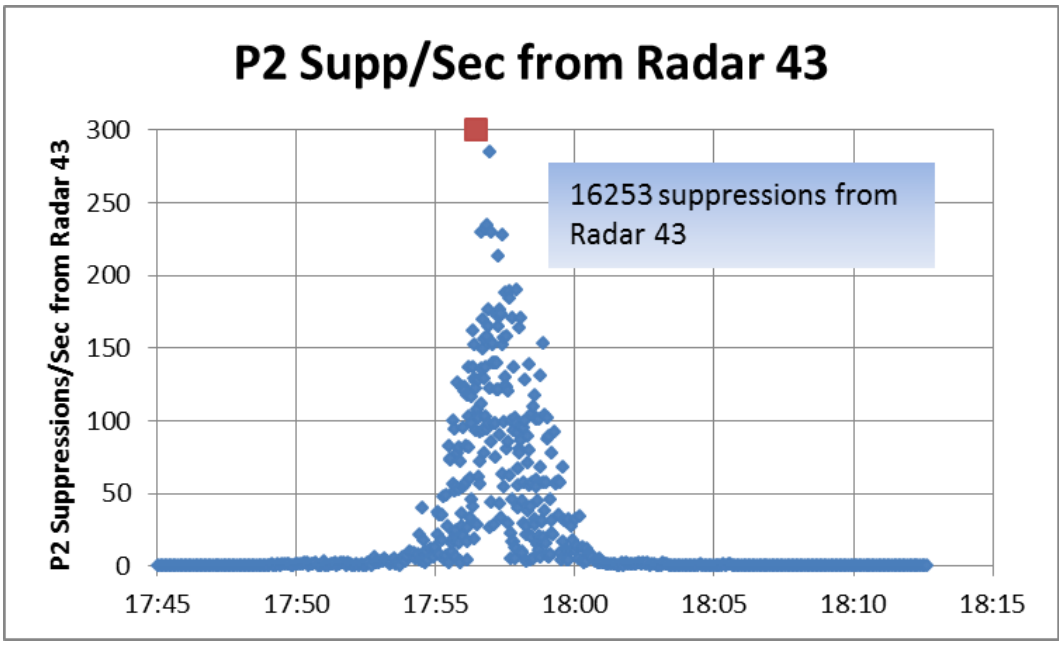


Figure 92. P2 Suppression counts – Radar 43 – 17:57

We checked to see why the suppression rate during the 15:03 pass is far larger than on the other three. Table 19 below shows the length of time between start and end of detection of suppressions for Radar 43 at the 4 crossover points. During the first crossing at 15:03:47, the elapsed time was almost 30 seconds longer than the other three times. All sets of data were processed with the same criteria.

Table 19. Length of Time Between Start and End of Detection of Suppressions for Radar 43

Peak Time of Radar 43	Start of Supp	End of Supp	Elapsed Time
15:03:47	14:59:30	15:06:07	0:06:37
15:31:26	15:27:59	15:34:07	0:06:08
17:30:10	17:26:40	17:32:49	0:06:09
17:57:30	17:54:03	18:00:01	0:05:58

There is more information on Radar 115 in another section that compares results in Day 3 and Day 4 of the testing.

A.3 LBTS Effect on 1030 MHz Transponder Occupancy – Day 3 & Day 4

Section 2.5 contains sufficient detail of the measured transponder occupancy rates from Day 3 and Day 4. Contained here is some additional deeper analysis of other findings from these days.

A.3.1 Investigation of High Mode 1 rate near Norfolk

Radar 115 has the capability of two different mode sequences (All Mode 1's or 1,2,A,C). The peak power of this radar in both modes is shown on the figures below. The peak power shown on Figure 105 is almost -40dBm indicating that it is probably less than 10 nmi from N39. These plots are plotted separately, but the time indicates many of the interrogations are interleaved. The big burst of Mode 1 interrogations doesn't start until about 15:14. The 1,2,A,C mode has gaps in time, but the big increase starts at about 15:09.

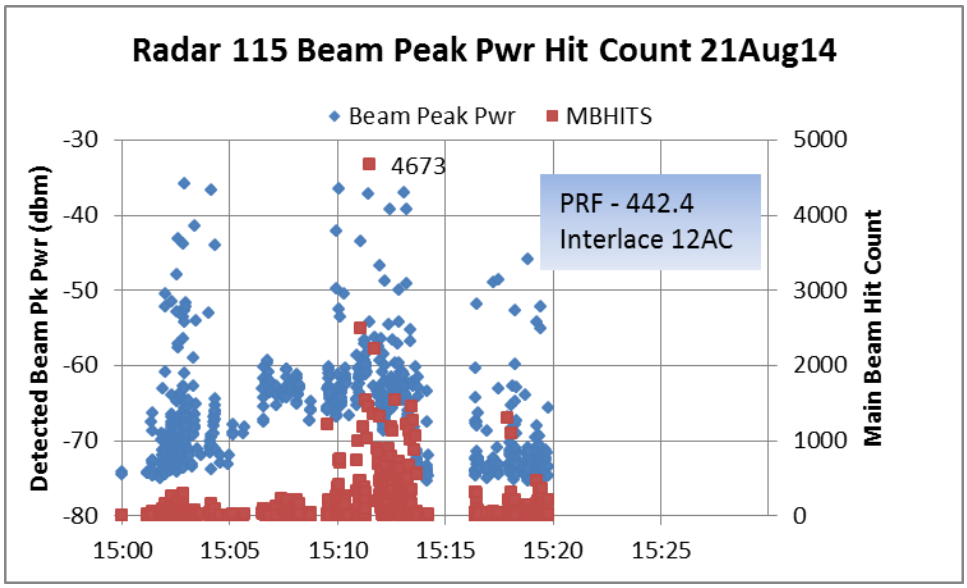


Figure 93. Radar 115 Pk Power and Hit count – Day 4 1,2,A,C

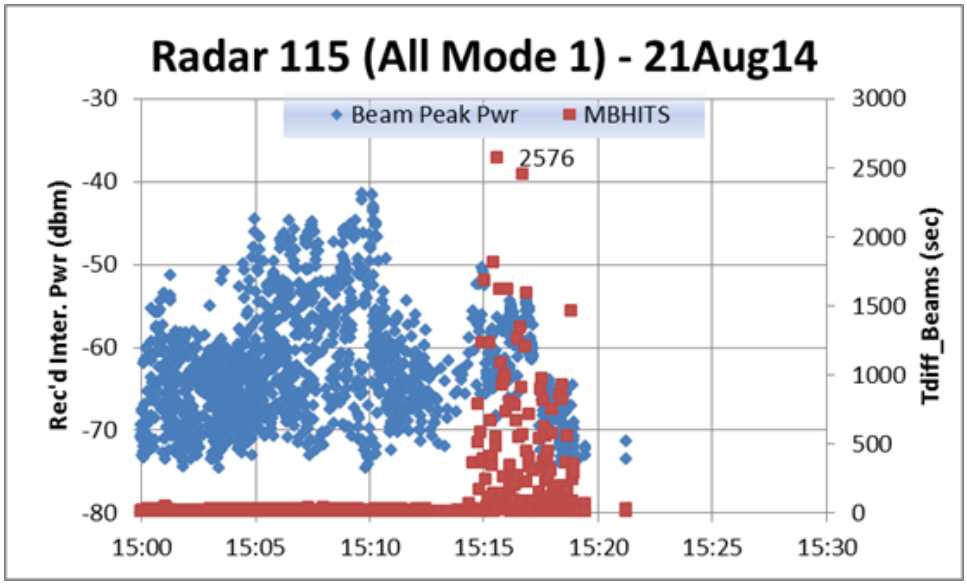


Figure 94. Radar 115 Pk Power and Hit count – Day 4 All Mode 1's

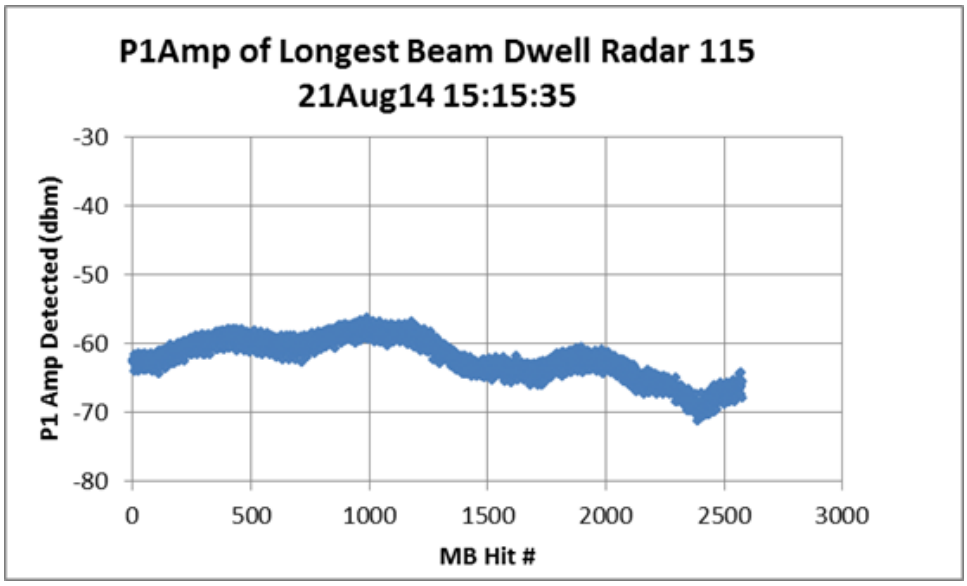


Figure 95. Amp of Longest Beam Dwell Radar 115 – Day 4 15:15:35

The P1 amplitude of all interrogations comprising the longest beam on Day 4 from this radar is shown on Figure 98. It was 2576 hits.

	FIXED PRT'S & Mode Int TO SEARCH FOR							
		PRT	MAX	MIN		#1		#3
34	R105	61000	63700	58300	163.9344			
234	R106	32835	35500	30170	304.5531	30865		
234	R107	30469.5	31079	29860	328.197	30865	30143	
1243	R108	40000	44000	36000	250	40171		
1243	R109	23600	23700	23500	423.7288			
1243	R110	40000	42000	38000	250			
1243	R111	29250	31000	27500	341.8803			1.004237
6	R112	22000	27000	17000	454.5455			0.995763
1243	R113	36101	39711	32491	277.0006			
1243	R114	36167	39784	32550	276.4951			
1	R115	22600	24000	21200	442.4779			
1243	R116	29520	32040	27000	338.7534			1.061947
								0.938053
								1.085366
								0.914634

Radar 109
+/- 0.4%

Radar 115
+/- 6%

5% Stagger

UPX37

Radar 116
*/- 8%

UPX37
Min PRF

Figure 96. P1 PRT Characteristics used for detection of Interrogation sources

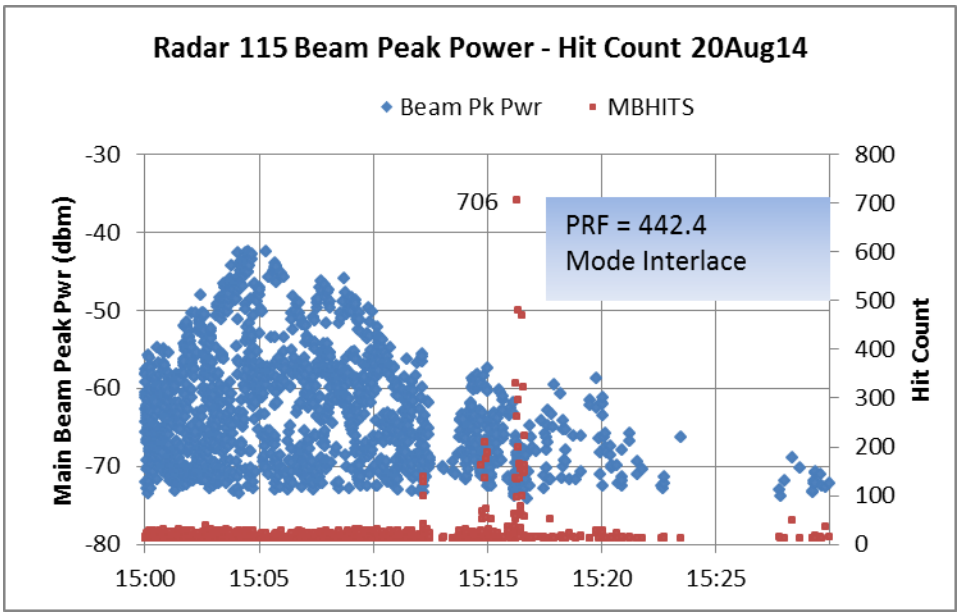


Figure 97. Radar 115 Beam Peak Power – Hit Count – Day 3

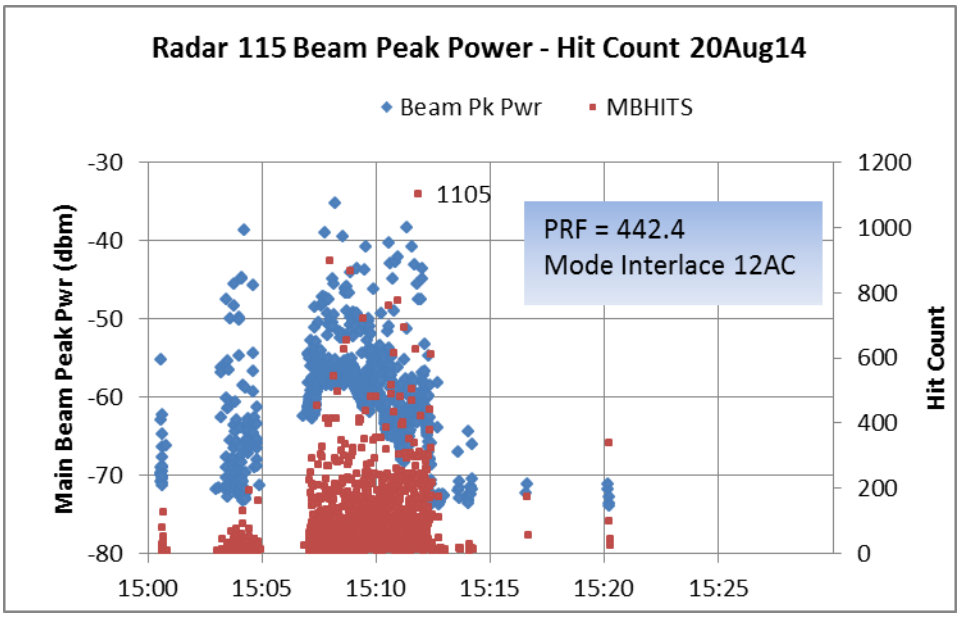


Figure 98. Radar 115 Beam Peak Power – Hit Count – Day 3 1,2,A,C Mode

The operating modes of Radar 115 are shown on the figures below for Day 3 and Day 4. The data was processed separately for the two modes of operation, sorted as a function of time. The time difference between all consecutive beams was then calculated. There were no beams declared at the same time, so it was assumed that the source was the same for both modes.

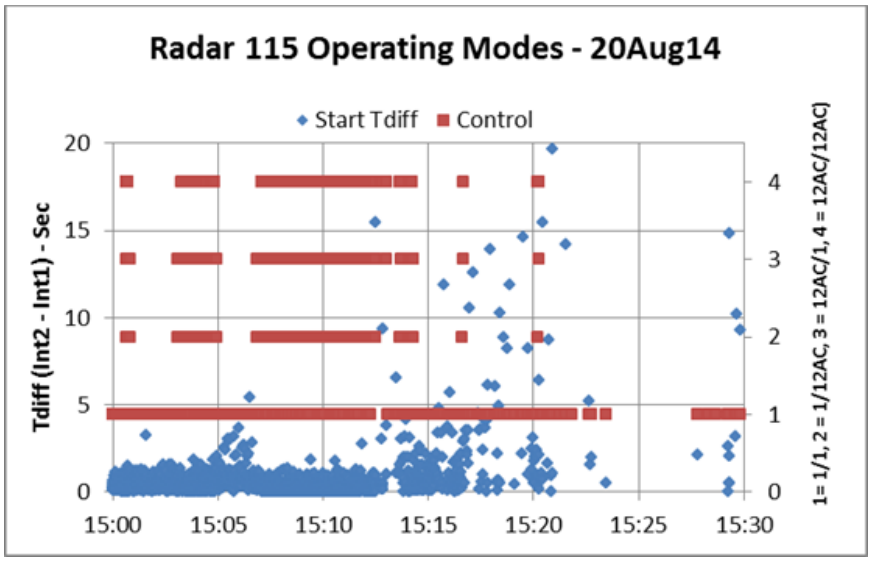


Figure 99. Radar 115 Operating Modes – Day 3

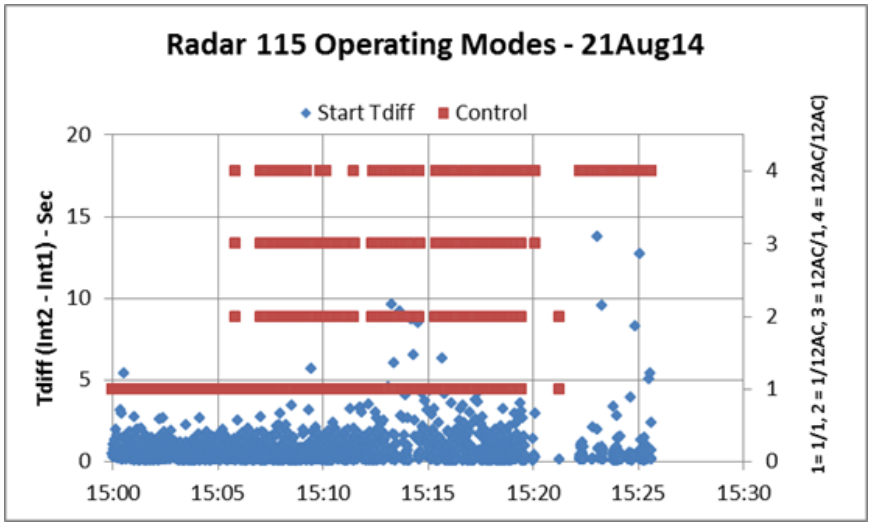


Figure 100. Radar 115 Radar 115 Operating Modes – Day 4

The system started out in the 'All 1's mode on both days. It switched almost immediately to 1,2,A,C on Day 3. It did not switch to this mode until after 15:05 on Day 4. The gap on the top three indicates that it has switched back to the 'All 1's mode. It continues to switch back and forth until the end. On Day 3, it ends up in the 'All 1's mode and on Day 4 it ends up in the 1,2,A,C mode.

A.3.2 Radar 109 and Radar 115 investigation Day 3 and Day 4 near Norfolk

On both Day 3 and Day 4, there were times when the reply rate from N39 (OWN) increased dramatically for a period of several minutes. Figure 101 and Figure 102 show this increase for Day 3.

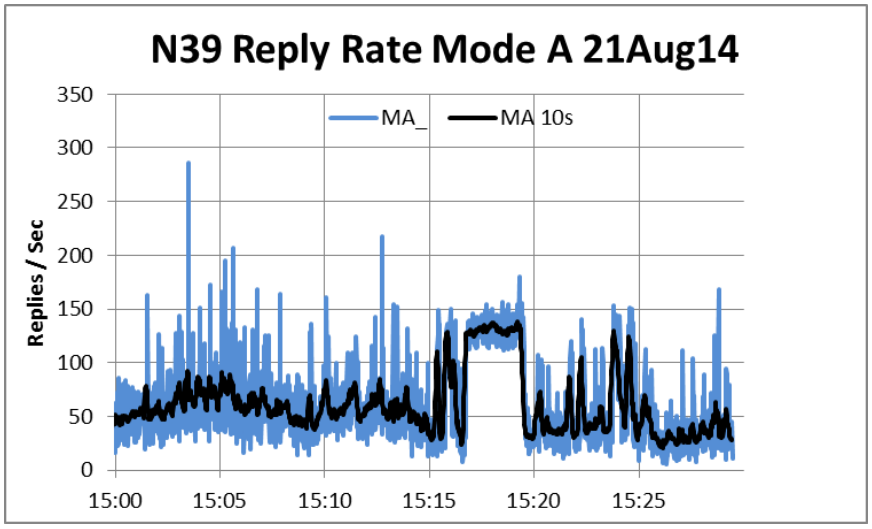


Figure 101. Continuous Mode A Replies from N39 – Day 4

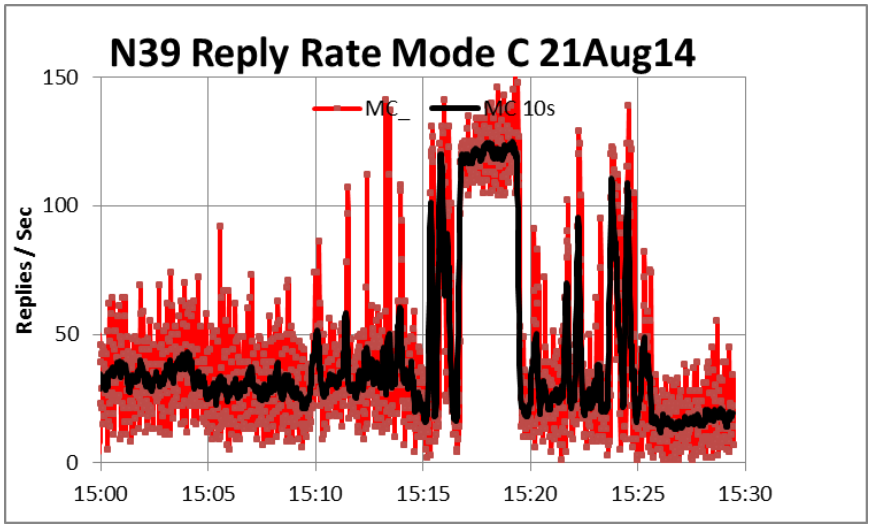


Figure 102. Continuous Mode C replies from N39 – Day 4

Both Modes increase approximately 75 replies per second at the same time.

The data for Radar 109 showed that the radar 'spotlighted' N39 for 32.9 seconds on Day 3, so this is a likely source. Figure 103 shows the scan time and hit count from Radar 109 during this period. The continuous large hit counts that start at approximately 15:07 appear to align perfectly with the increase shown in the reply count

Some of the characteristics of the radars are shown on the figures below.

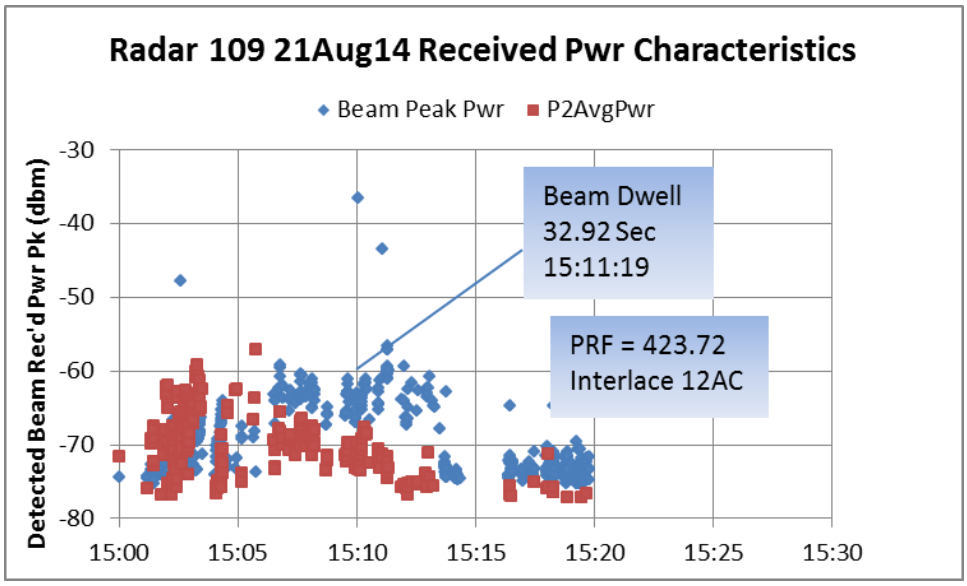


Figure 103. Radar 109 Day 4 Received Power Characteristics

Figure 104 shows that most of the interrogations are below -60dBm which indicates the source is probably at least 40 nmi from N39. The hit count is pretty low until about 15:09. The longest beam is at 15:11:19 when the beam dwell was 32.92 seconds.

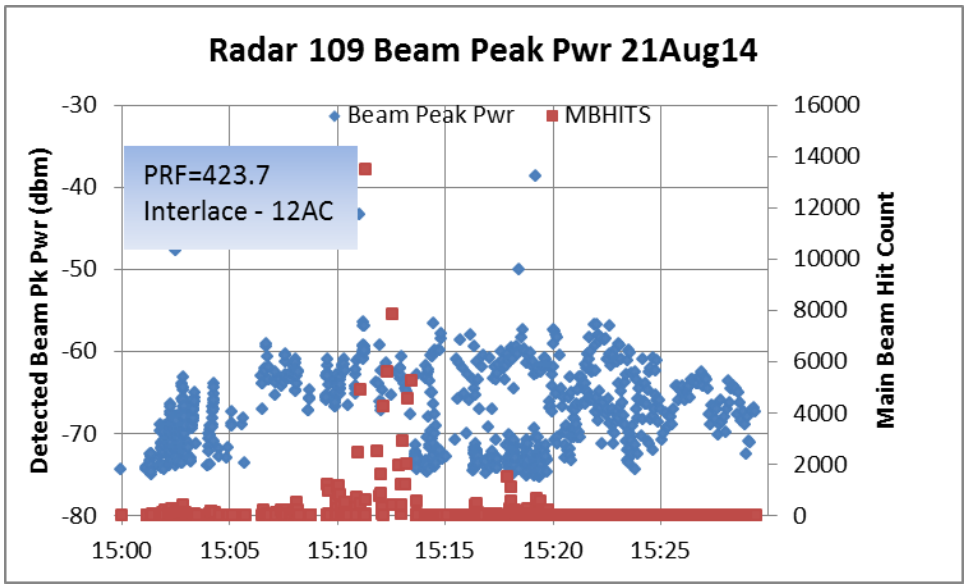


Figure 104. Radar 109 Day 4 Received Power – Hit Count

Radar 115 has the capability of two different mode sequences (All Mode 1's or 1,2,A,C). The peak power of this radar in both modes is shown on the figures below. The peak power shown on Figure 105 is almost -40dBm indicating that it is probably less than 10 nmi from N39. These plots are plotted separately, but the time indicates many of the interrogations are interleaved. The

big burst of Mode 1 interrogations doesn't start until about 15:14. The 1,2,A,C mode has gaps in time, but the big increase starts at about 15:09.

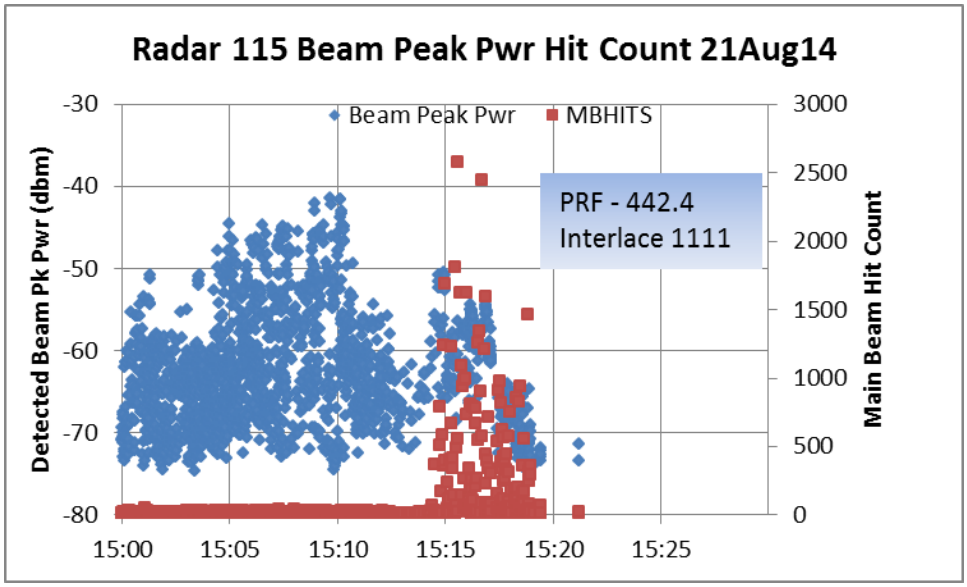


Figure 105. Radar 115 Pk Power and Hit count –Day 4 All 1's

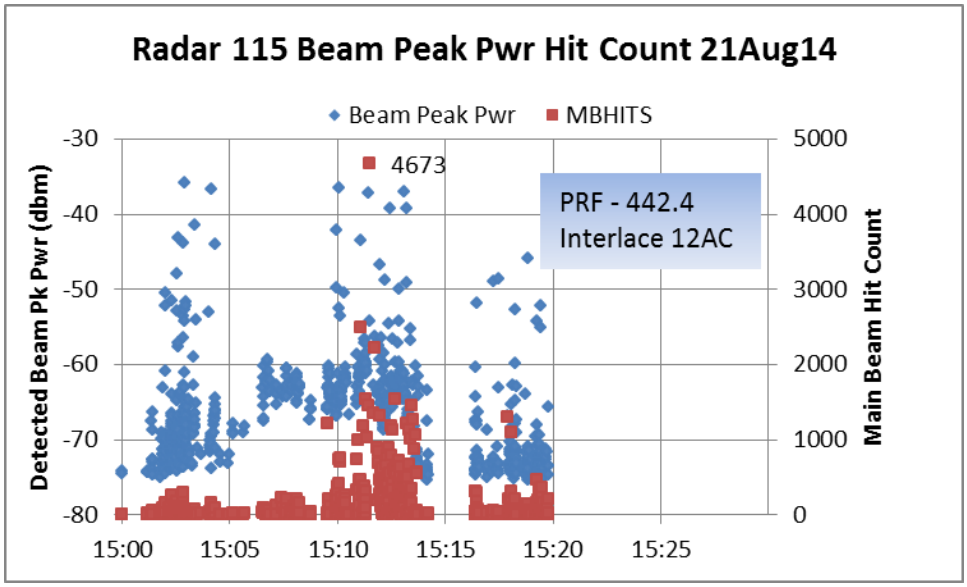


Figure 106. Radar 115 Pk Power and Hit count –Day 4 1,2,A,C

The same data is shown below for the same time period on Day 3.

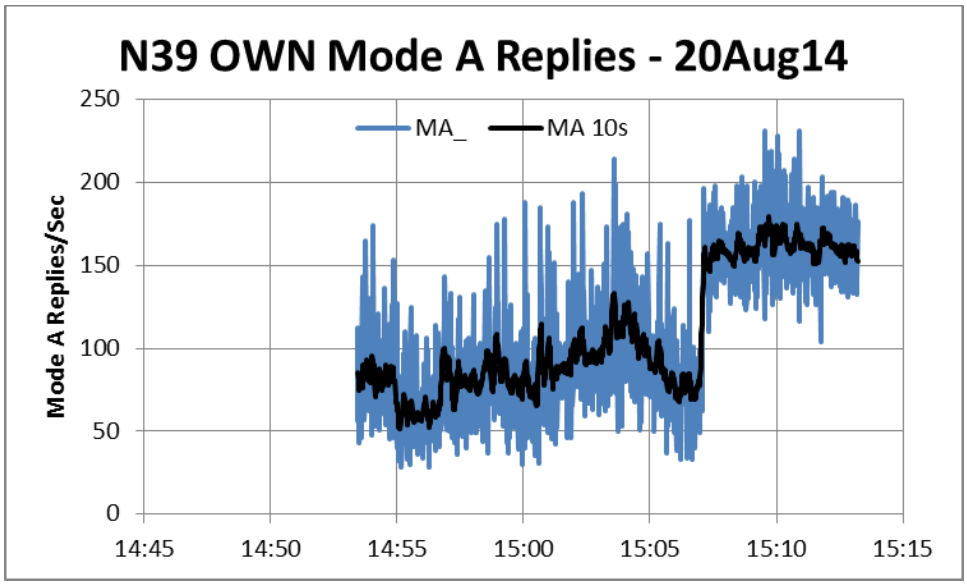


Figure 107. N39 OWN Mode A Replies – Day 3

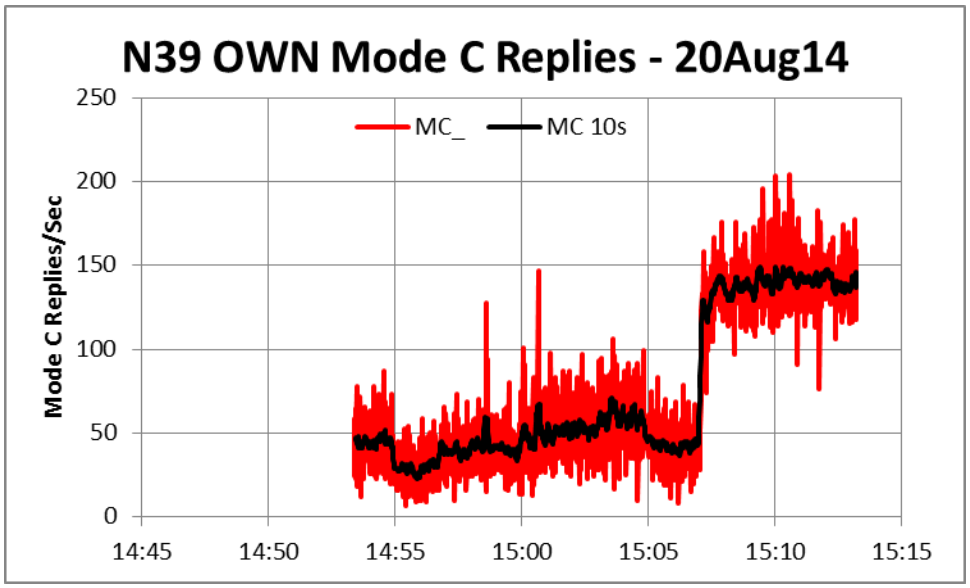


Figure 108. N39 OWN Mode C Replies – Day 3

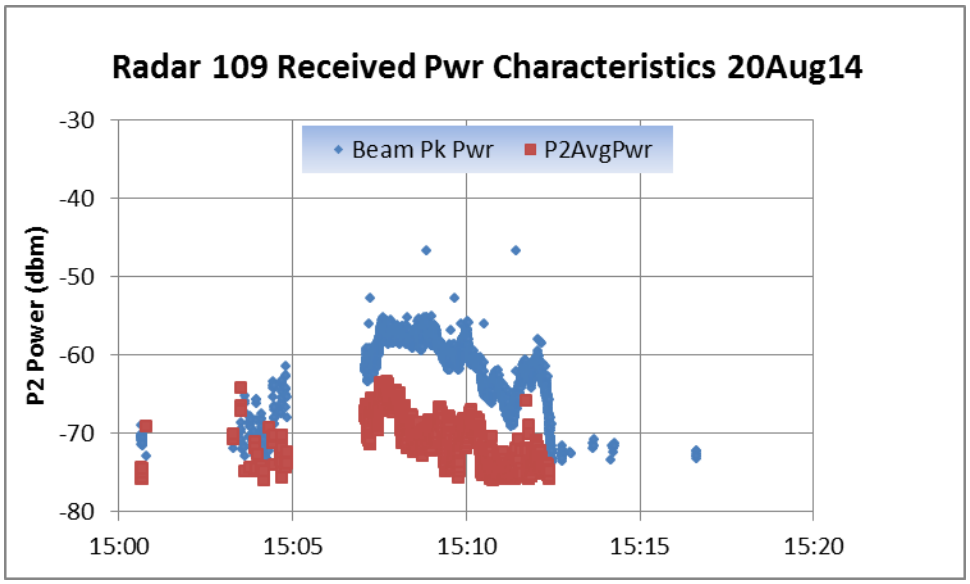


Figure 109. Radar 109 Received Pwr Characteristics – Day 3

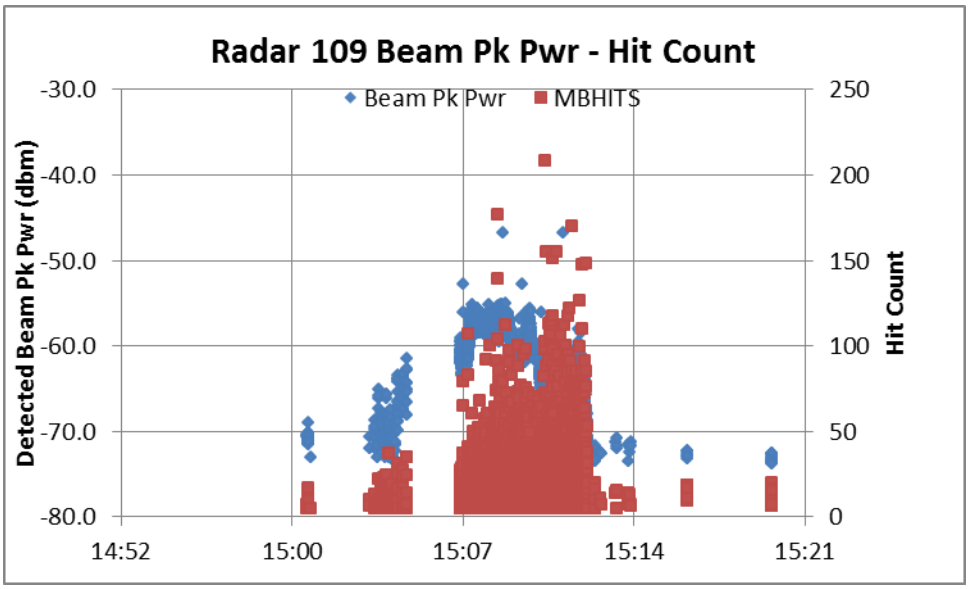


Figure 110. Radar 109 Beam Peak Power – Hit Count

This big increase in hit count coincides exactly with the increase in N39 replies.

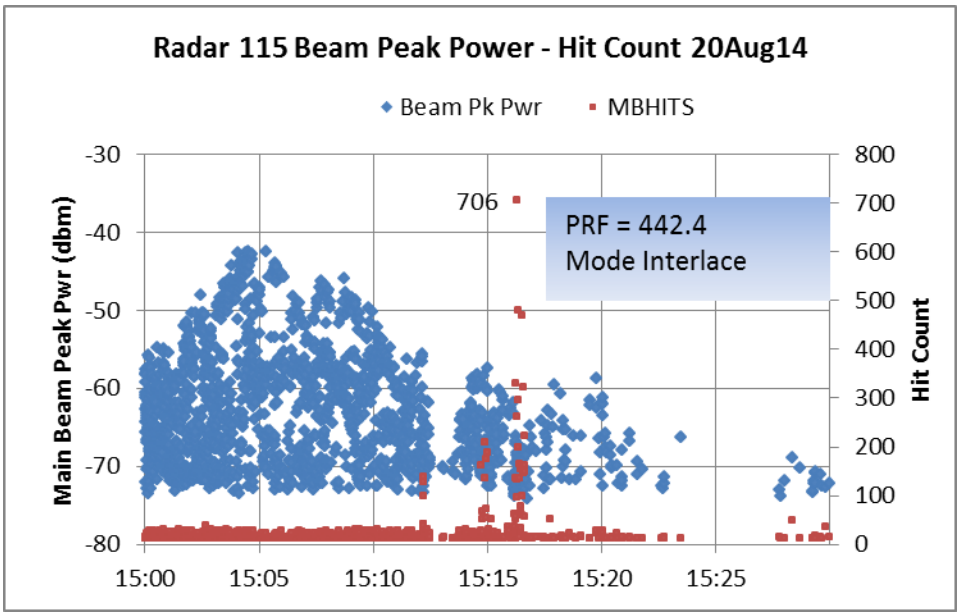


Figure 111. Radar 115 Beam Peak Power – Hit Count – Day 3

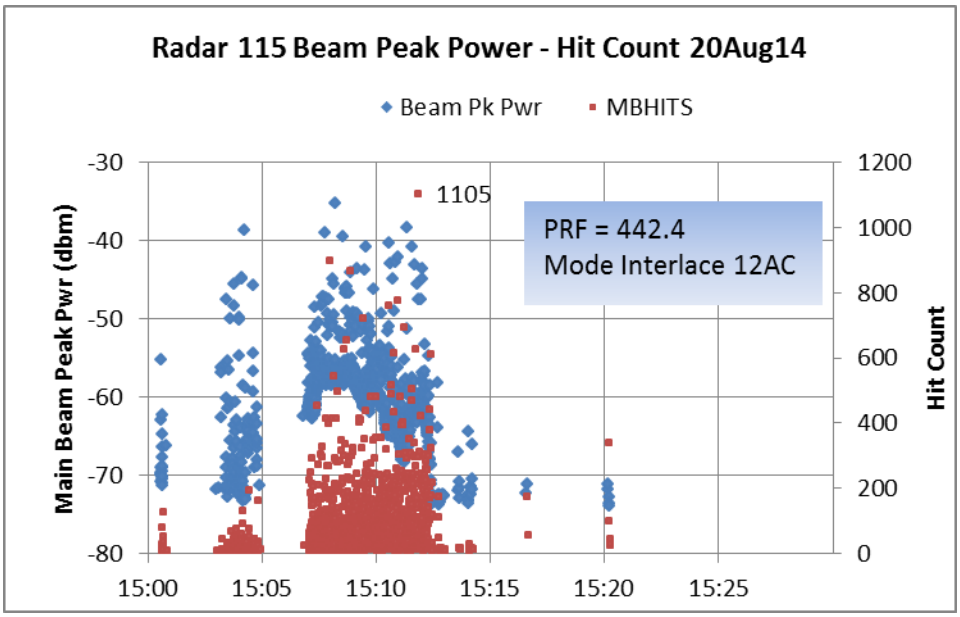


Figure 112. Radar 115 Beam Peak Power – Hit Count 1,2,A,C Mode

This also coincides exactly with the increase of N39 replies.

A.4 LBTS Effect on 1090 MHz RF Environment – Day 3 & Day 4

On Days 3 and 4, N39 flew a circuit around the eastern Maryland/Virginia area. The flight paths are shown in Figure 113 and Figure 114. During the airborne testing, all four LBTS were cycled Active and Off simultaneously every 5 minutes. The frequency of the cycling enables a comparison of 4 AN/UPX-41 systems' effect on the 1090 MHz environment with reasonably similar airspace for adjacent Active/Off cycles. A similar route was flown each day, but N39's altitude on Day 3 was 20,000 feet and Day 4 was 9,000 feet.

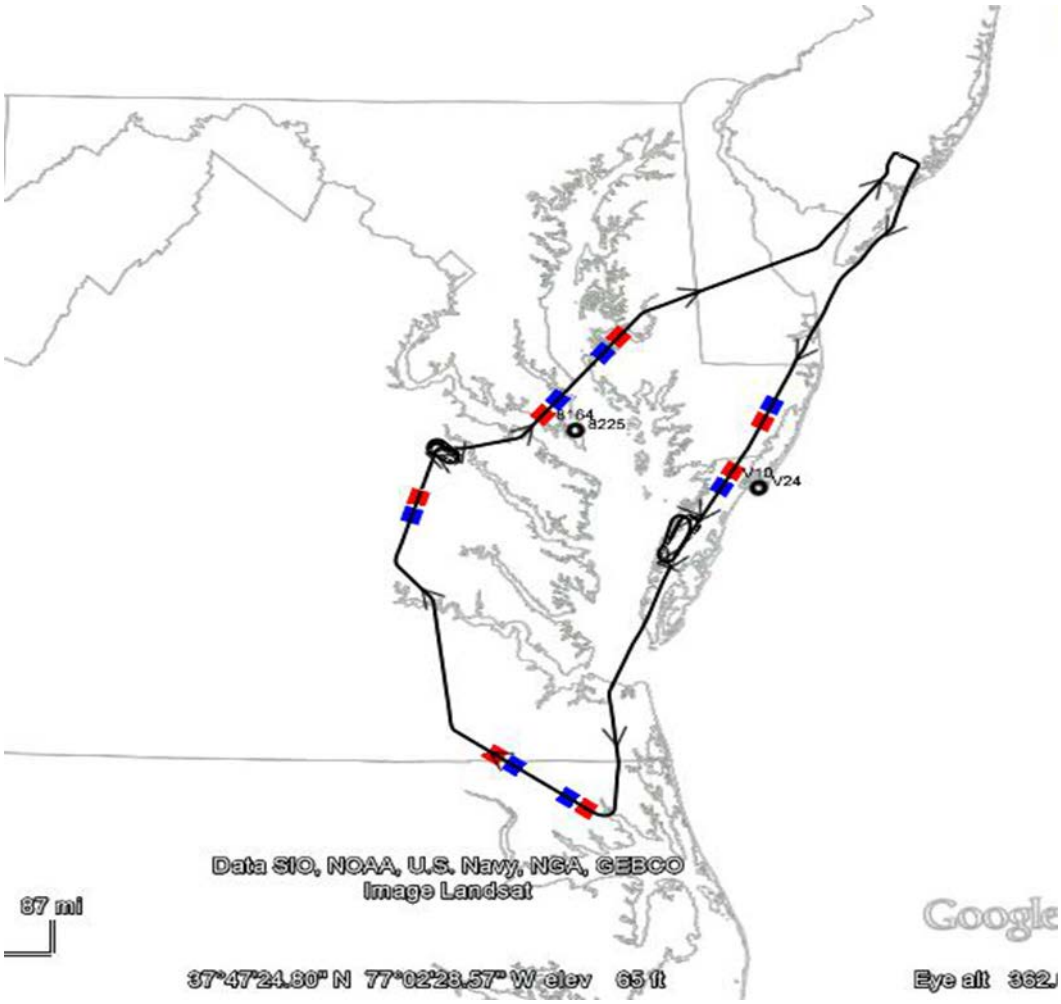


Figure 113. Test Aircraft Flight Path, Day 3

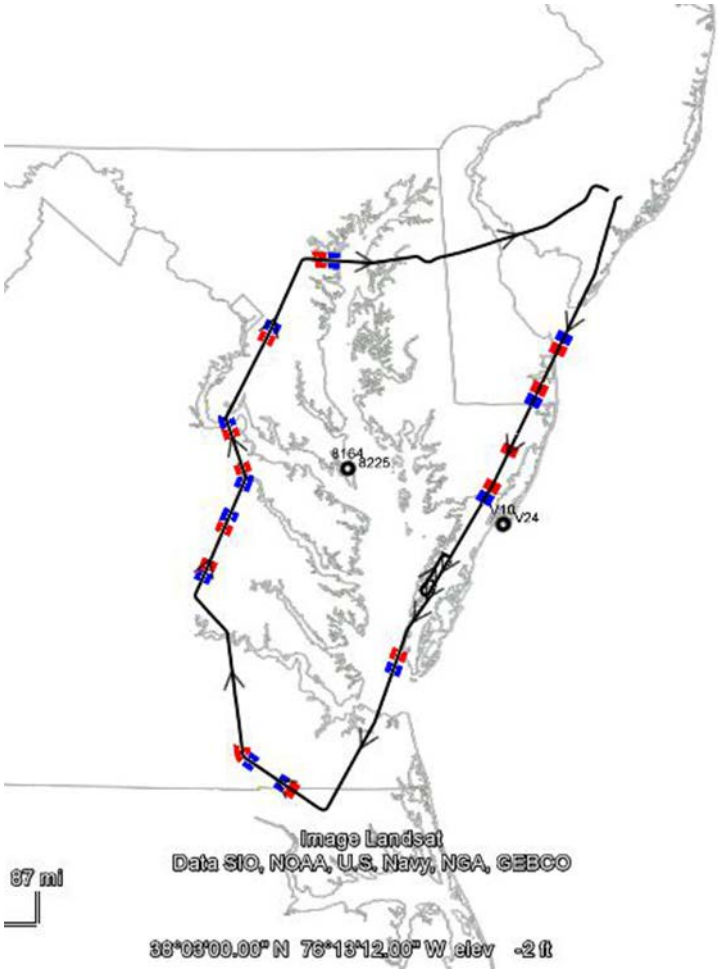


Figure 114. Test Aircraft Flight Path, Day 4

The 1090 MHz ATCRBS FRUIT rate was measured with a receiver MTL of -79 dBm and the Mode S FRUIT rate was measured with an MTL of -84 dBm. The 1090 MHz data is processed separately for the top and bottom antenna receiver channels. With the 20,000 feet altitude on Day 3, both top and bottom FRUIT rates are analyzed. With the lower 9,000 feet altitude on Day 4, only the top antenna data is analyzed. Following is a series of plots that show the measured 1090 MHz FRUIT rates for ATCRBS and Mode S, and top and bottom antenna where appropriate. With the plots, the blue data points are when the LBTS were Off, and the red data points are when they were Active and transmitting. Green is transitional. The darker bands are the 10-second average. The distance from the LBTS pairs is shown with the silver line showing the distance from Webster Field (8164 & 8225) and the gold lines showing the distance from the Wallops Island sites (V-10 & V-24).

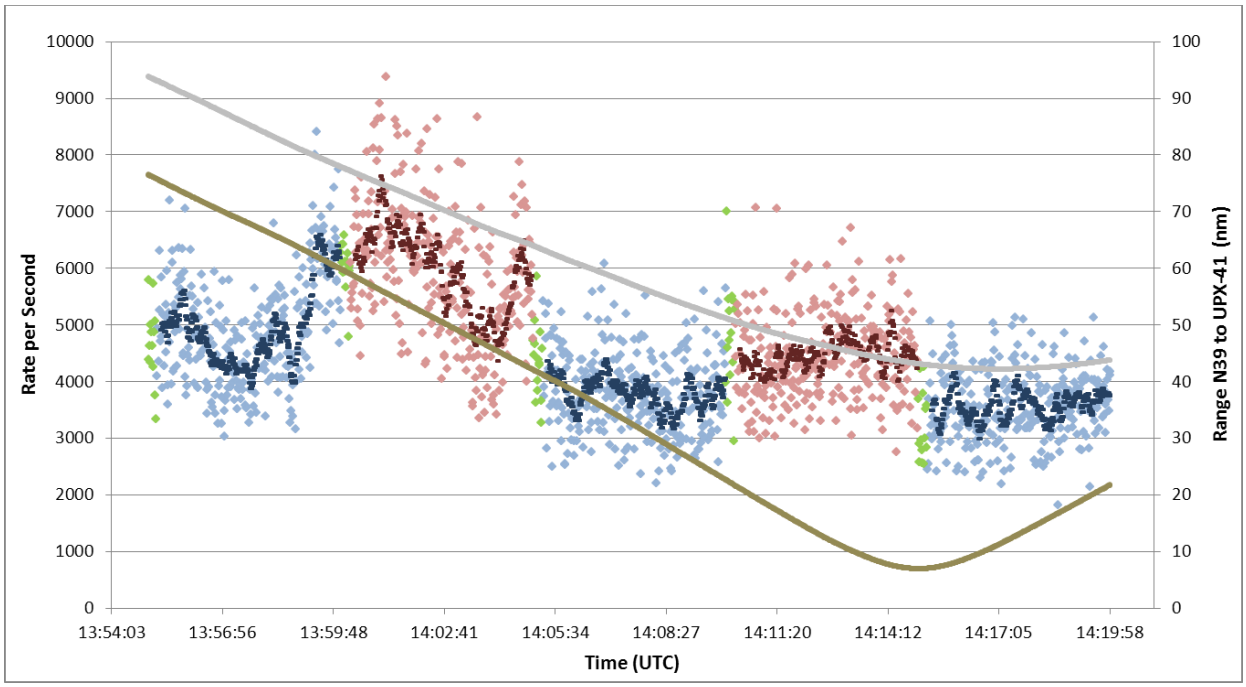


Figure 115. Day 3 – 1090 MHz ATCRBS FRUIT Top Antenna, Plot #1

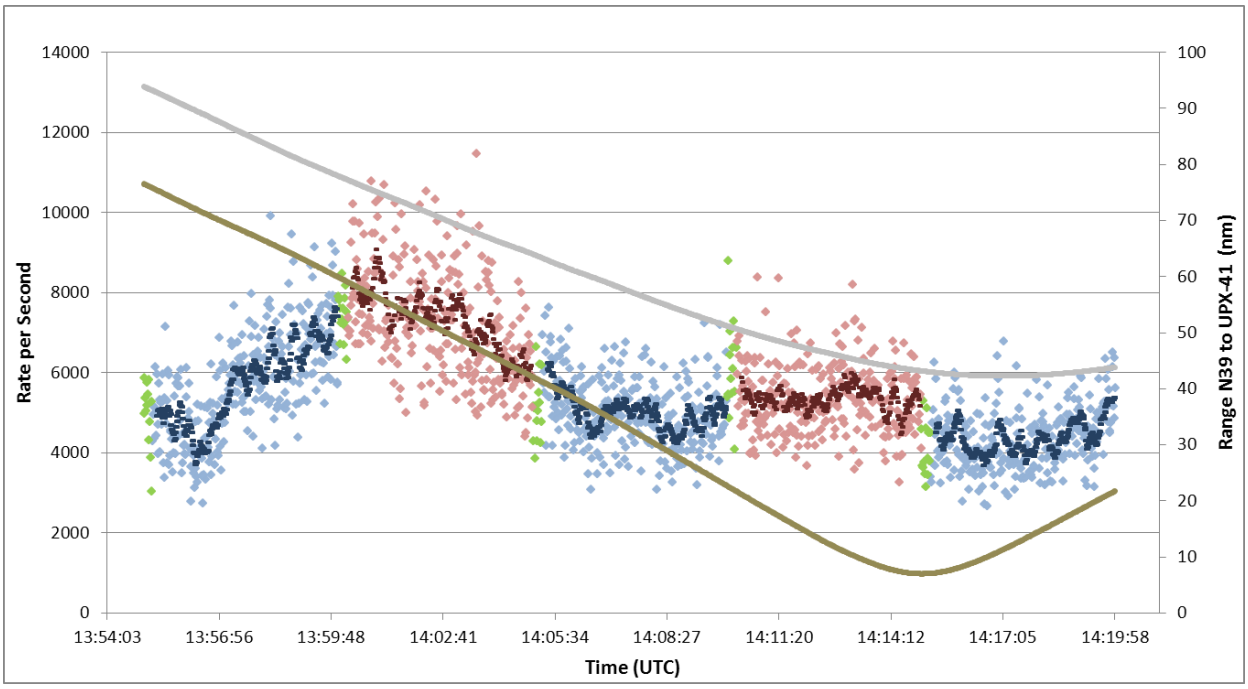


Figure 116. Day 3 – 1090 MHz ATCRBS FRUIT Bottom Antenna, Plot #1

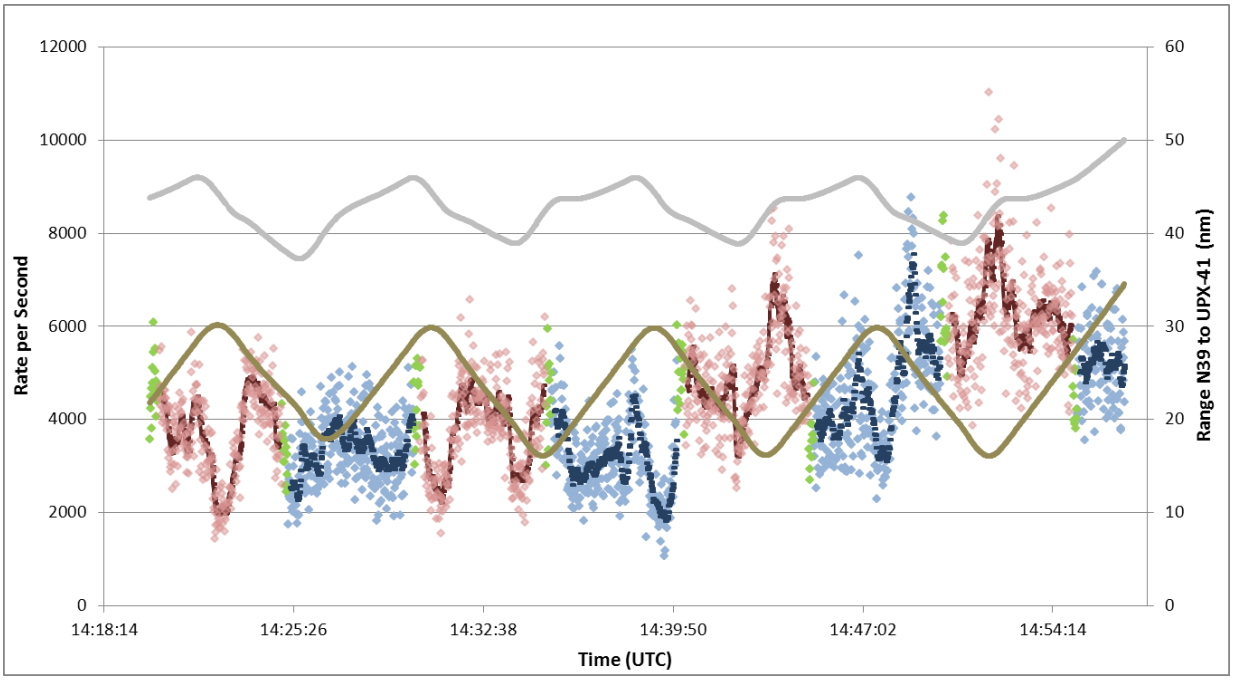


Figure 117. Day 3 – 1090 MHz ATCRBS FRUIT Top Antenna, Plot #2

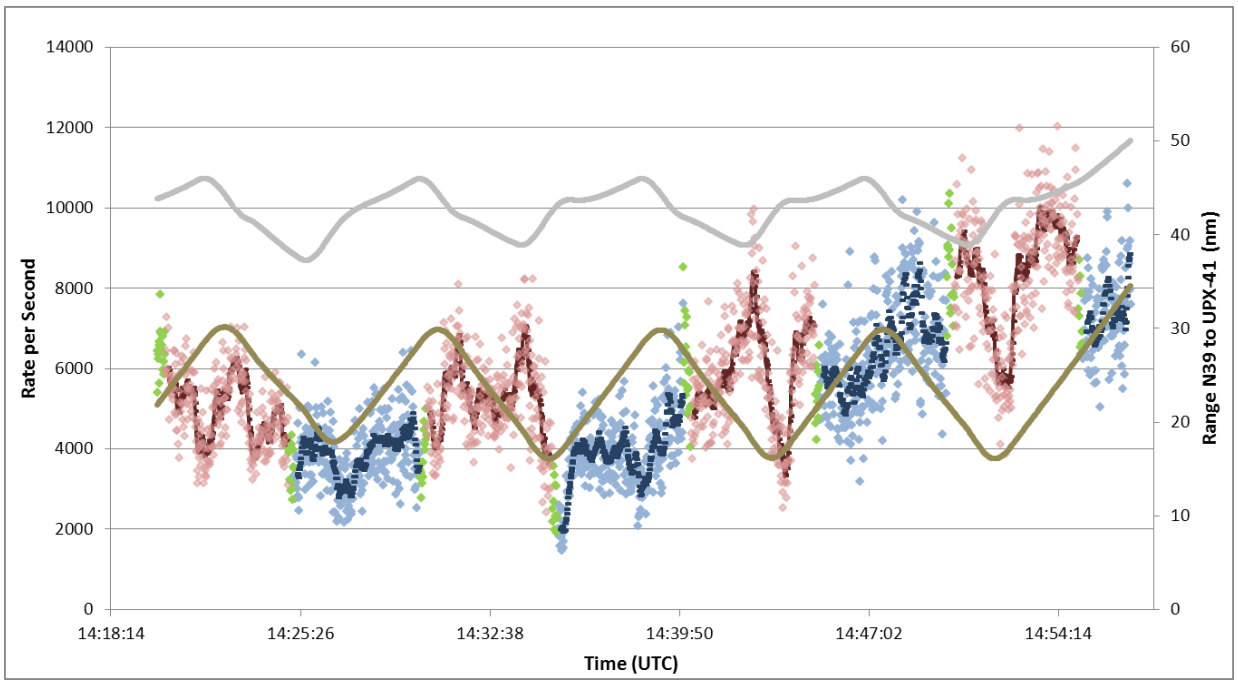


Figure 118. Day 3 – 1090 MHz ATCRBS FRUIT Bottom Antenna, Plot #2

N39 was in a holding pattern during the flight segment shown in Figure 117 and Figure 118. The aircraft banking during the turns to maintain the hold caused wide variations in the FRUIT measurements.

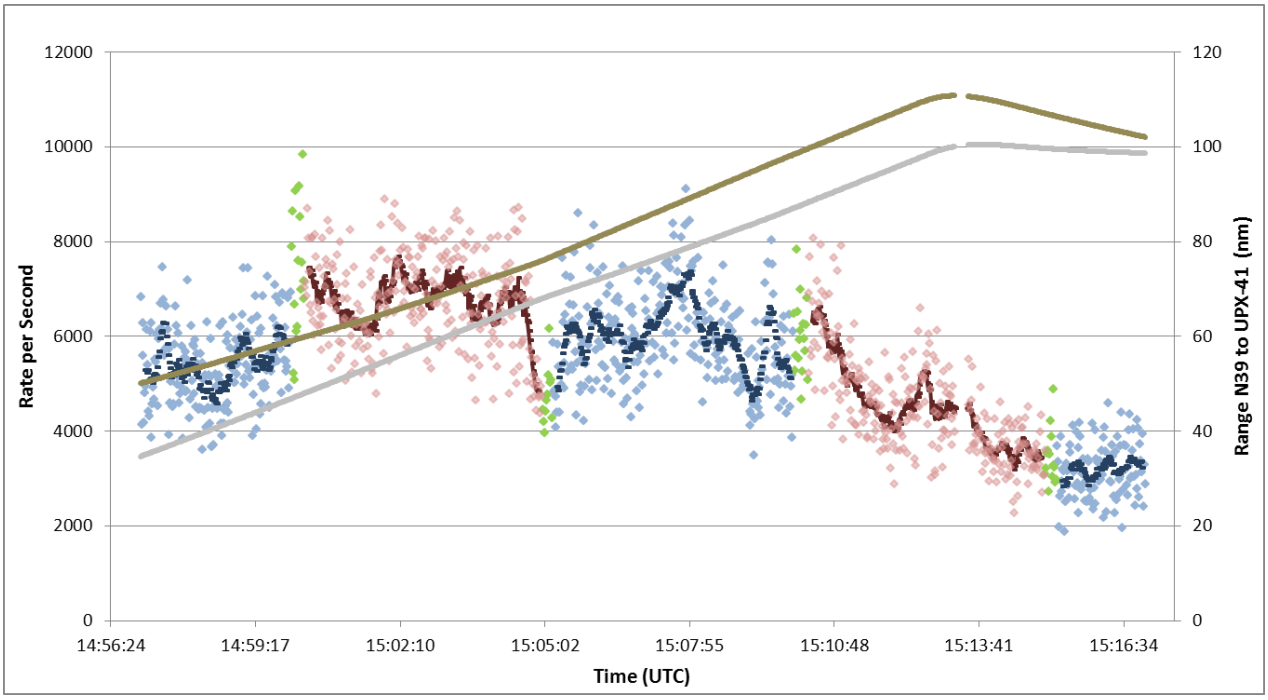


Figure 119. Day 3 – 1090 MHz ATCRBS FRUIT Top Antenna, Plot #3

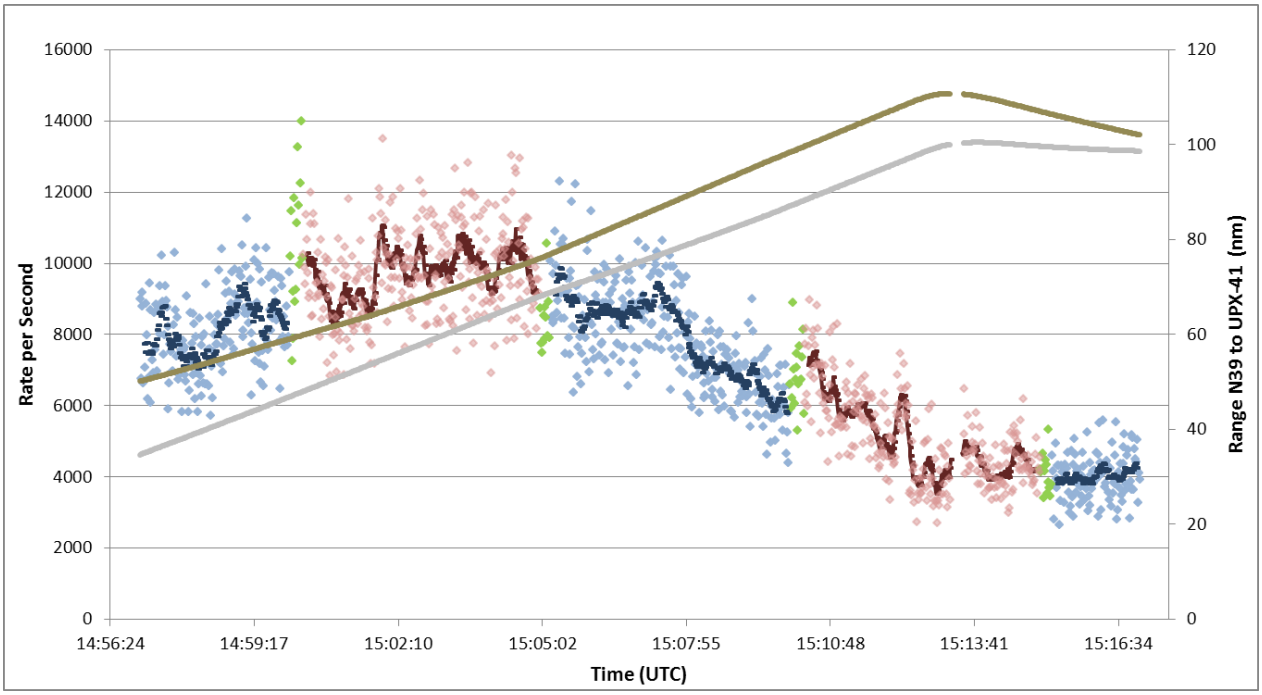


Figure 120. Day 3 – 1090 MHz ATCRBS FRUIT Bottom Antenna, Plot #3

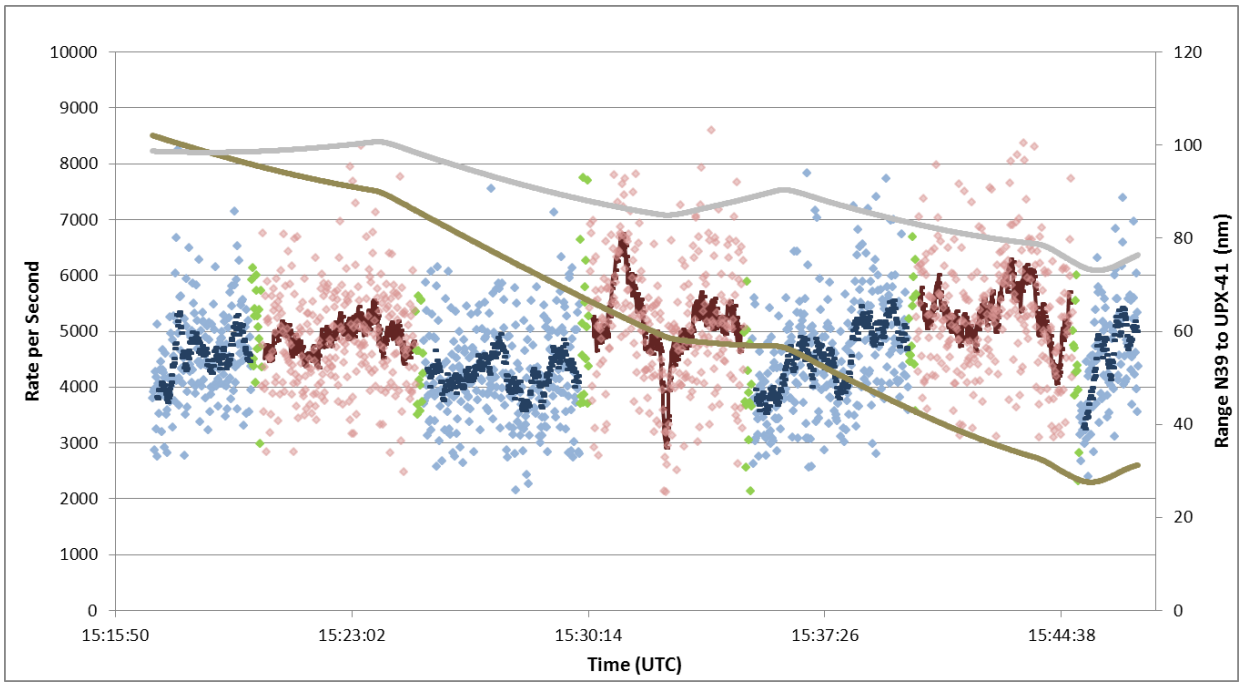


Figure 121. Day 3 – 1090 MHz ATCRBS FRUIT Top Antenna, Plot #4

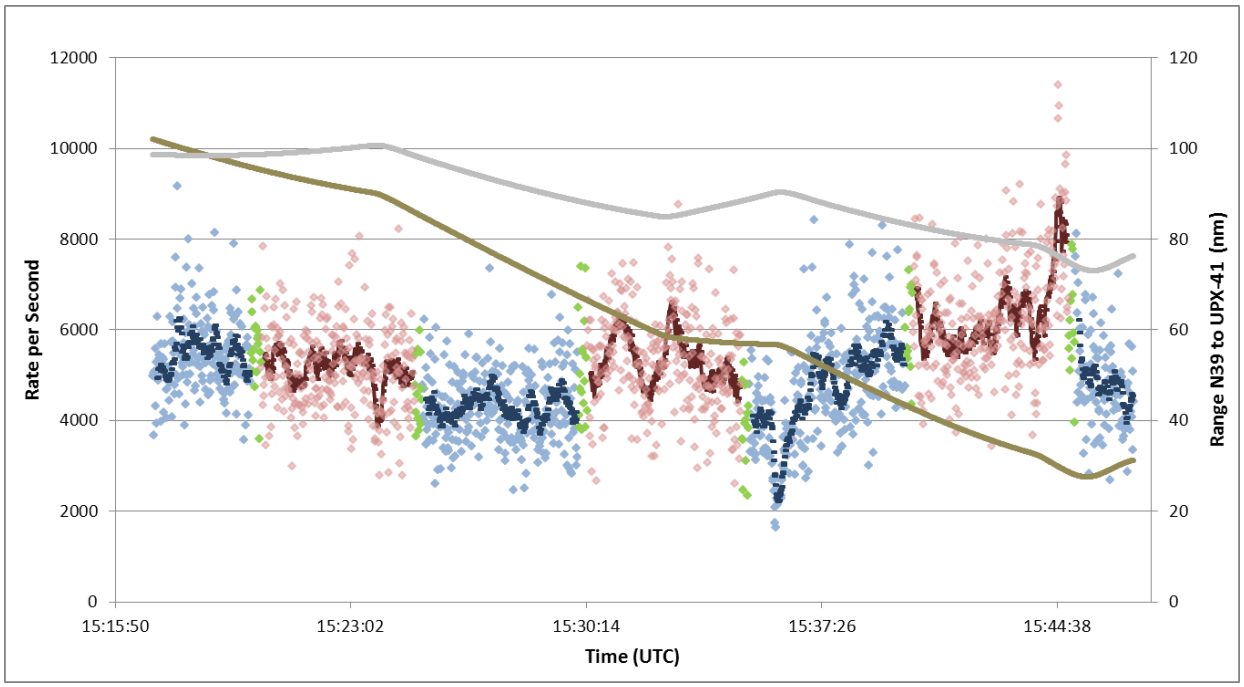


Figure 122. Day 3 – 1090 MHz ATCRBS FRUIT Bottom Antenna, Plot #4

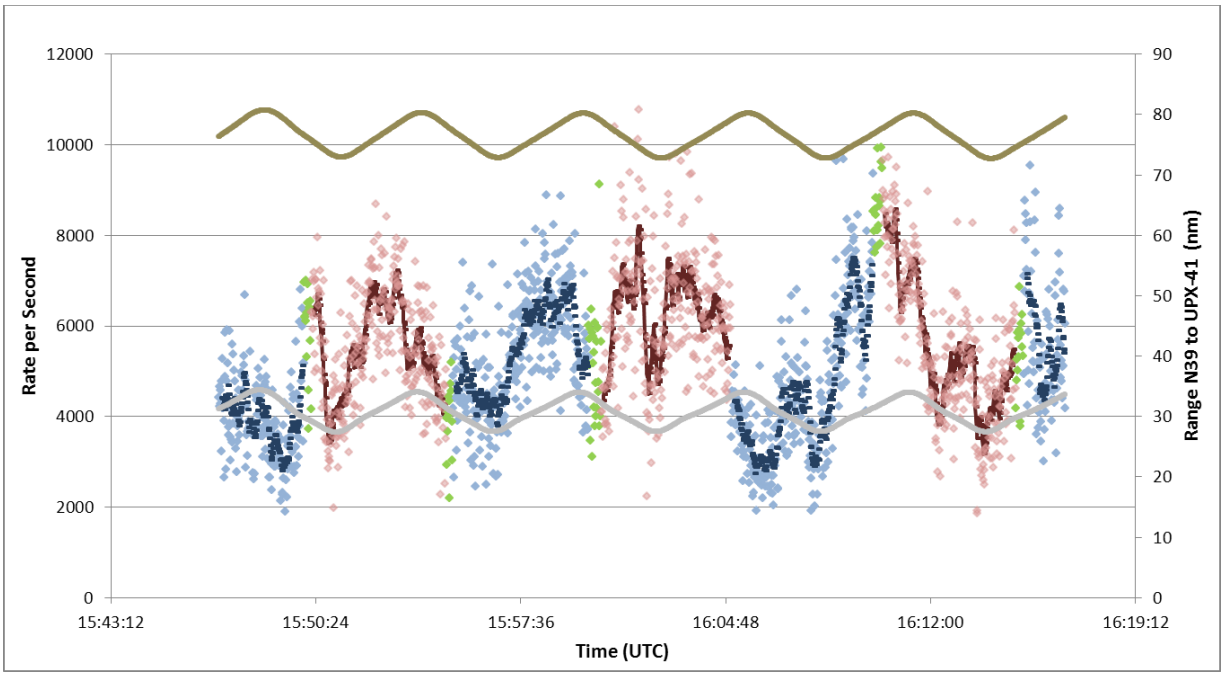


Figure 123. Day 3 – 1090 MHz ATCRBS FRUIT Top Antenna, Plot #5

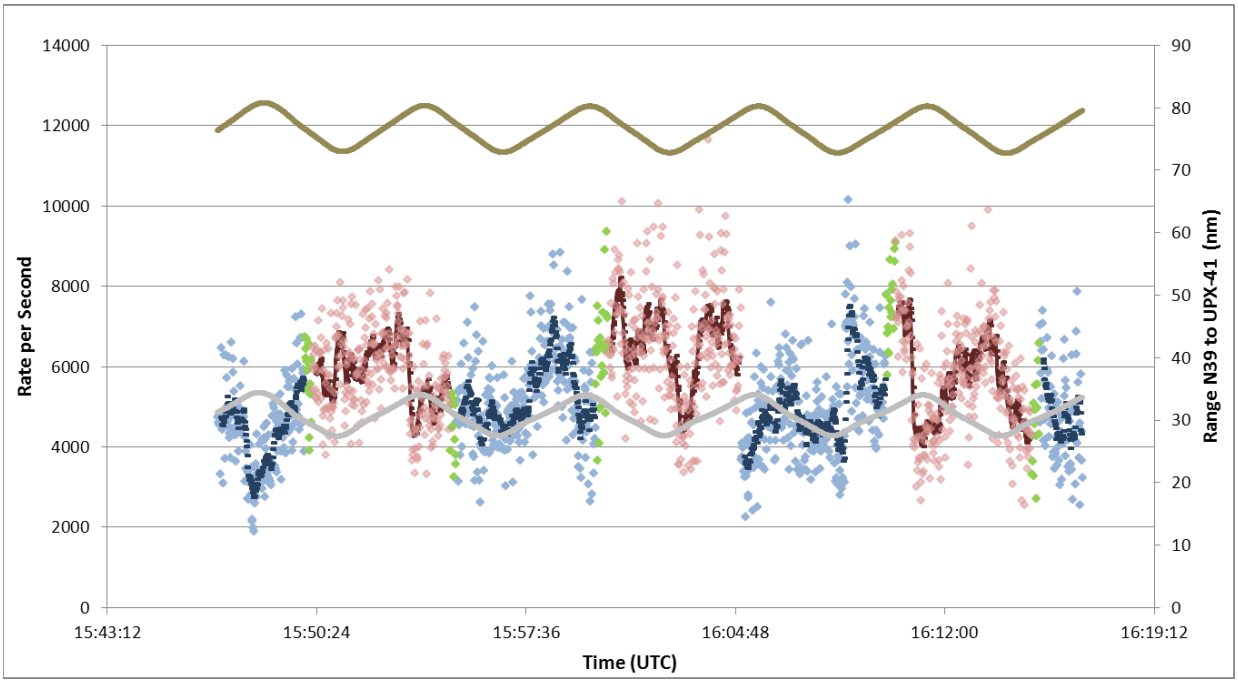


Figure 124. Day 3 – 1090 MHz ATCRBS FRUIT Bottom Antenna, Plot #5

N39 was in the second hold on the western side of the circuit in Figure 123 and Figure 124.

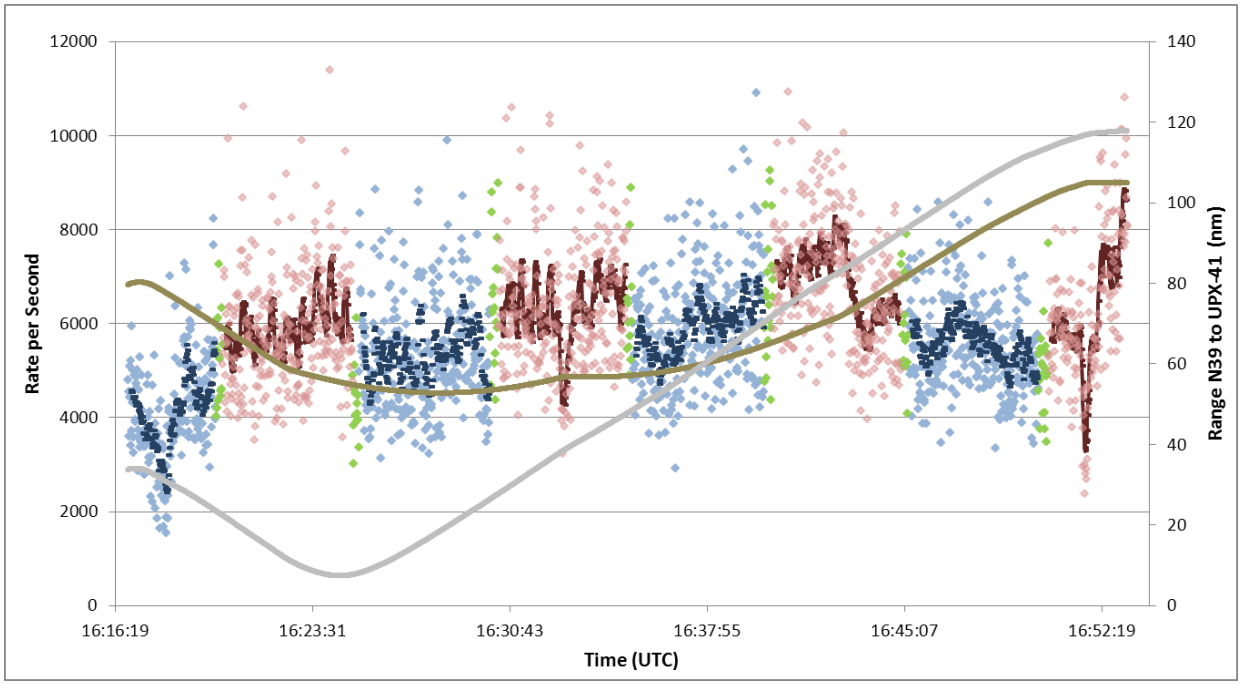


Figure 125. Day 3 – 1090 MHz ATCRBS FRUIT Top Antenna, Plot #6

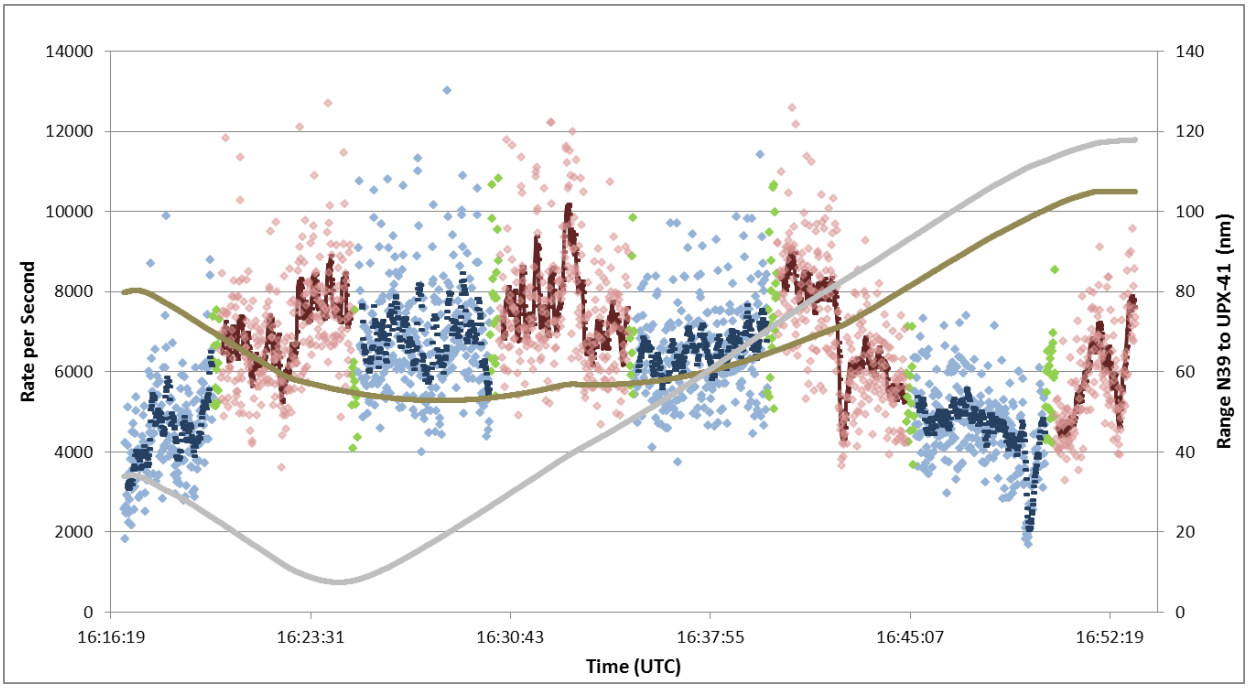


Figure 126. Day 3 – 1090 MHz ATCRBS FRUIT Bottom Antenna, Plot #6

The following is a series of plots showing the Mode S FRUIT Rates measured on Day 3.

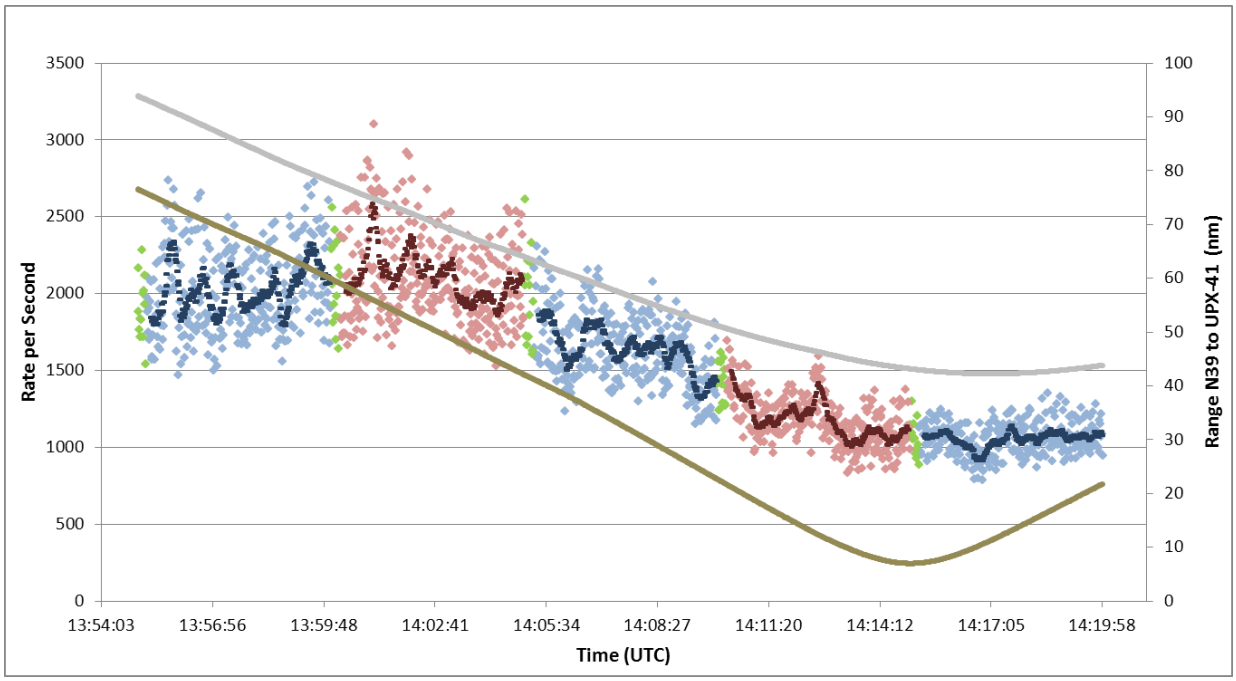


Figure 127. Day 3 – 1090 MHz Mode S FRUIT Top Antenna, Plot #1

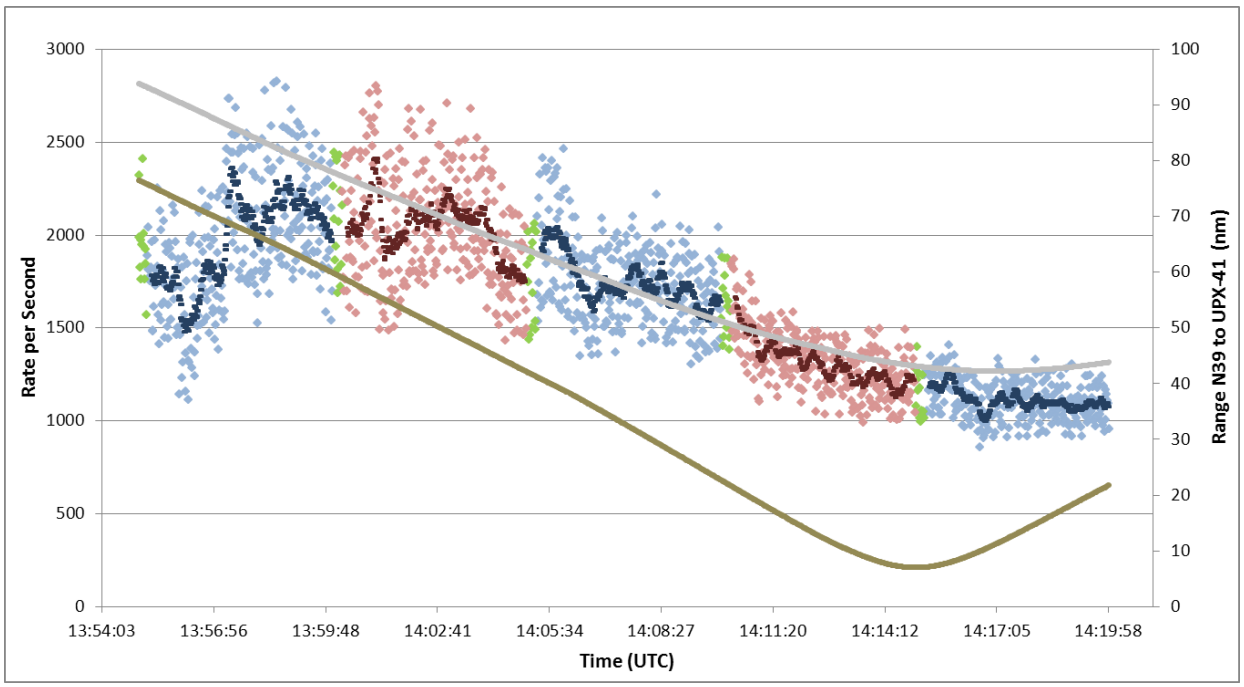


Figure 128. Day 3 – 1090 MHz Mode S FRUIT Bottom Antenna, Plot #1

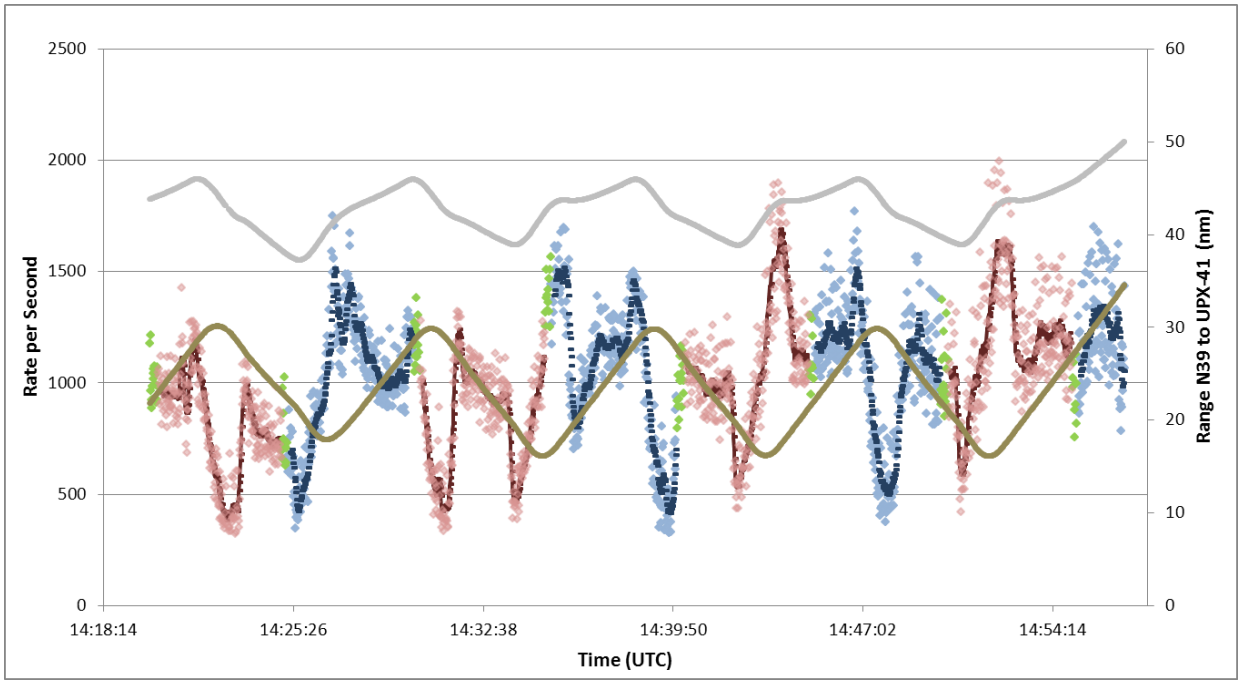


Figure 129. Day 3 – 1090 MHz Mode S FRUIT Top Antenna, Plot #2

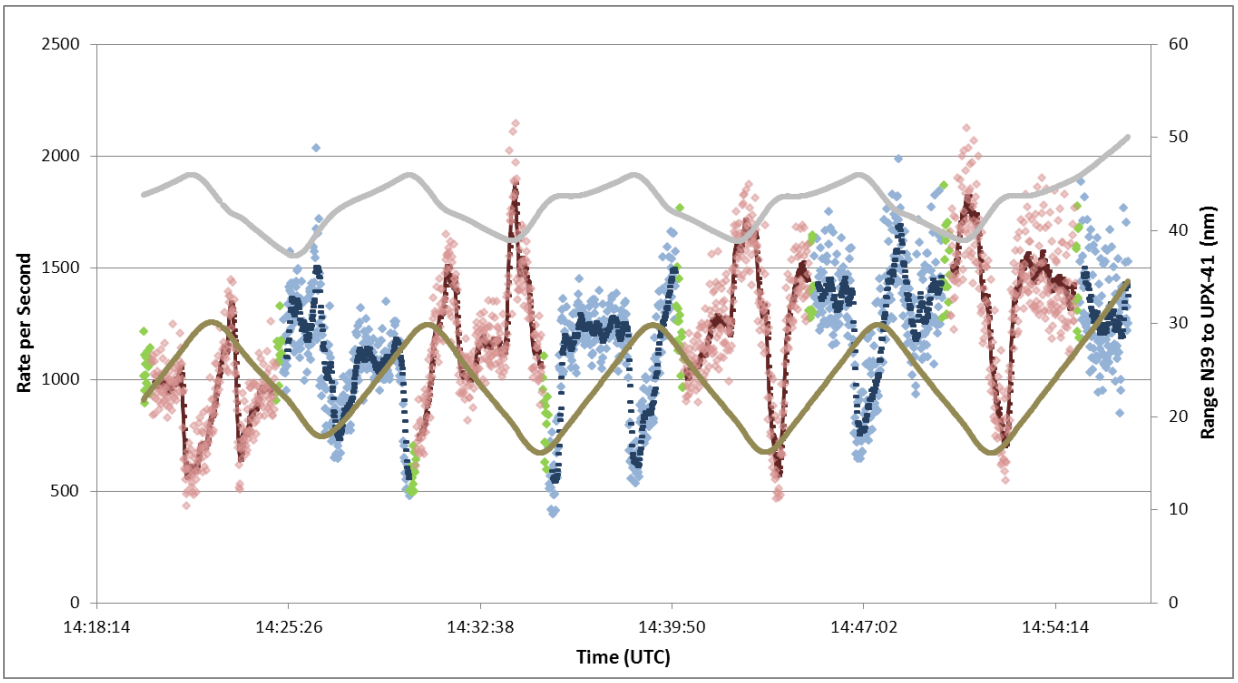


Figure 130. Day 3 – 1090 MHz Mode S FRUIT Bottom Antenna, Plot #2

N39 was in a holding pattern in Figure 129 and Figure 130.

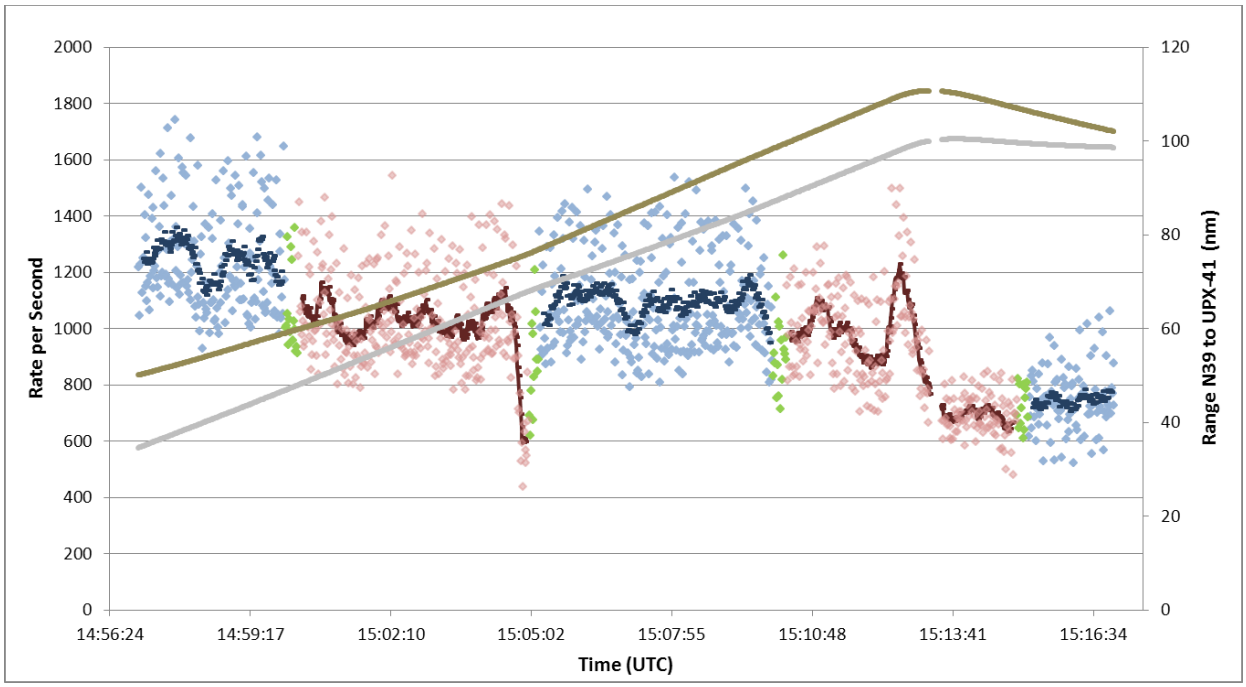


Figure 131. Day 3 – 1090 MHz Mode S FRUIT Top Antenna, Plot #3

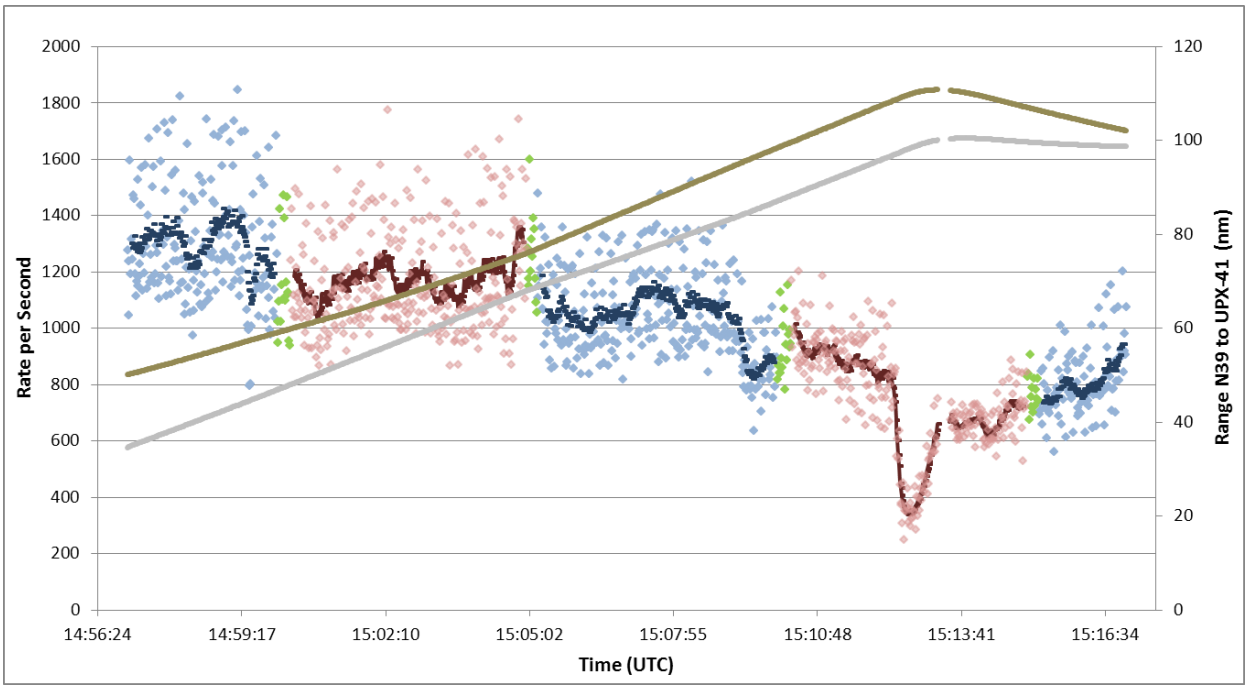


Figure 132. Day 3 – 1090 MHz Mode S FRUIT Bottom Antenna, Plot #3

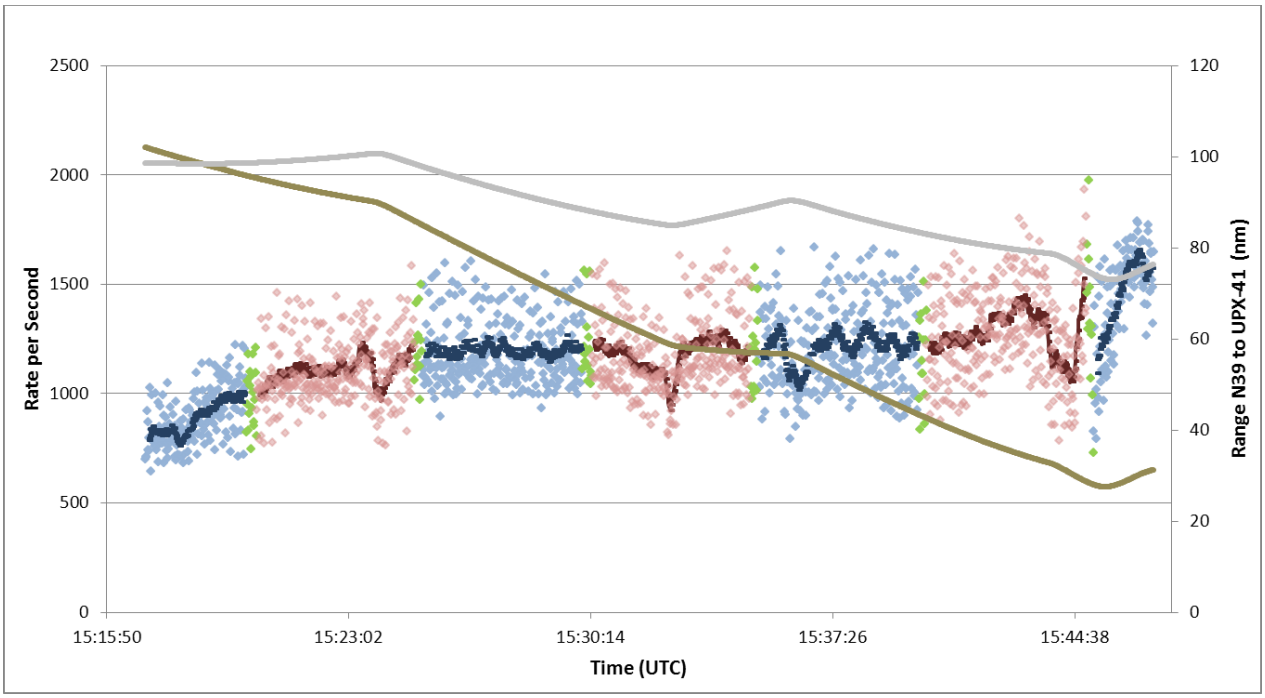


Figure 133. Day 3 – 1090 MHz Mode S FRUIT Top Antenna, Plot #4

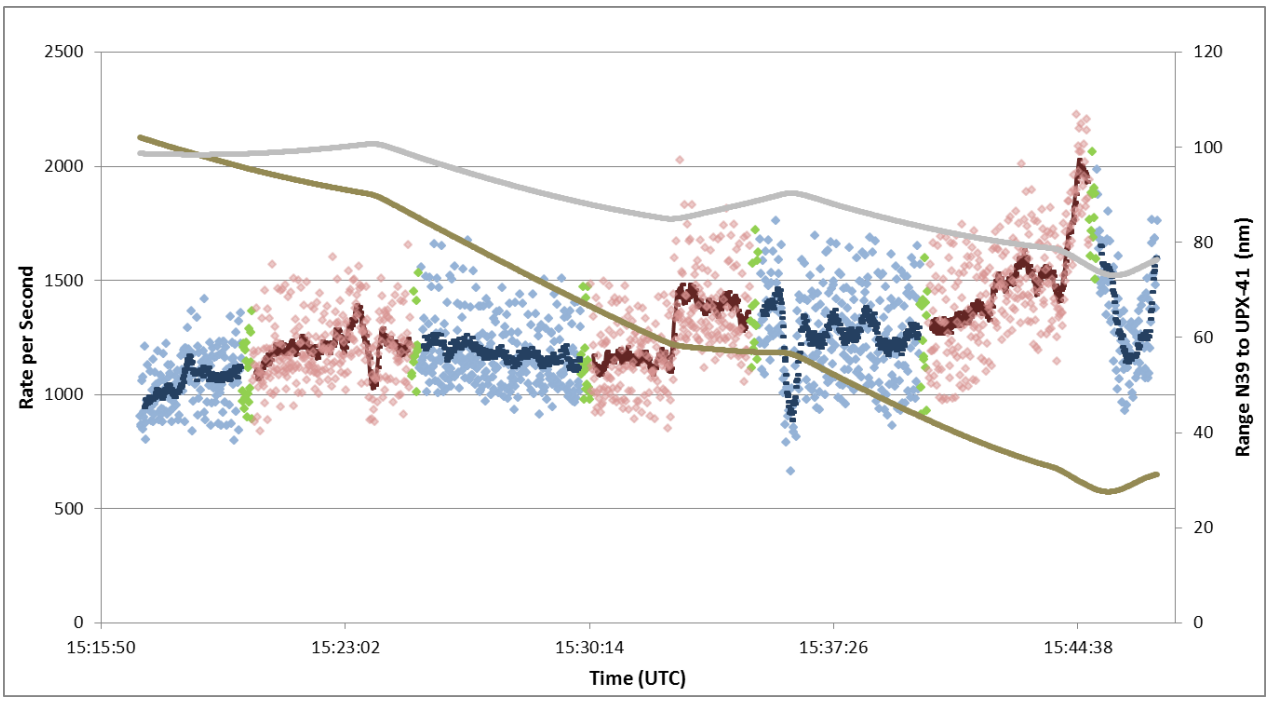


Figure 134. Day 3 – 1090 MHz Mode S FRUIT Bottom Antenna, Plot #4

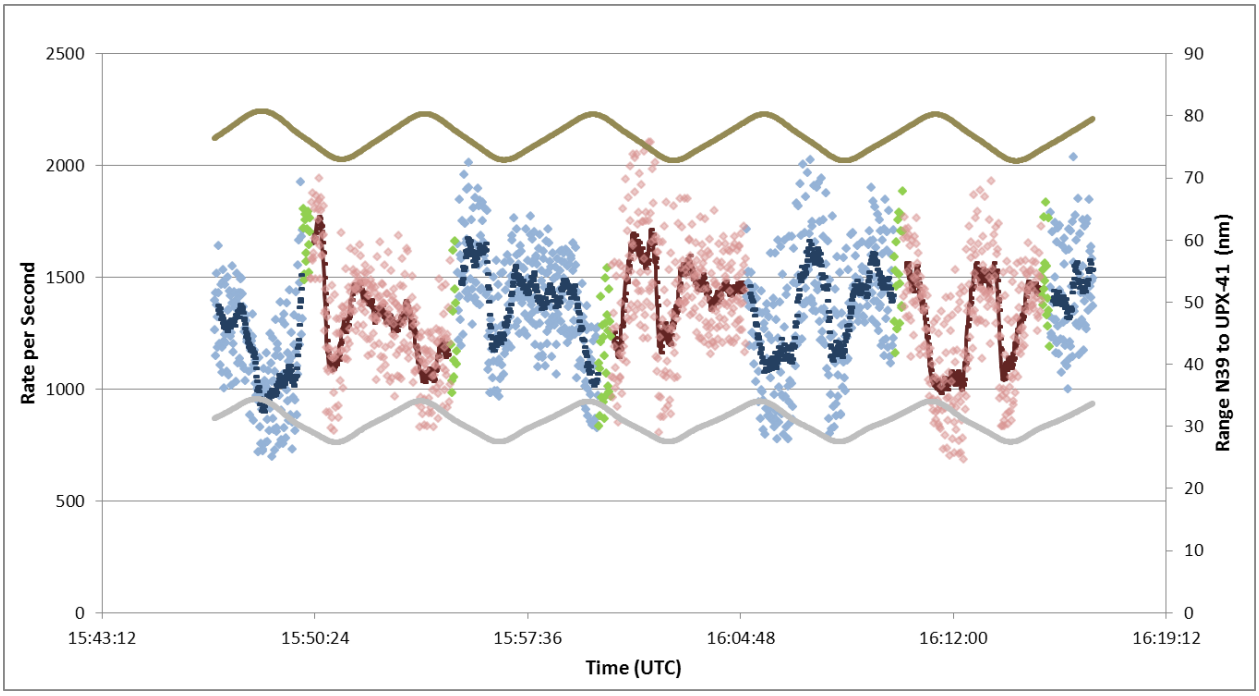


Figure 135. Day 3 – 1090 MHz Mode S FRUIT Top Antenna, Plot #5

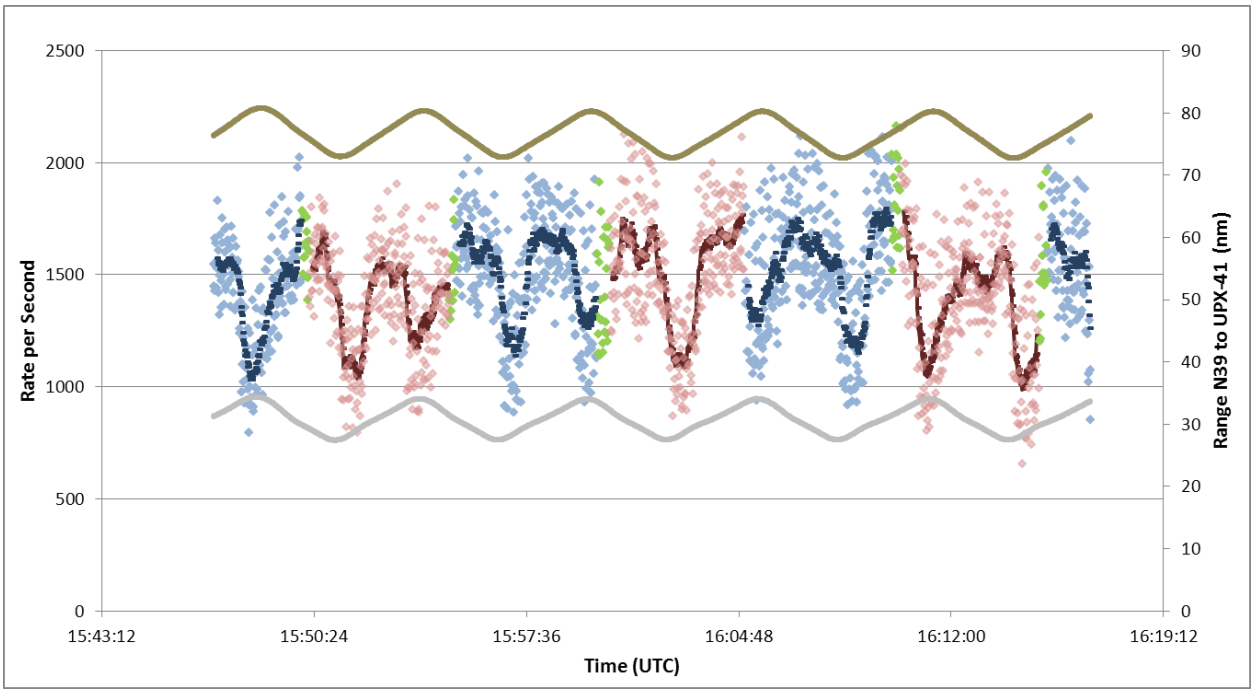


Figure 136. Day 3 – 1090 MHz Mode S FRUIT Bottom Antenna, Plot #5

N39 was in the second hold on the western side of the circuit in Figure 135 and Figure 136.

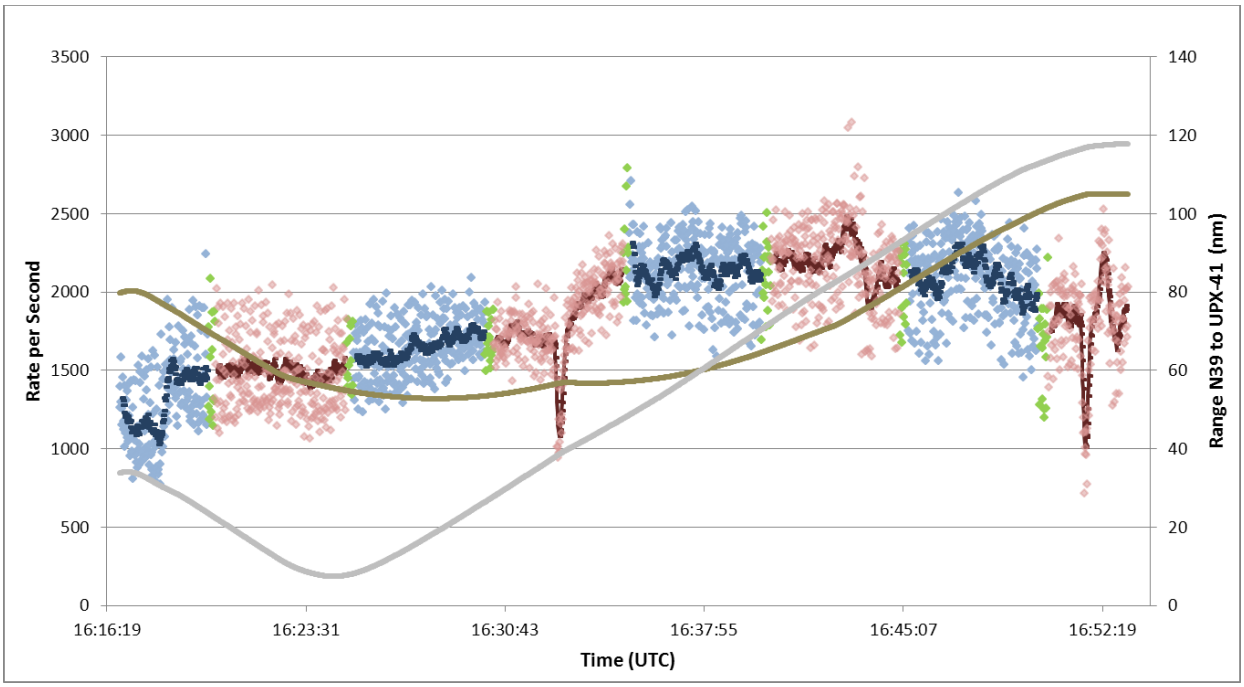


Figure 137. Day 3 – 1090 MHz Mode S FRUIT Top Antenna, Plot #6

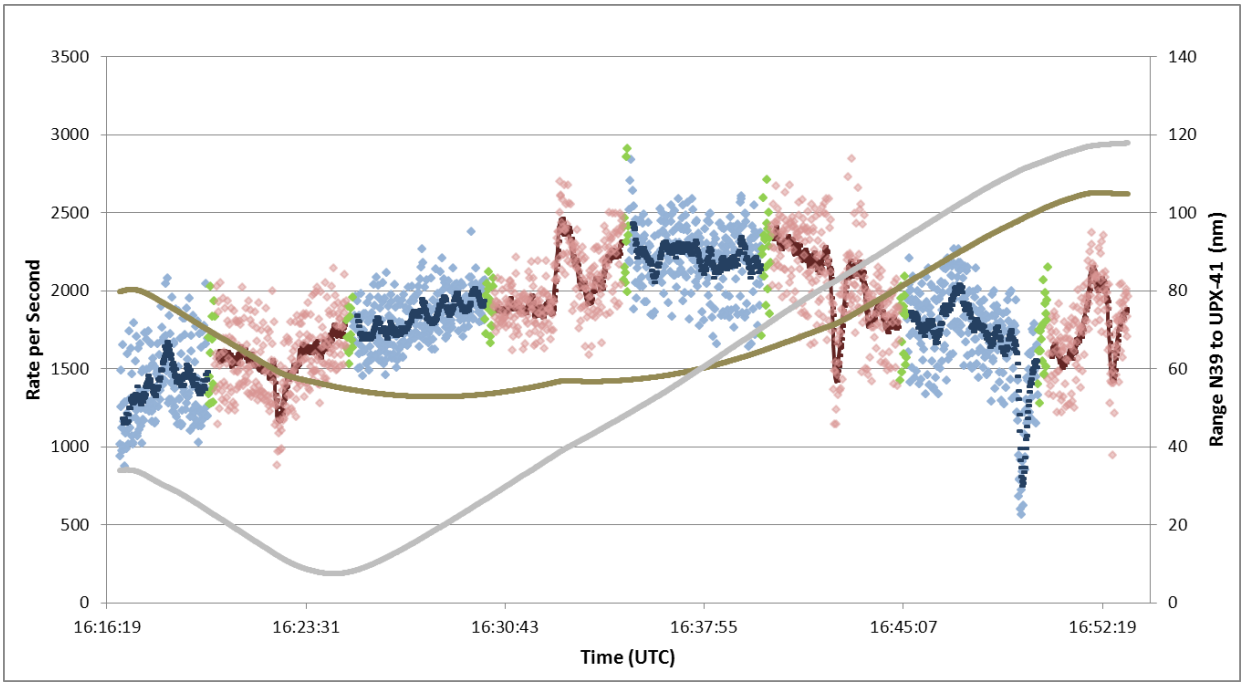


Figure 138. Day 3 – 1090 MHz Mode S FRUIT Bottom Antenna, Plot #6

The following list of figures show the 1090 MHz ATCRBS and Mode S FRUIT Rates measured from the top antenna on Day 4.

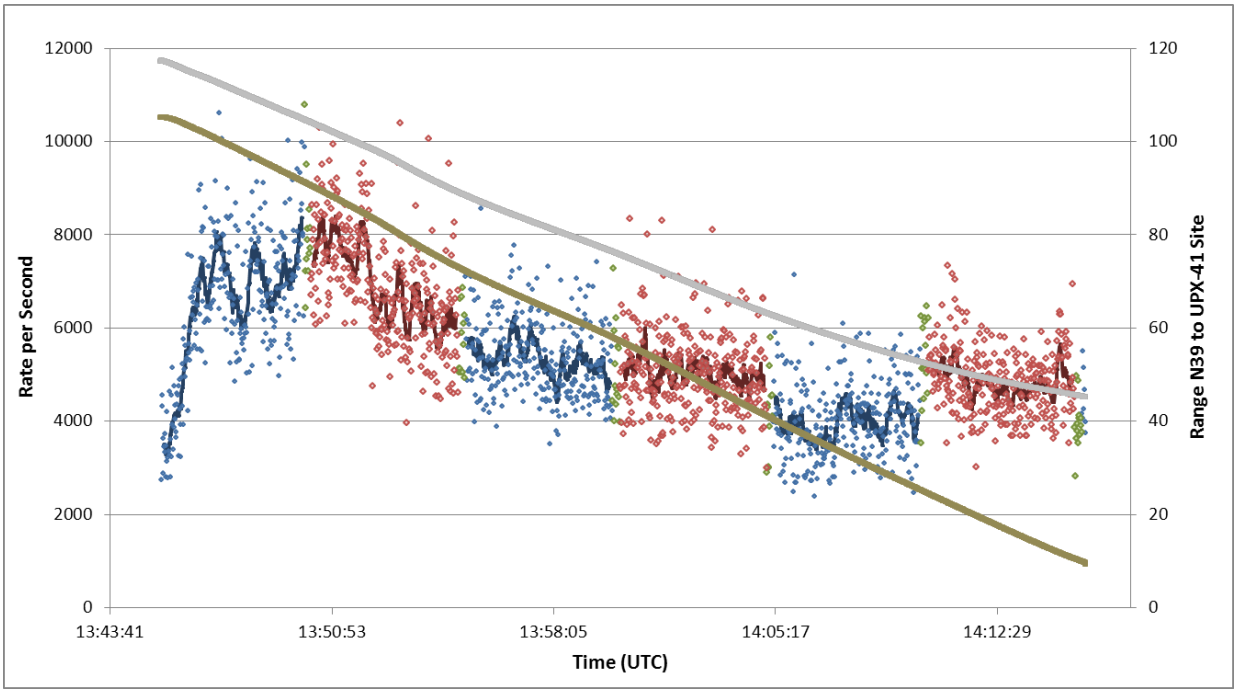


Figure 139. Day 4 – 1090 MHz ATCRBS FRUIT Top Antenna, Plot #1

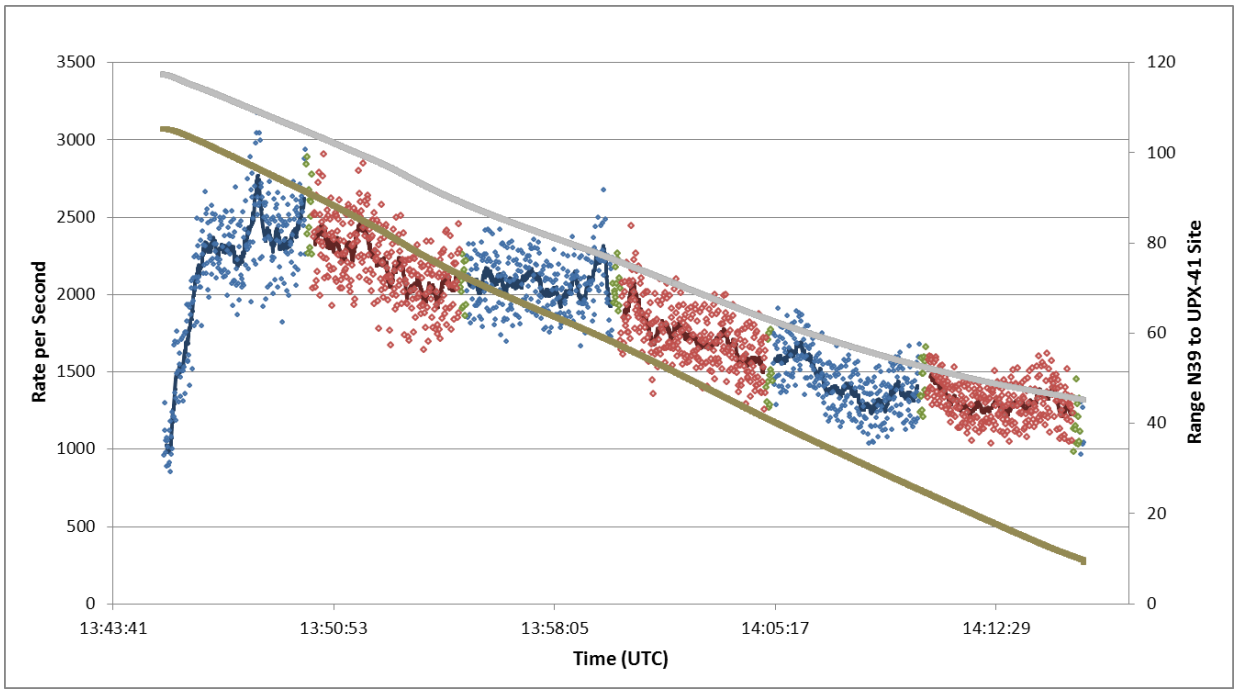


Figure 140. Day 4 – 1090 MHz Mode S FRUIT Top Antenna, Plot #1

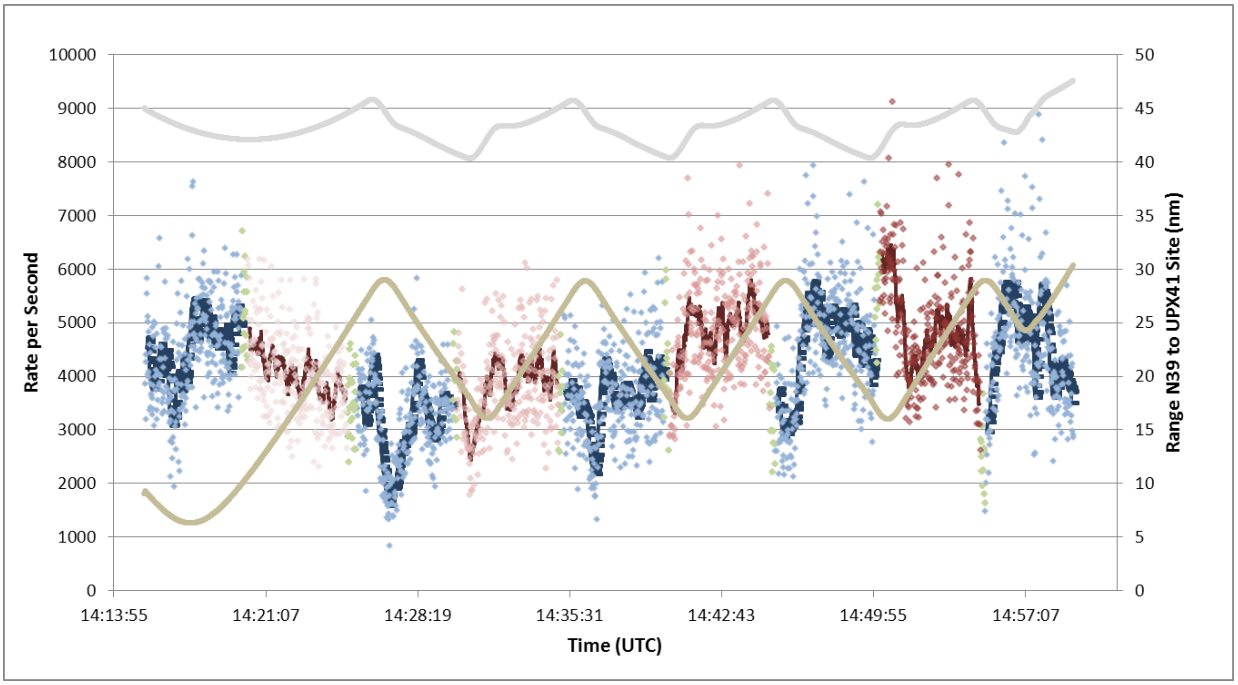


Figure 141. Day 4 – 1090 MHz ATCRBS FRUIT Top Antenna, Plot #2

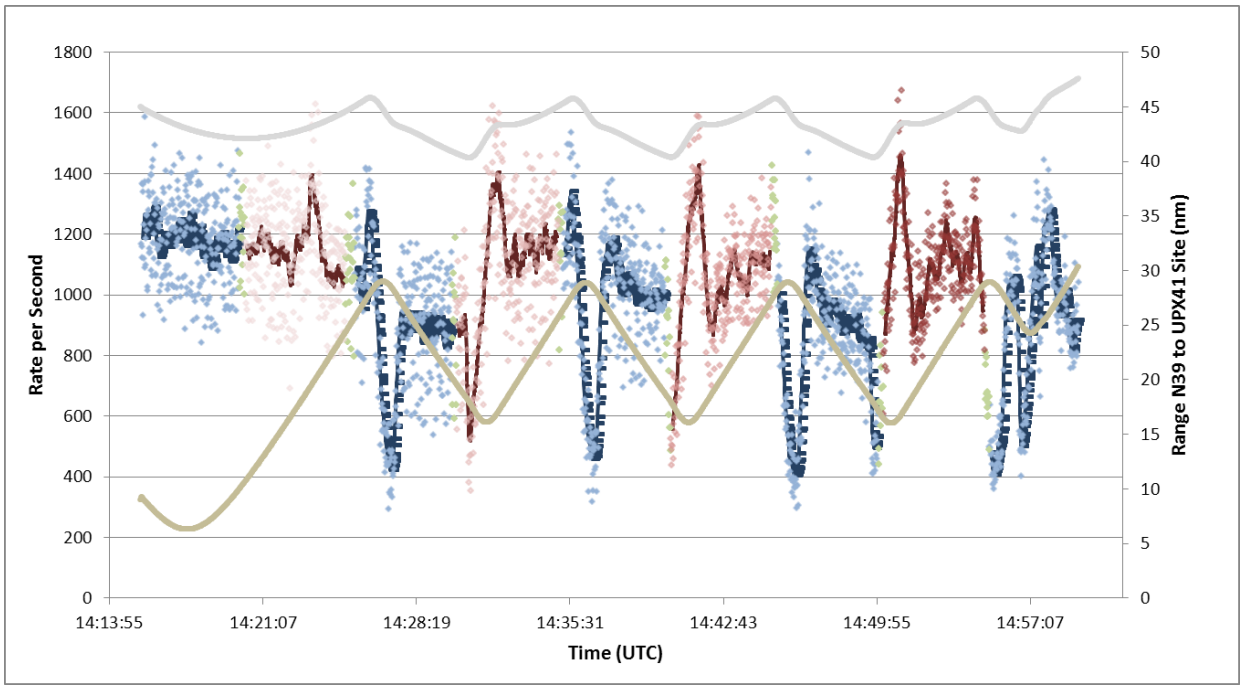


Figure 142. Day 4 – 1090 MHz Mode S FRUIT Top Antenna, Plot #2

N39 was in a holding pattern in Figure 141 and Figure 142.

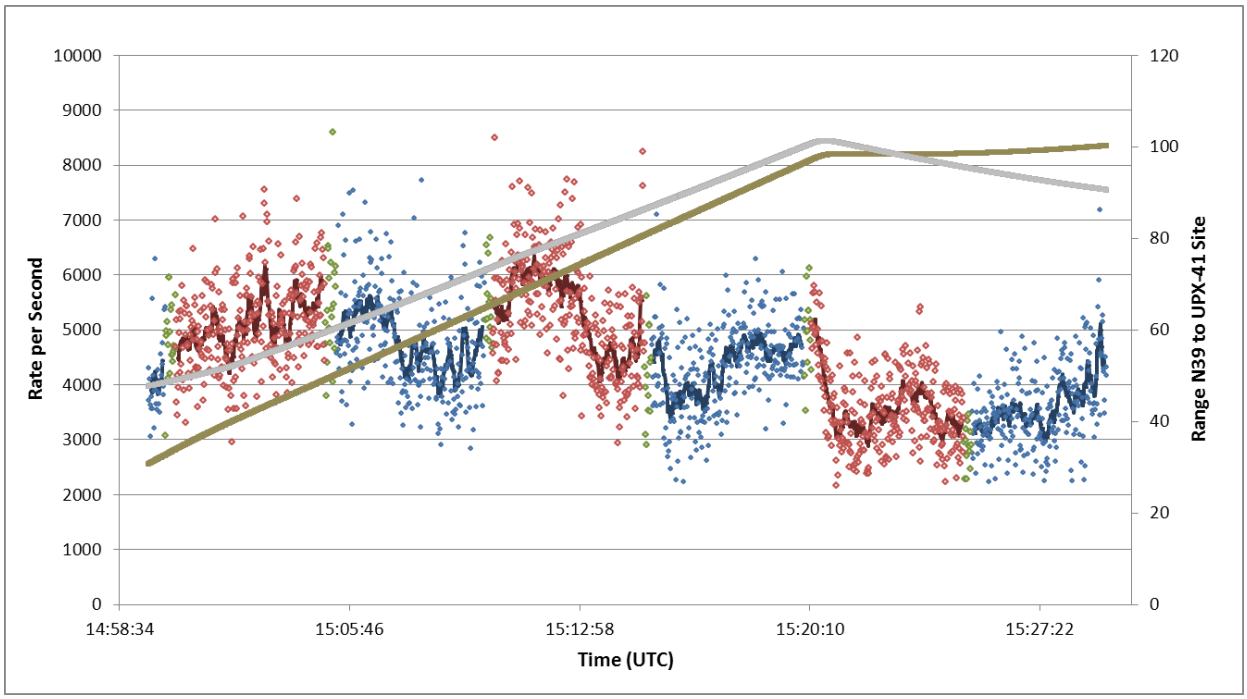


Figure 143. Day 4 – 1090 MHz ATCRBS FRUIT Top Antenna, Plot #3

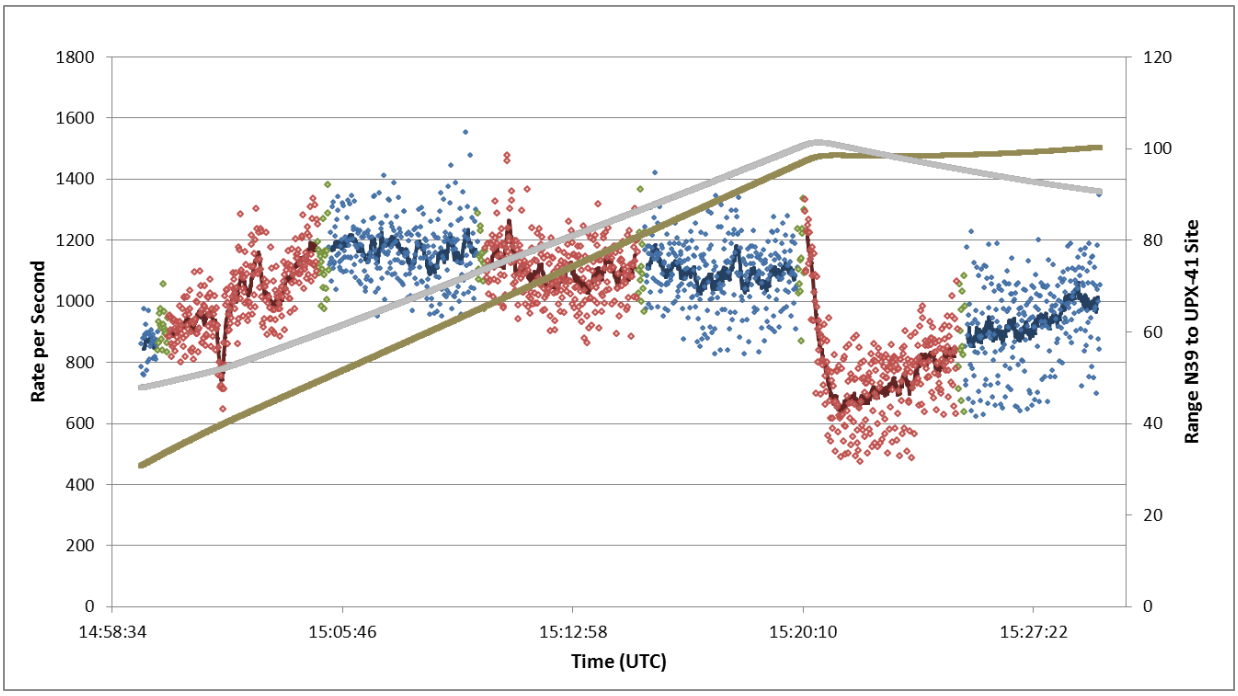


Figure 144. Day 4 – 1090 MHz Mode S FRUIT Top Antenna, Plot #3

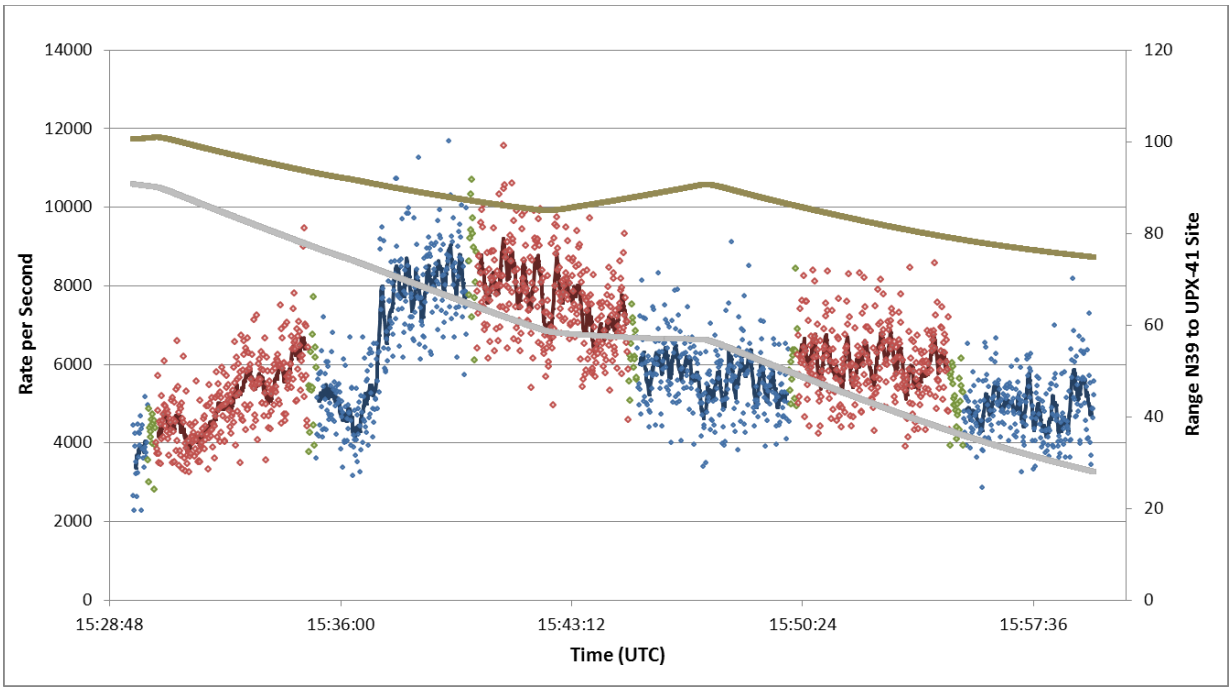


Figure 145. Day 4 – 1090 MHz ATCRBS FRUIT Top Antenna, Plot #4

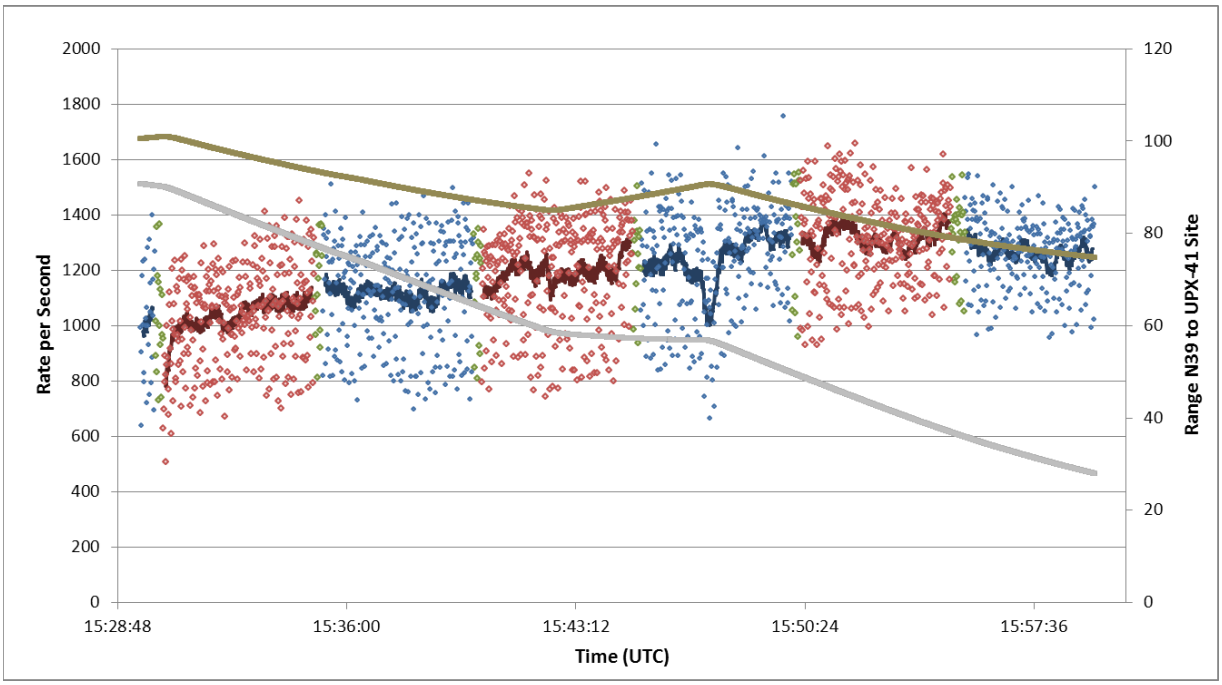


Figure 146. Day 4 – 1090 MHz Mode S FRUIT Top Antenna, Plot #4

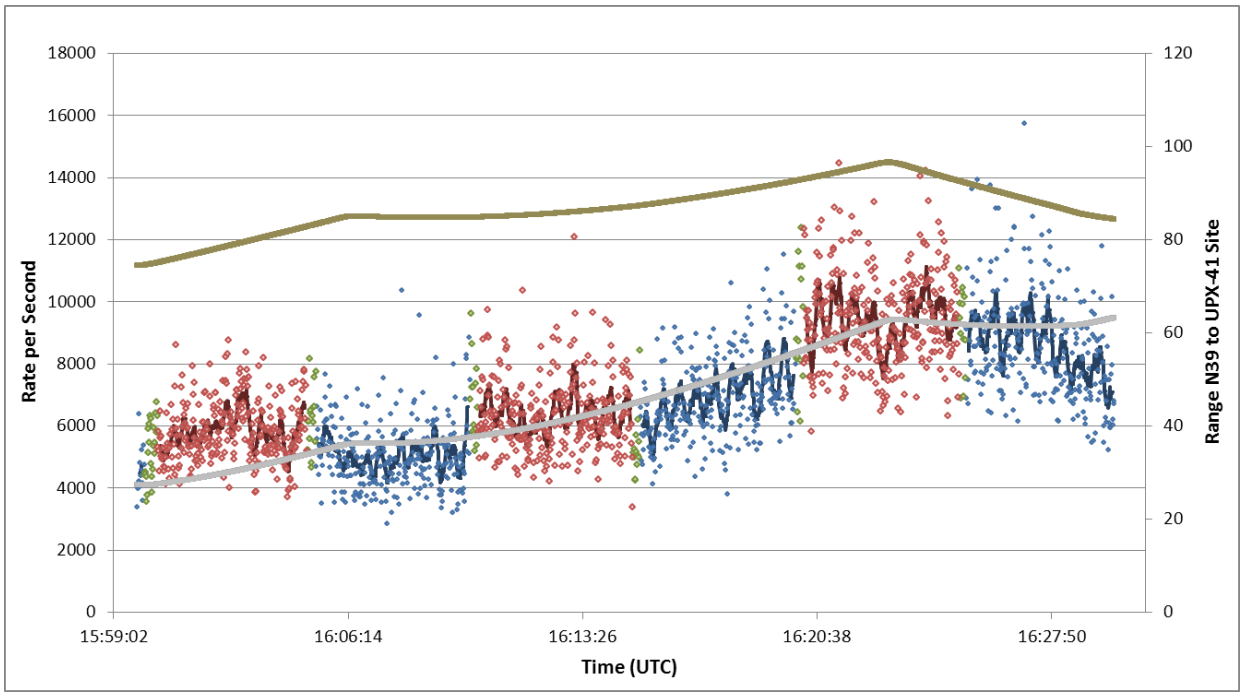


Figure 147. Day 4 – 1090 MHz ATCRBS FRUIT Top Antenna, Plot #5

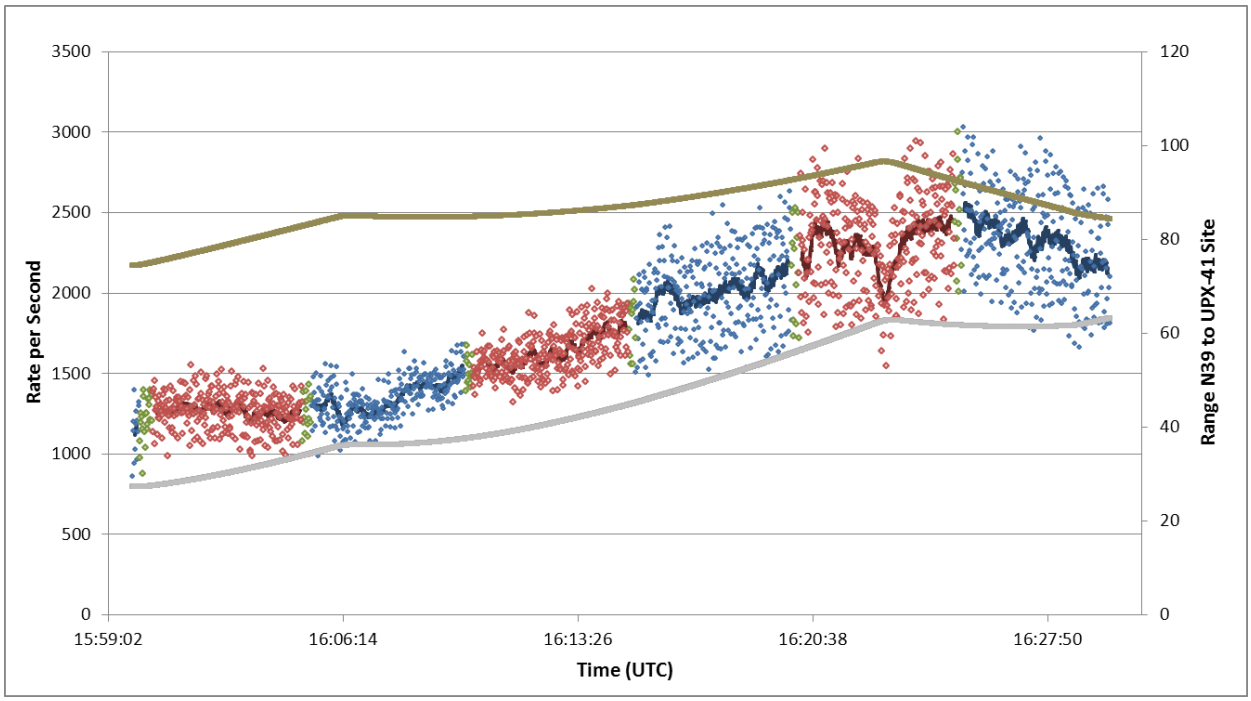


Figure 148. Day 4 – 1090 MHz Mode S FRUIT Top Antenna, Plot #5

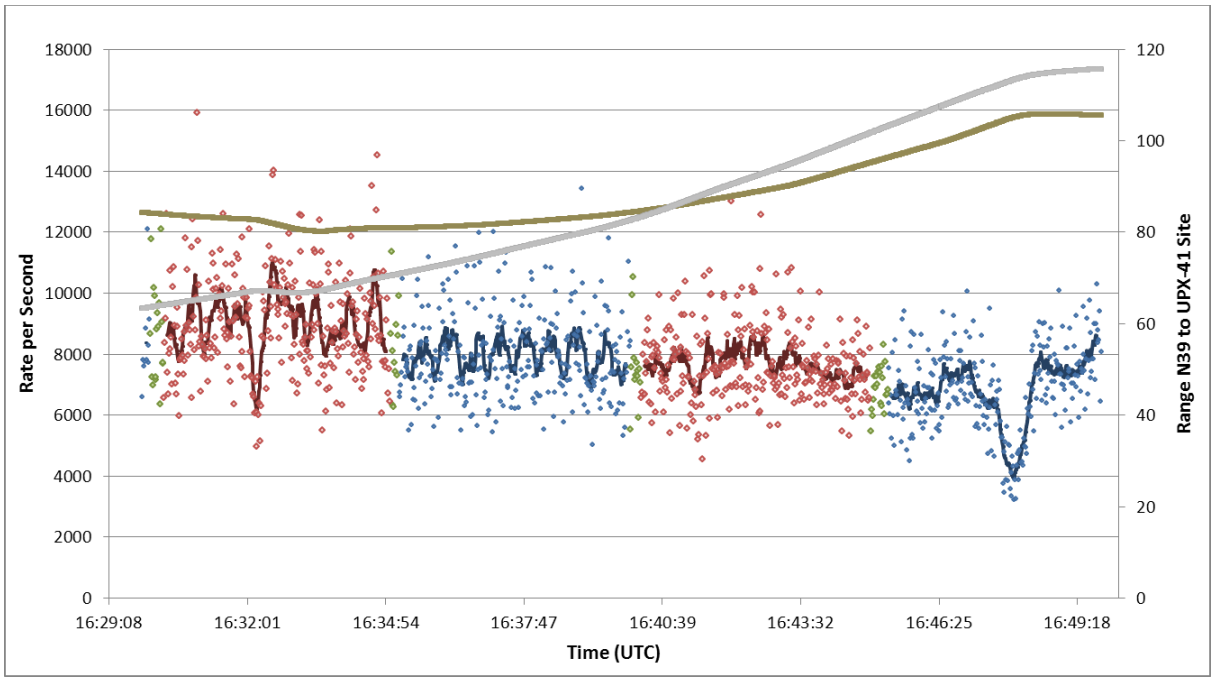


Figure 149. Day 4 – 1090 MHz ATCRBS FRUIT Top Antenna, Plot #6

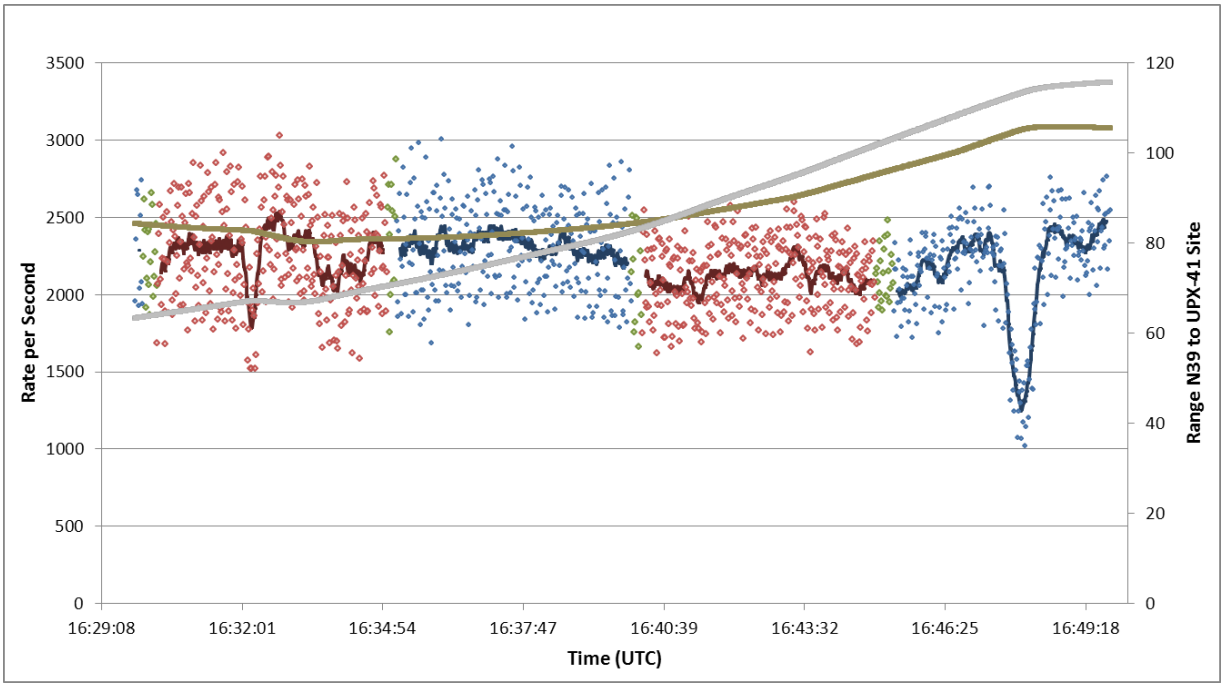


Figure 150. Day 4 – 1090 MHz Mode S FRUIT Top Antenna, Plot #6

The preceding series of plots show the complete 1090 MHz measurement data for ATCRBS and Mode S FRUIT from Day 3 and Day 4. The purpose of the test conducted was to measure the AN/UPX-41(C) system's impact on the 1090 MHz FRUIT environment. From previous efforts to measure 1090 MHz FRUIT environments, it is known that there are significant variations in

FRUIT rates from even slight changes in time and location. Even more significant variations occur when the aircraft is tilted when turning. This occurs due to changing the orientation of the external antennas and shielding from the aircraft fuselage and wings. These variations can be seen in most of the preceding plots. Therefore only some of the 5-minute Active/Off intervals can be used to compare FRUIT rates to attempt to assess AN/UPX-41(C) system's impact.

There were 18 5-minute on cycles recorded on Day 3 and another 18 on Day 4. Two times during Day 3 and one time on Day 4 a holding pattern was executed with the intention of taking measurements in a semi fixed geographic area but this proved to be useless because the frequent turning of the aircraft and resulting tilting of the antennas caused even greater variations in data rates at the antennas. These 5-minute samples were excluded from analysis. Other 5-minute samples taken in level flight were excluded because the overall 1090 MHz FRUIT level was trending up or down, compromising the ability to determine changes that may be associated with the AN/UPX-41(C) system. Seven samples from Day 3 and thirteen samples from Day 4 were selected for analysis because of the stability of the aircraft and environment. To further reduce variability, the selected samples were reduced to using only the last 60 seconds before and the first 60 seconds after a transition from Off-to-Active or Active-to-Off. The geographic locations of the selected samples are marked on the flight path plots (Figure 113 and Figure 114) with the Off cycle in blue and the Active cycle in red.

Figure 151 and Figure 152 show the measured ATCRBS FRUIT rate from the top and bottom antennas on test day 3 for each of the 7 selected 60-seconds Active to 60-seconds Off (or Off to Active) cycles that were used to measure the AN/UPX-41(C) system's impact on 1090 MHz ATCRBS environment. Each data point is the 1-second FRUIT rate and the dark centered line is the 60-seconds average. Again, blue indicates that the four LBTS are Off, and red indicates that all four are Active. The time mark on the horizontal axis indicates the start of the 120-second test intervals. The test sample intervals are not necessarily consecutive in time. With the ATCRBS 1090 MHz data, the average FRUIT rate is always higher in the 60-second Active half of each 120-second sample. The overall measured differences are quantified in Table 20.

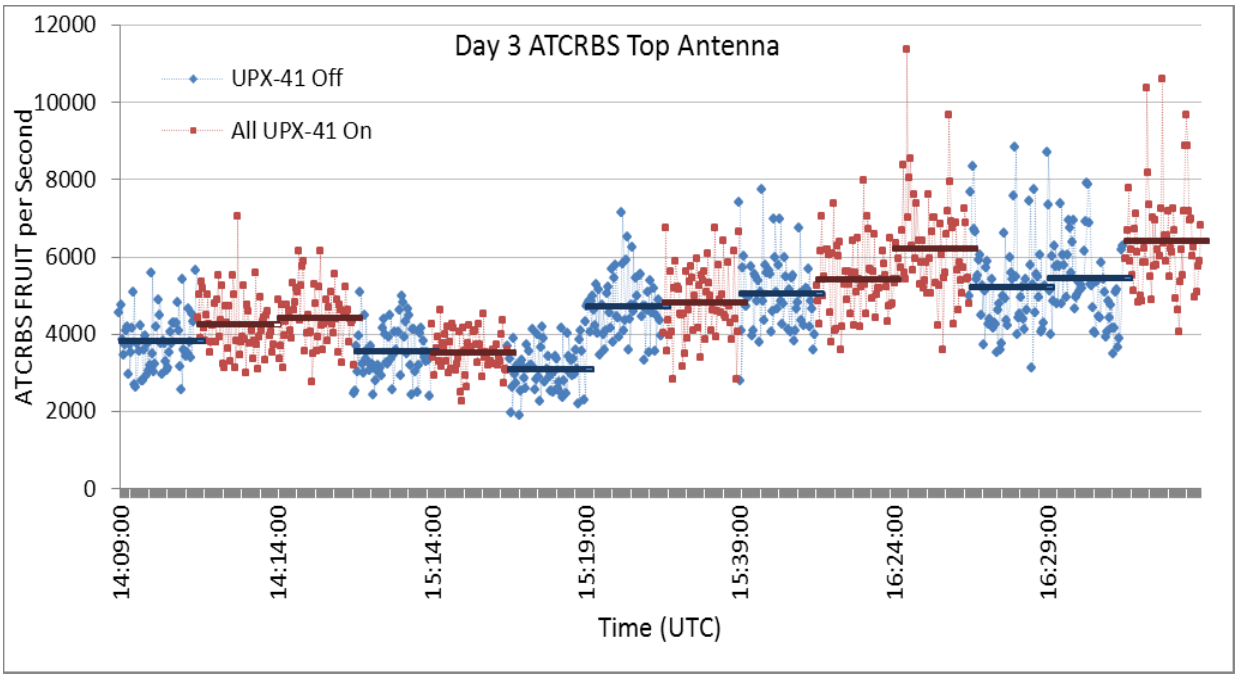


Figure 151. Day 3 – Top Antenna ATCRBS FRUIT Rate, 60-Seconds Active vs. 60-Seconds Off Samples

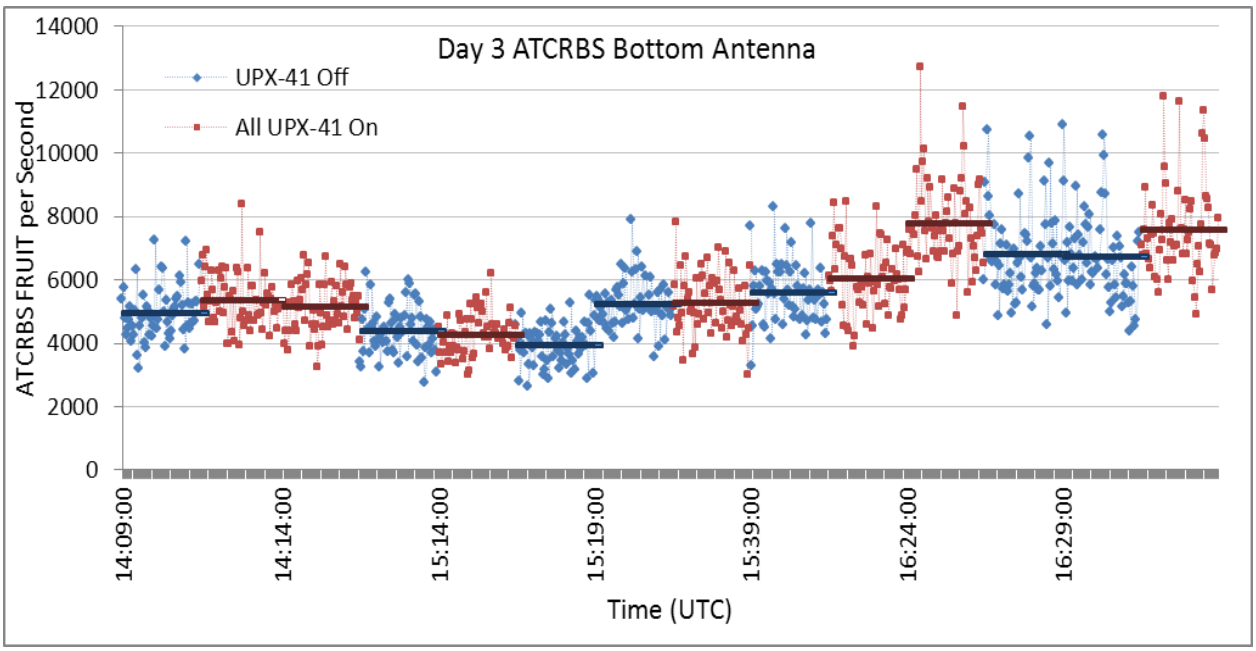


Figure 152. Day 3 – Bottom Antenna ATCRBS FRUIT Rate, 60-Seconds Active vs. 60-Seconds Off Samples

The measured Mode S 1090 MHz FRUIT rates from the same samples from Day 3 are shown in Figure 153 and Figure 154. With the Mode S 1090 MHz data, the average FRUIT rate is usually similar in the two 60-second halves of each sample. The AN/UPX-41(C) system is not expected to impact Mode S FRUIT. The overall measured differences are quantified in Table 21.

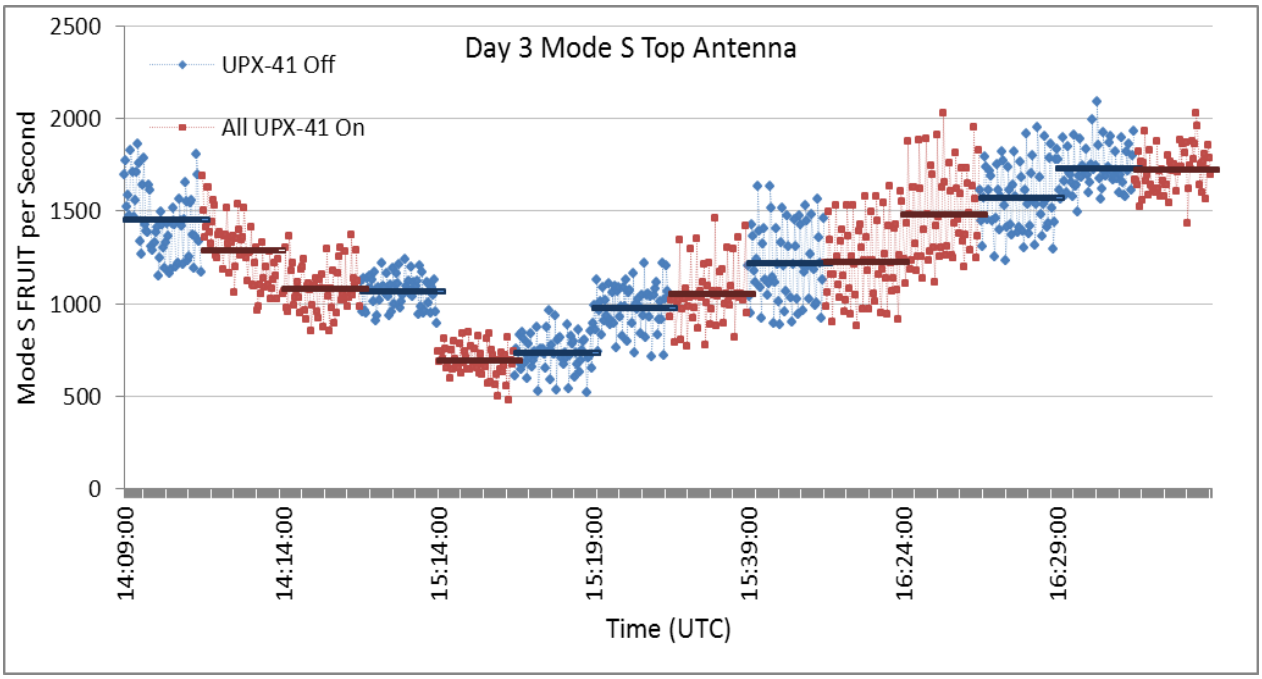


Figure 153. Day 3 – Top Antenna Mode S FRUIT Rate, 60-Seconds Active vs. 60-Seconds Off Samples

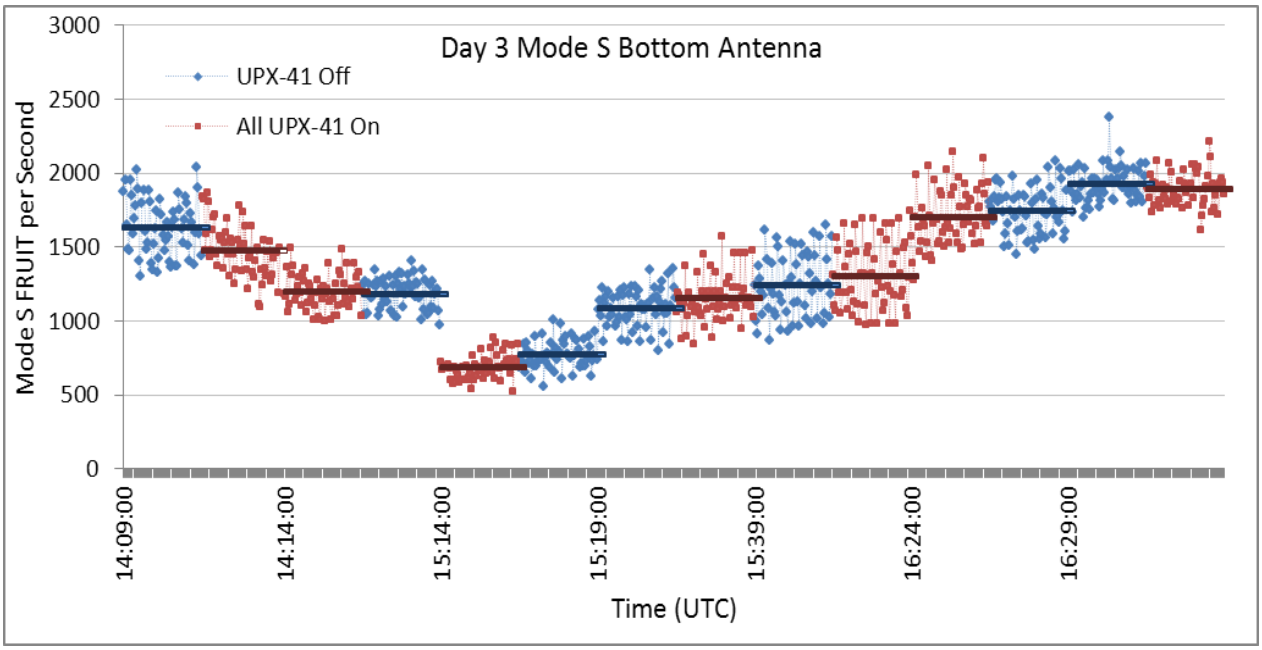


Figure 154. Day 3 – Bottom Antenna Mode S FRUIT Rate, 60-Seconds Active vs. 60-Seconds Off Samples

Figure 155 and Figure 156 use the same format to show the thirteen Day 4 test samples. In this case, only the top antenna data was used so Figure 155 is the measured ATCRBS FRUIT rates and Figure 156 is the Mode S FRUIT rates. Again, the ATCRBS FRUIT rates show a more definite increase when the LBTS are Active. The increase is quantified in subsequent sections.

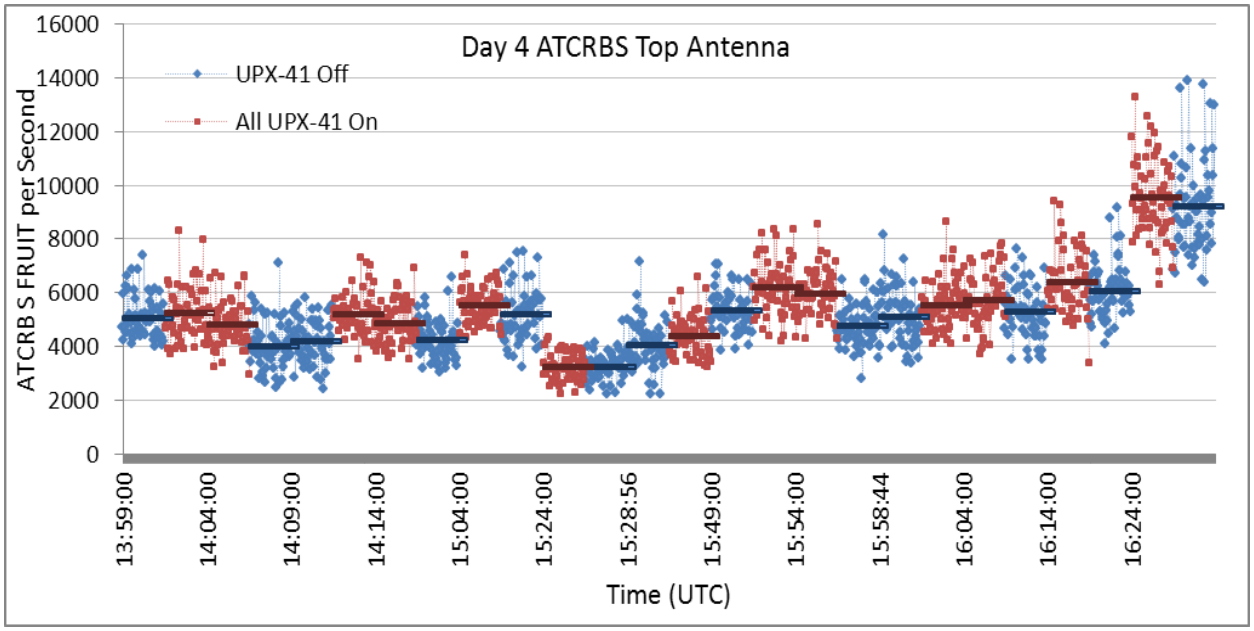


Figure 155. Day 4 – Top Antenna ATCRBS FRUIT Rate, 60-Seconds Active vs. 60-Seconds Off Samples

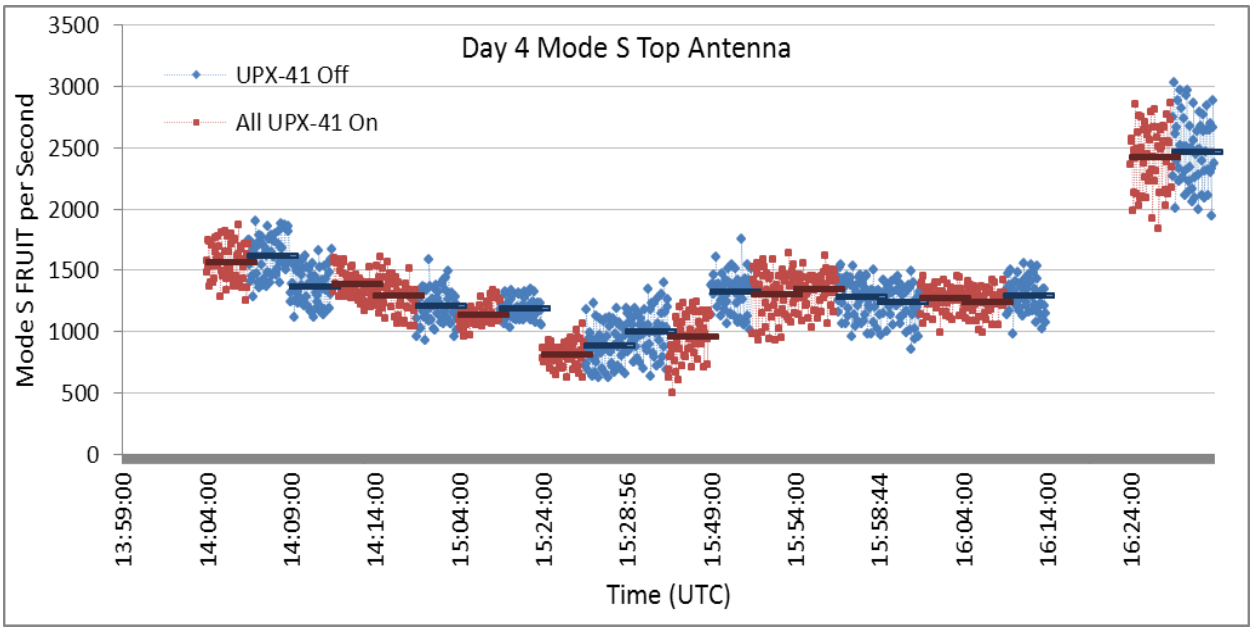


Figure 156. Day 4 – Top Antenna Mode S FRUIT Rate, 60-Seconds Active vs. 60-Seconds Off Samples

Table 20 shows a compilation of the measured 1090 MHz impact from the AN/UPX-41(C) system from Day 3. There a row of values for each of the seven samples showing the 60-second average Mode S and ATCRBS FRUIT rates with the LBTS Off and Active along with the delta. The bottom row shows the overall average. The delta varies significantly from sample to sample especially with ATCRBS. There are a lot of contributors to the 1090 MHz environment in addition to the AN/UPX-41(C) systems. There are other interrogators, the aircraft density varies, the L-band antennas used for measuring are somewhat shielded especially when the aircraft is

maneuvering, The overall average delta for Mode S shows a low negative value that is just measurement variation. The overall average deltas for ATCRBS are 597.6 and 541.7.

Table 20. AN/UPX-41(C) System Impact on the 1090 MHz Environment – Day 3

Day 3	Mode S						ATCRBS					
	Top Antenna			Bottom Antenna			Top Antenna			Bottom Antenna		
Transition Time	LBTS Off	LBTS Active	Delta	LBTS Off	LBTS Active	Delta	LBTS Off	LBTS Active	Delta	LBTS Off	LBTS Active	Delta
14:10	1452.0	1287.9	-164.1	1637.5	1474.9	-162.6	3811.7	4244.4	432.7	4952.6	5374.5	421.9
14:15	1067.4	1083.1	15.7	1186.7	1199.9	13.2	3554.5	4440.8	886.3	4386.1	5136.5	750.4
15:15	733.9	691.1	-42.8	771.0	686.2	-84.8	3108.2	3542.3	434.1	3947.3	4275.4	328.1
15:20	978.8	1052.3	73.5	1090.3	1153.0	62.7	4729.6	4821.8	92.2	5253.9	5274.9	21.0
15:40	1219.6	1229.7	10.1	1240.8	1303.9	63.1	5049.9	5424.8	374.9	5584.5	6051.3	466.8
16:25	1569.4	1483.0	-86.4	1748.7	1699.2	-49.5	5234.7	6226.6	991.9	6805.7	7775.8	970.1
16:30	1731.7	1721.5	-10.2	1927.4	1889.2	-38.2	5446.1	6416.9	970.8	6738.2	7571.8	833.6
Average	1250.4	1221.2	-29.2	1371.8	1343.8	-28.0	4419.2	5016.8	597.6	5381.2	5922.9	541.7

Table 21 is a similar table showing the measured values from Day 4. Again, only the top antenna data was used for the analysis of Day 4. A similar overall average was measured the ATCRBS delta here being 531.9. The measured results for the two days are consistent.

Table 21. AN/UPX-41(C) System Impact on the 1090 MHz Environment – Day 4

Day 4	Mode S			ATCRBS			
	Top Antenna (Measured)			Top Antenna (Measured)			Calculated Delta
Transition Time	LBTS Off	LBTS Active	Delta	LBTS Off	LBTS Active	Delta	
14:00				5085.1	5255.5	170.4	510.0
14:05	1615.0	1563.4	-51.6	4032.0	4840.3	808.3	614.0
14:10	1373.2	1386.0	12.8	4195.3	5216.2	1020.9	621.0
14:15	1211.3	1300.4	89.1	4228.1	4891.2	663.4	670.0
15:05	1186.6	1134.0	-52.6	5191.3	5547.2	355.9	602.0
15:25	893.2	816.1	-77.1	3266.9	3272.0	5.1	433.0
15:30	1006.9	956.9	-50.0	4064.1	4415.8	351.7	437.0
15:50	1324.4	1304.4	-20.0	5361.5	6223.4	861.9	471.0
15:55	1284.6	1343.9	59.3	4795.3	5972.5	1177.2	441.0
16:00	1246.1	1275.3	29.2	5106.0	5544.9	438.9	518.0
16:05	1292.8	1243.3	-49.5	5287.5	5729.5	442.0	504.0
16:15				6086.1	6394.7	308.6	651.0
16:25	2469.9	2425.3	-44.6	9219.5	9529.6	310.1	755.0
Average	1354.9	1340.8	-14.1	5070.7	5602.5	531.9	555.9

In addition to the measured results presented in Table 21, the last column contains a calculated delta. These values for each sample interval were derived using recorded AN/UPX-41(C) system data. The data contained target reports from replying aircraft each second. The target reports were filtered to include only aircraft that were within 60 nmi of N39 (60 nmi is the approximate MTL range of the test receiver for ATCRBS). The per-second target count was multiplied by the run length as determined by each targets range from the interrogator (see Table 22). This was calculated for each of the four LBTS. The 60-second average was calculated for each Off cycle and each adjacent Active cycle and the difference is shown in the delta column. The overall average delta is 555.9 and this value is consistent with the measured impact. Based on the measured data and the calculated assessment of the AN/UPX-41(C) system's impact on the 1090

MHz environment, with the aircraft density in the test area and four systems operating, the 1090 MHz ATCRBS FRUIT was increased by about 530 to almost 600 replies per second.

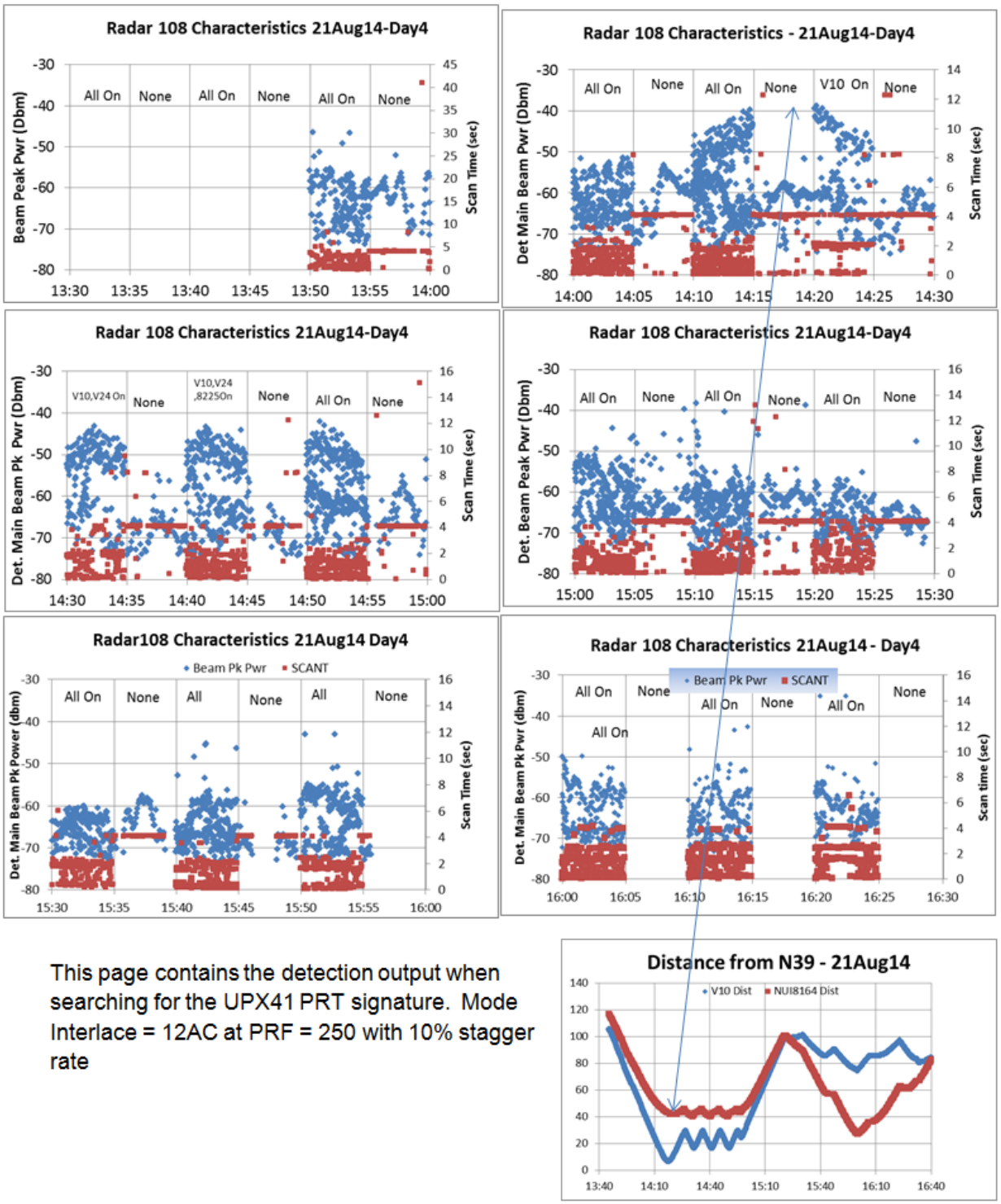
Table 22. Approximate AN/UPX-41(C) System Run Lengths Determined by Data Analysis

Range (nm)	<= 10	10 to 20	20 to 30	30 to 60	60 to 80	80 to 120	120 to 140	140 +
Determined run length (3A&C)	18	16	15	14	13	12	11	10

A.4.1 Comparison of PRT data on Day 3 and Day 4

The data presented on Figure 157 and Figure 158 shows the same time of day for the flights of Day 3 and Day 4. The LBTS were alternating (Active/Off) in 5 minute intervals for the entire portion of the flight shown here. There was one exception, the period of 14:05 to 14:10 of Day 3. V-10 was not turned off until 14:08:50. Note the amplitude continues to increase for part of the interval. This was verified by the log of activity for that day.

There is definitely at least one additional interrogator present on both days that has the same characteristics as the AN/UPX-41(C) system. On Day 4 it appears to be a single interrogator. Note the detected beam power pattern that continues when all LBTS are Off. It is not performing the same way on the two days, however. On the Day 4 flight, the interrogator has a scan rate of approximately 4 seconds, the same as the AN/UPX-41(C) system. On Day 3, however, it appears to not to have a definite scan rate. It is performing more like an E-scan radar or could be multiple sources. The data was compared at the times between 14:35 to 14:40, 14:40 to 14:45, 15:35 to 15:40 and 15:45 to 19:50 when the LBTS were Off to check for a Mode 4 cycle. The interrogator detected during that time did not have a Mode 4 scan.



This page contains the detection output when searching for the UPX41 PRT signature. Mode Interlace = 12AC at PRF = 250 with 10% stagger rate

Figure 157. Radar 108 – Standard AN/UPX-41(C) System Criteria – Day 4

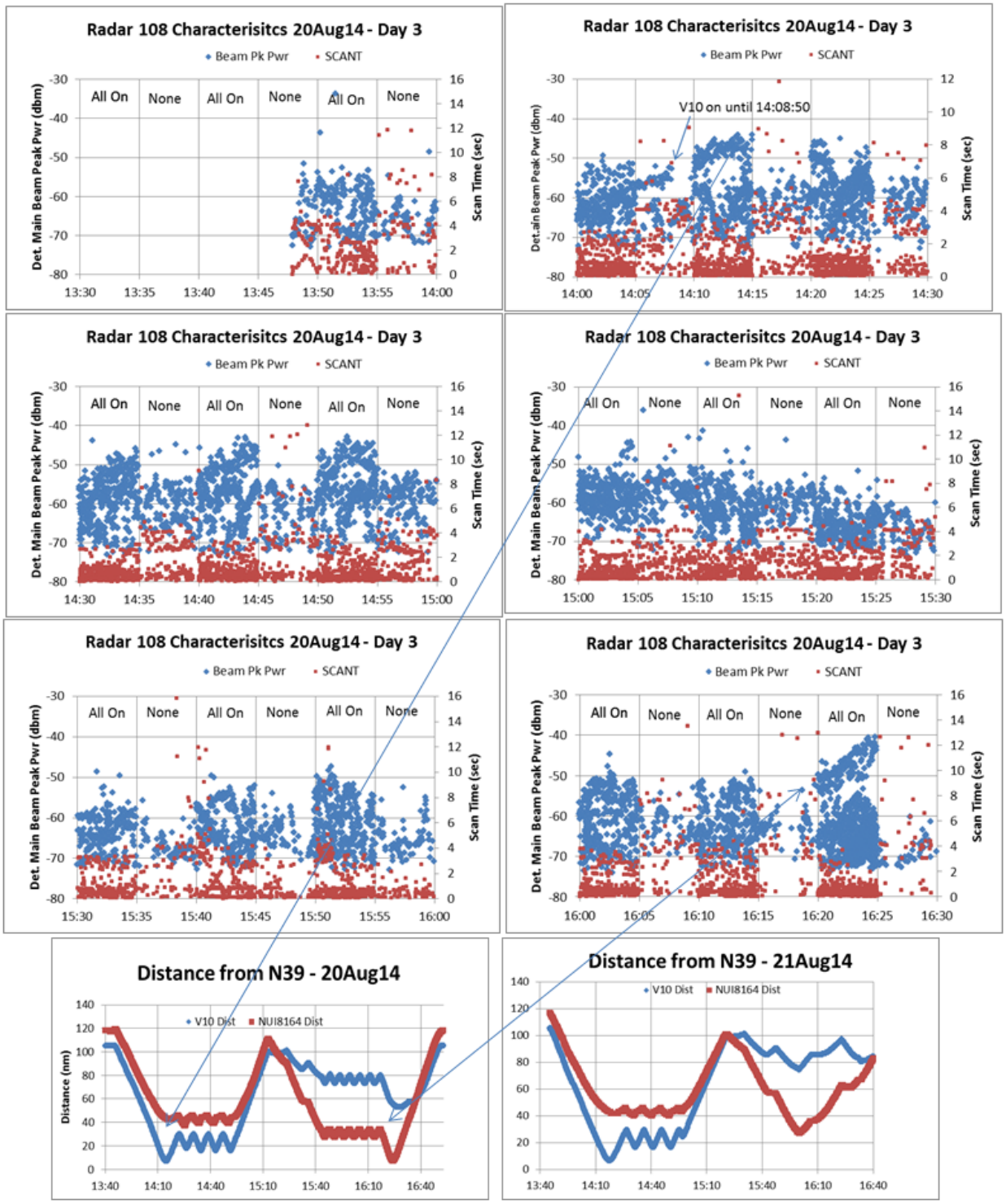


Figure 158. Radar 108 – Standard AN/UPX-41(C) System Criteria – Day 3

A.4.2 Radar 70 Investigation

When we were preparing the data for the PRT processing, we noticed that the number of Mode A interrogations far exceeded all other modes during the data for Day 4. When we investigated, we found that this was from a radar that was also seen during the 7Apr11 flight and 27Jul07 flight. It contains only Mode A interrogations. It has a PRF of approximately 384 per second with a 5% stagger rate. Figure 160 shows the received interrogation power from this interrogator.

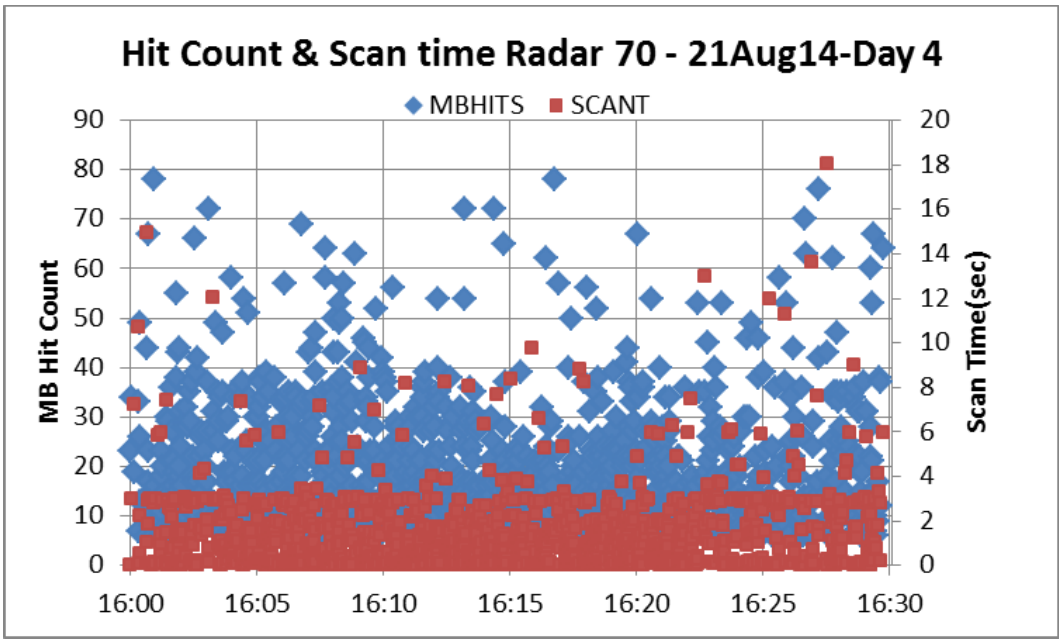


Figure 159. Hit Count & Scan Time – Radar 70 – Day 4

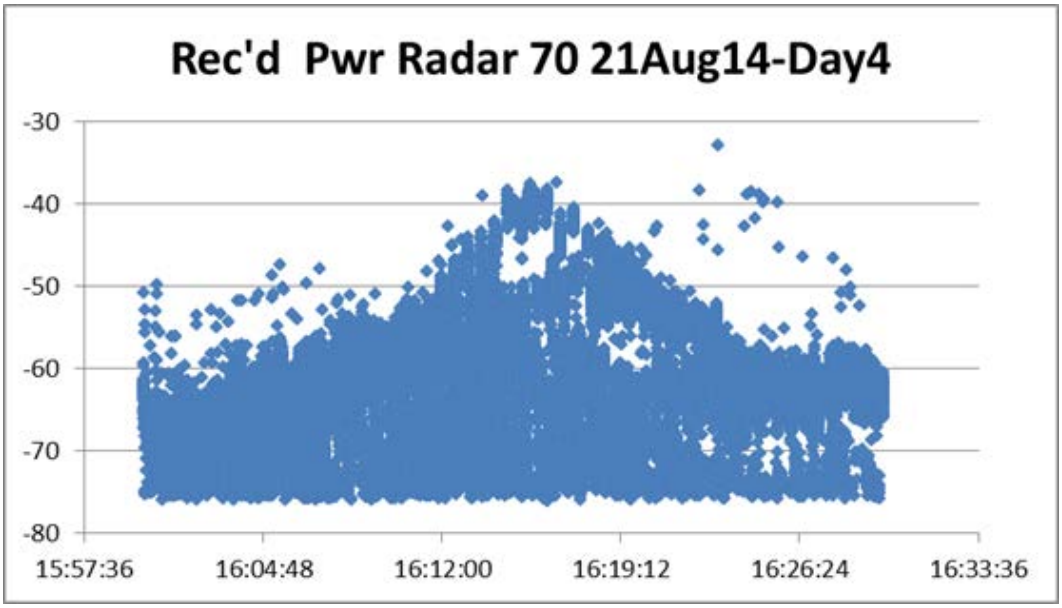


Figure 160. Received Interrogation Power – Radar 70 – Day 4

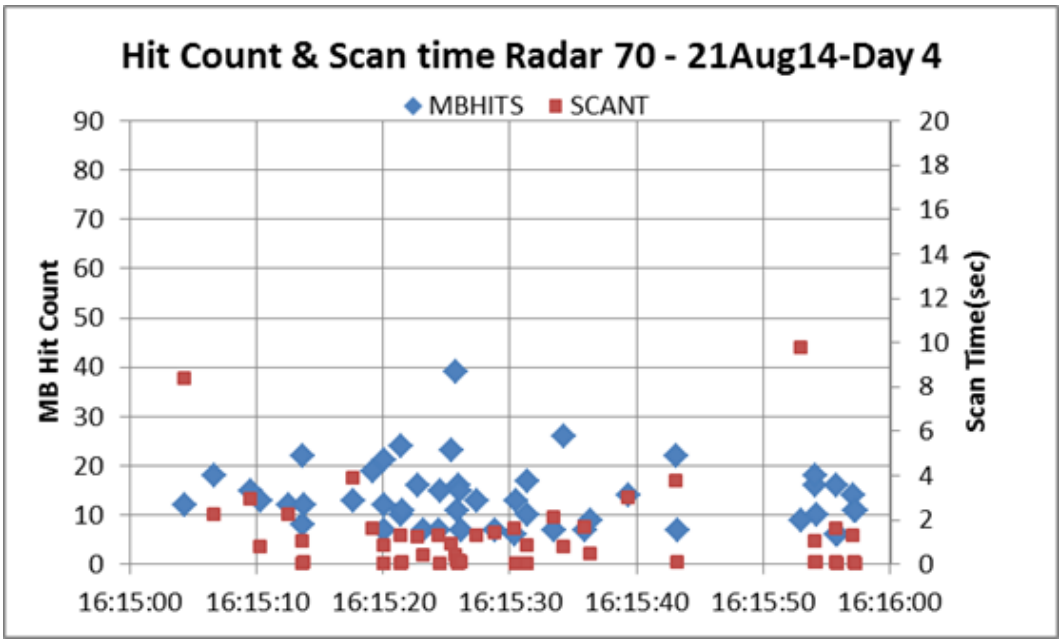


Figure 161. Expanded Hit Count and Scan time Radar 70 – Day 4

This is an E-Scan radar as indicated by the expanded plots above. N39 was pretty close to the source at about 16:15 as the received power was -40dBm. This radar elicited more than 25000 replies from N39 during this period. <u>This sounds like a lot, but it is only about 14 replies per second, so this is not a big deal in itself. There were a total of 88409 unsuppressed Mode A interrogations detected during this 30 minute period, so this means that 28.5% of the Mode A's were from this single radar, so this really is a big deal.</u>

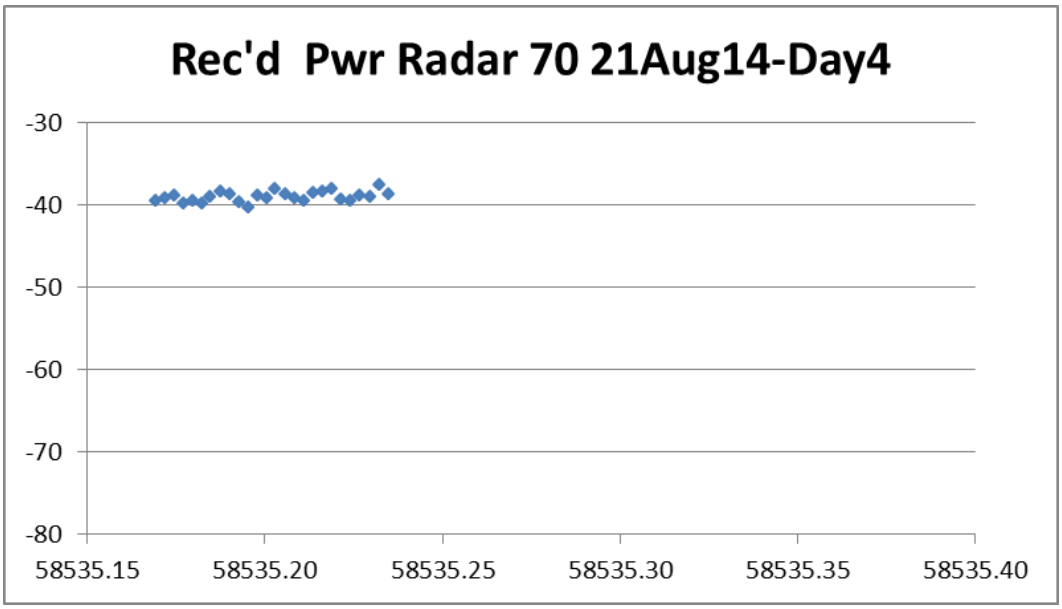


Figure 162. Typical Mainbeam pattern when near to Radar 70 – Day 4

A.4.3 Radar 116 Investigation

Much effort was expended trying to associate interrogation sources to ships in the area. We had no success in this effort. One particular source was unique in that it was not in our existing database and the results showed multiple sources that fit the pattern. The source was named Radar 116 and added to our database. It has an average PRF of 338.7 and a mode interlace pattern of 1,2,A,C.

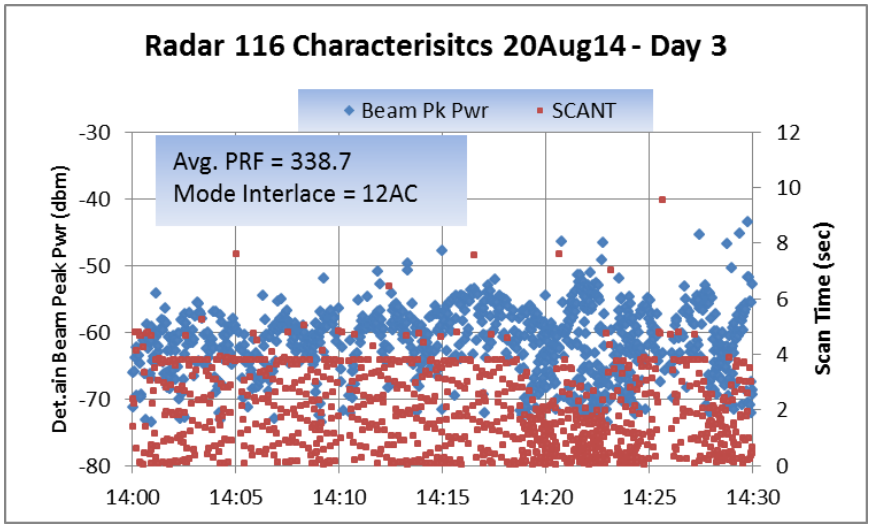


Figure 163. Radar 116 Detected Beam Peak Power and Scan time – Day 3

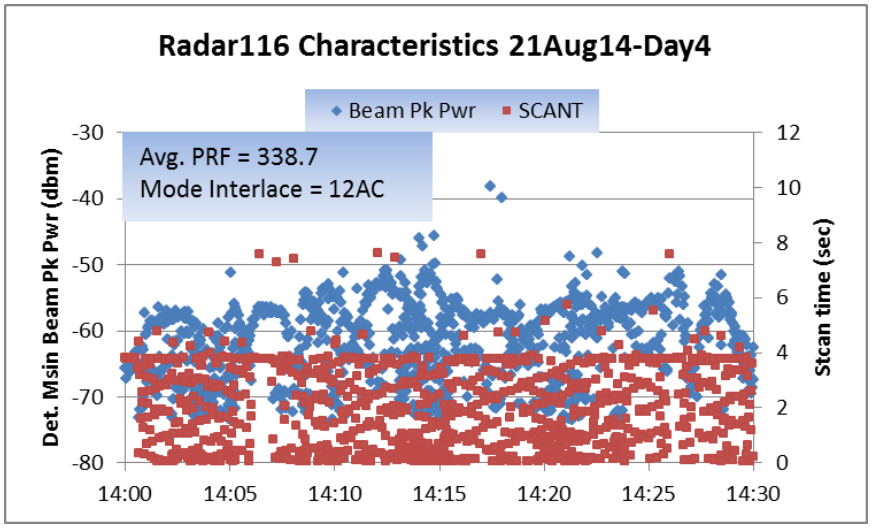


Figure 164. Radar 116 Detected Beam Peak Power and Scan time – Day 4

The scan times indicate multiple sources at near the same scan rate. N39 was headed down the Atlantic coastline, so the probable source is ships off the coast. The total number of interrogations is approximately the same for both days (33458 and 35691 for Day 3 and 4

respectively). This means that the rate per second is about 19 per second (all modes) from this interrogator.

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Appendix B. ADS-B Air-to-Air

B.1 Background

This section is devoted to discussion of the AN/UPX-41(C)'s impact on the viability of the FAA's ADS-B 1090 MHz air-to-air link. The Radio Technical Commission for Aeronautics (RTCA) developed DO-338, Minimum Aviation System Performance Standards (MASPS) for ADS-B, specifying the required 95% state vector update rates required to support specific air-to-air application ranges using the ADS-B 1090 Extended Squitter (ES) payload. Unfortunately, the availability of the 1090 MHz band for meeting the update rates needed is in jeopardy for high density areas. In 2006, the FAA's SBS Program office (ADS-B system owner) labeled this congestion as high risk meaning that program success was likely to be jeopardized if no mitigations were undertaken to stem the congestion. In light of this, SBS has initiated multiple 1090 MHz spectrum congestion studies to determine mitigations for reducing interference. While some easily implementable mitigations have been identified, removal of the Terra Fix and a modified Mode Select (Mode S) interrogation sequence, and are in the process of implementation, more mitigations are required to be able to meet the performance metrics for ADS-B air-to-air. Therefore, at this time, any new interrogators added to the environment must prove that their impact to ADS-B air-to-air update rates is negligible.

The required air-to-air update rates for the application ranges, as given in Table 23, are taken from the *2012 FAA 1090 MHz Spectrum Mitigation Alternatives Analysis (Interim Report)* (Ref. 5), herein referred to as the Mitigation Analysis, and are derived from the DO-338 MASPS as well as input from SBS engineers. The update rates are applicable to class A1 and A3 avionics. The FAA study uses the Johns Hopkins University Applied Physics Laboratory (JHUAPL) Civil Airspace 1090 MHz Extended Squitter (CATS) simulation platform to predict update intervals for transmitter-receiver pairs at the application ranges in Table 23. Using many probes that squitter 1090 MHz ADS-B and Traffic Information Service - Broadcast (TIS-B) signals, CATS simulates ADS-B receiver performance at the chip level by injecting a statistical FRUIT interference environment converted into individual timed FRUIT signals at the receiver to determine its ability to correctly decode the signals. The following analysis leverages previous work Ref. 5 to demonstrate the impact of the proposed AN/UPX-41(C) Stage 4 configuration on ADS-B air-to-air update rates.

Table 23. ADS-B Air-to-Air Update Interval Requirements

Range	10 nmi	20 nmi	40 nmi	60 nmi	90 nmi
95% Update Interval	3 sec	7 sec	12 sec	12 sec	12 sec

B.2 Impact of AN/UPX-41(C) Stage 4 Configuration

As proven in Section 2.6, the AN/UPX-41(C) system only generates Air Traffic Control Radar Beacon System (ATCRBS) FRUIT. During this test, that amount was about 550/sec from the four LBTS for power levels greater than or equal to -79 dBm. To determine the impact that a 550/sec increase in ATCRBS FRUIT/sec has on ADS-B receiver performance, a sensitivity analysis from the Mitigation Analysis will be discussed.

The Mitigation Analysis first calculated baseline ADS-B air-to-air performance for future years based on 0.5%, 1.7%, and 2.5% yearly air traffic growth rates in five year increments from 2020 to 2035. Since the Mitigation Analysis and the 1090 MHz congestion reports preceding it were intended to satisfy an FAA Aviation Rulemaking Committee (ARC) request to assess congestion impacts and candidate mitigations for the 2035 timeline, the Mitigation Analysis used the 2035 baseline to assess the impact of a reduction in 1090 MHz channel utilization through the implementation of mitigation alternatives. The ADS-B air-to-air performance for 2035 with a yearly air traffic growth rate of 1.7% is given in Table 24 and Table 25 for A1-to-A1 and A3-to-A3 equipage pairs, respectively.

Table 24. ADS-B Air-to-Air Performance with Mitigations for A1-to-A1 Pairs for 2035 and 1.7%/year Air Traffic Growth Rate

	10 NM	20 NM	40 NM
Requirement	3 s	7 s	12 s
2035 baseline	1.1	4	28
Monopulse SSRs	1.1	3	16
Passive WAM	0.9	1.5	5
Hybrid TCAS	1.1	3	21
Monopulse SSRs + Hybrid TCAS	1	2	10
Passive WAM + Hybrid TCAS	0.8	1.4	4

Table 25. ADS-B Air-to-Air Performance with Mitigations for A3-to-A3 Pairs for 2035 and 1.7%/year Air Traffic Growth Rate

	10 NM	20 NM	40 NM	60 NM	90 NM
Requirement	3 s	7 s	12 s	12 s	12 s
2035 baseline	0.7	1.4	4	9	23
Monopulse SSRs	0.7	1.2	3	6	13
Passive WAM	0.7	1.1	2	4	8
Hybrid TCAS	0.7	1.1	3	7	18
Monopulse SSRs + Hybrid TCAS	0.7	1.1	2	4	11
Passive WAM + Hybrid TCAS	0.6	1	1.6	3	5

For the analysis of the proposed AN/UPX-41(C) Stage 4 configuration's impact to ADS-B air-to-air performance, the Monopulse SSRs mitigation is of particular interest by providing context for the impact. This mitigation assumes that all sliding window SSRs remaining in the NAS,

both FAA and DoD, will be converted to monopulse operation. With the Monopulse SSR mitigation, the nominal 18 ATCRBS replies elicited per aircraft transponder per scan by a sliding window SSR is reduced to about six. As illustrated in Figure 165, this only reduces ATCRBS FRUIT/sec and, since the AN/UPX-41(C) only elicits ATCRBS FRUIT, the change in update rate per ATCRBS FRUIT/sec associated with the Monopulse SSR mitigation guides the calculation of the change in update rate per ATCRBS FRUIT/sec that would be seen from the proposed AN/UPX-41(C) Stage 4 configuration. At -79 dBm, the decrease in ATCRBS FRUIT/sec with the Monopulse SSR mitigation is 6849/sec, as shown in in Figure 166. The increase in ATCRBS FRUIT/sec (550/sec) from the proposed AN/UPX-41(C) Stage 4 configuration accounts for only 8% of that change. Assuming the update rate changes linearly with the change in ATCRBS FRUIT/sec, Table 26 gives the expected change in ADS-B air-to-air performance for the proposed AN/UPX-41(C) Stage 4 configuration.

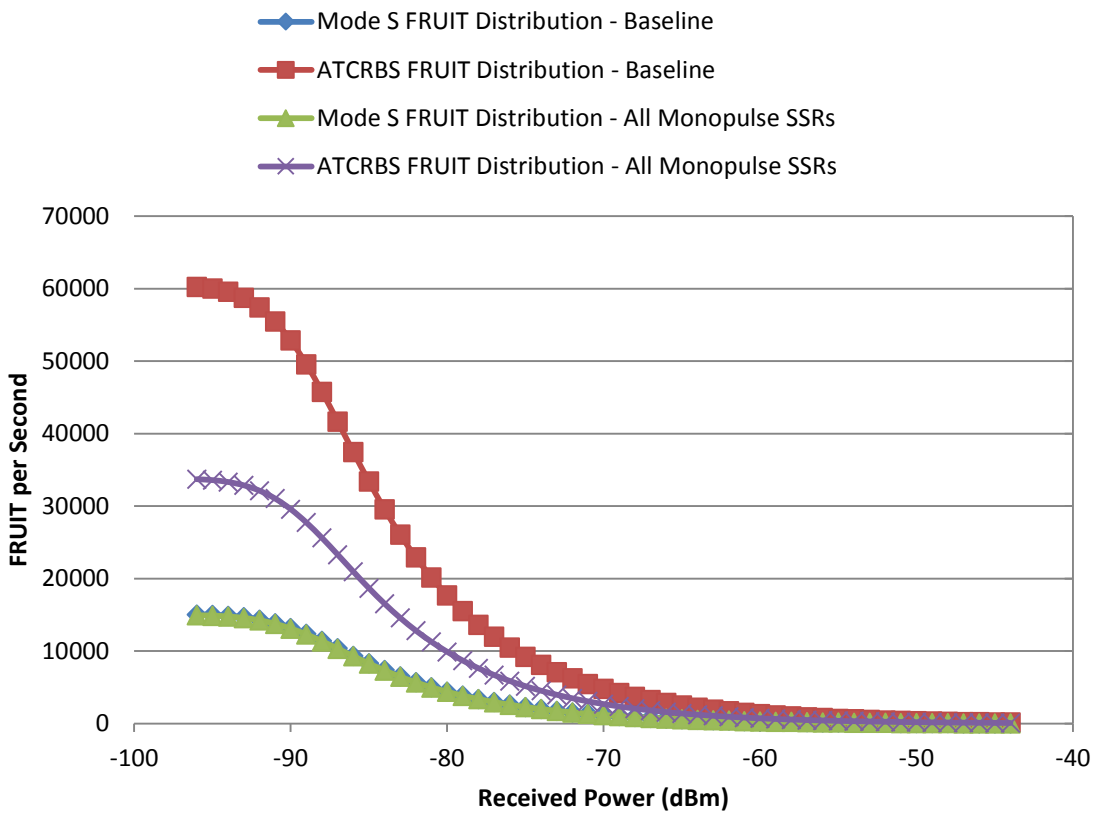

Figure 165. Effect of Monopulse SSR Mitigation on the 2035 Modeled FRUIT Distribution for the 1.7%/year Air Traffic Growth Rate

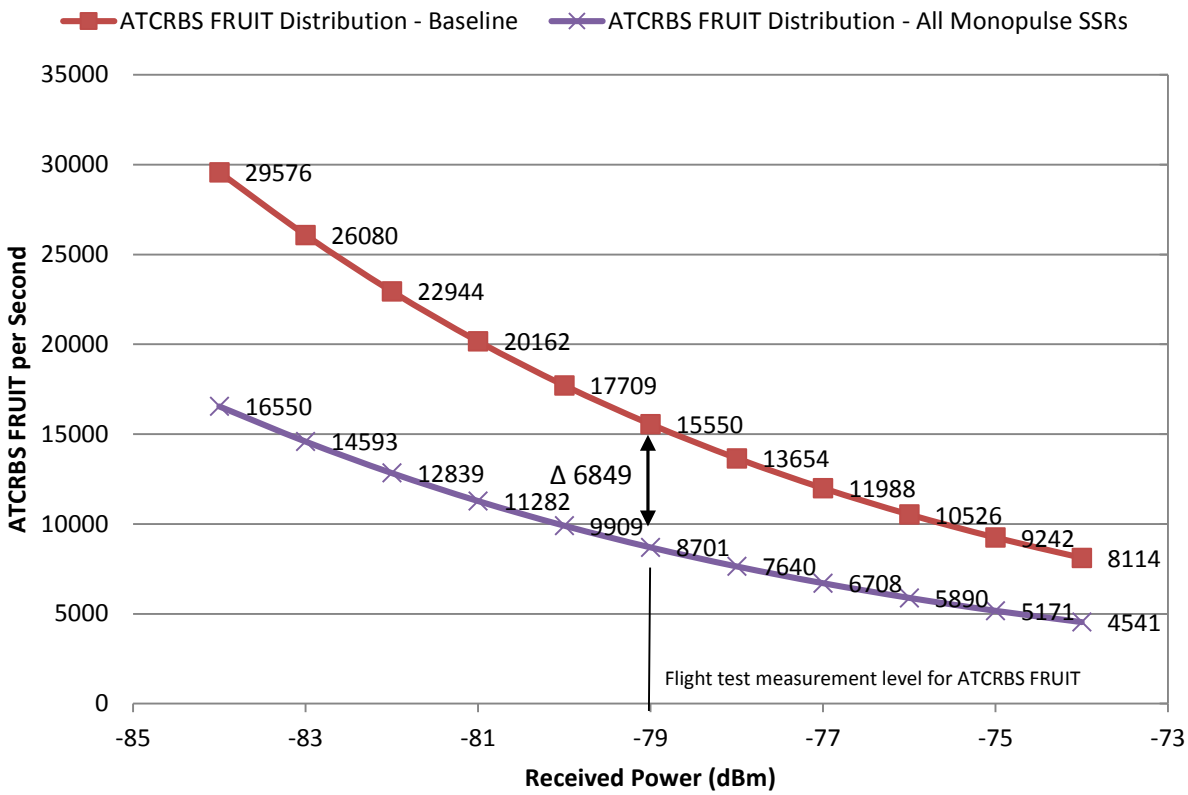

Figure 166. Effect of Monopulse SSR Mitigation on the 2035 Modeled ATCRBS FRUIT Distribution for the 1.7%/year Air Traffic Growth Rate

Table 26. Change in ADS-B Air-to-Air Performance with Monopulse SSR Mitigation and AN/UPX-41(C) Stage 4 Configuration for 2035 and 1.7%/year Air Traffic Growth Rate

	A1-to-A1			A3-to-A3				
Range	**10 nmi**	**20 nmi**	**40 nmi**	**10 nmi**	**20 nmi**	**40 nmi**	**60 nmi**	**90 nmi**
Requirement	3 s	7 s	12 s	3 s	7 s	12 s	12 s	12 s
2035 Baseline	1.1 s	4 s	28 s	0.7 s	1.4 s	4 s	9 s	23 s
Δ 2035 Baseline to Monopulse	0.0 s	1 s	12 s	0.0 s	0.2 s	1 s	3 s	10 s
Update Rate Increase with Stage 4	0.0 s	0.08 s	0.96 s	0.0 s	0.02 s	0.08 s	0.24 s	0.8 s

B.3 Discussion

The predicted change in ADS-B air-to-air performance, based on the ATCRBS FRUIT/sec elicited by the proposed AN/UPX-41(C) Stage 4 configuration, is negligible considering that the change in update rate was less than 10% of the maximum allowed time between updates for each application range. To further bound this result, note that performance changes are based on predicted 2035 performance since there are no published performance tables for the 2014 environment. The Mode S FRUIT/sec for performance modeling is double the rates of today's environment, shown in Section 2.6. Figure 167 shows that the impact of Mode S FRUIT/sec on squitter detection is greater than that of ATCRBS FRUIT/sec. As background, the performance curves in Figure 167 were determined from FAA bench tests where a 1090ES receiver was injected, as a Poisson process, with extremely high rates (approximately two and three times the ATCRBS FRUIT rate and one and a half and two times the Mode S FRUIT rate in the 2035 baseline for high and very high, respectively) of FRUIT as shown in Figure 168. In consideration of this, the ADS-B air-to-air performance in the 2014 FRUIT environment will be much better than the performance given with the 2035 baseline FRUIT rates.

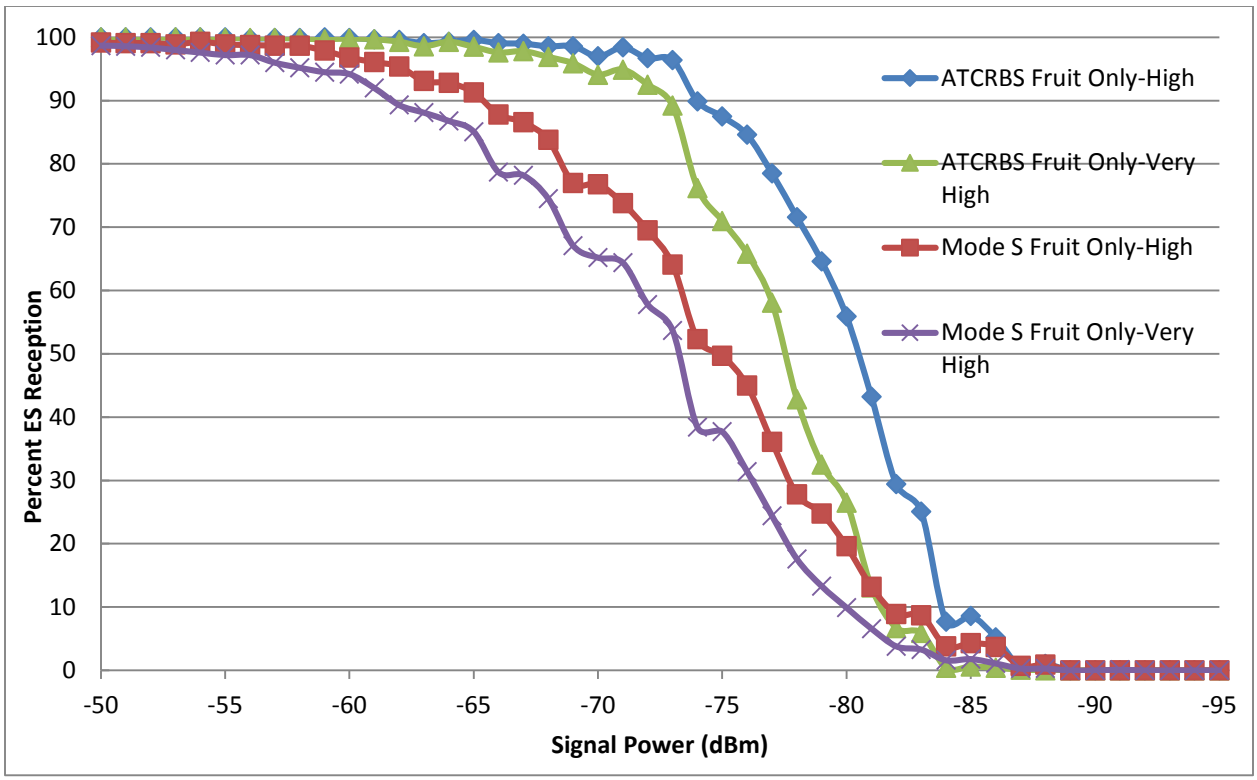

Figure 167. 1090 MHz Extended Squitter Detection Probability

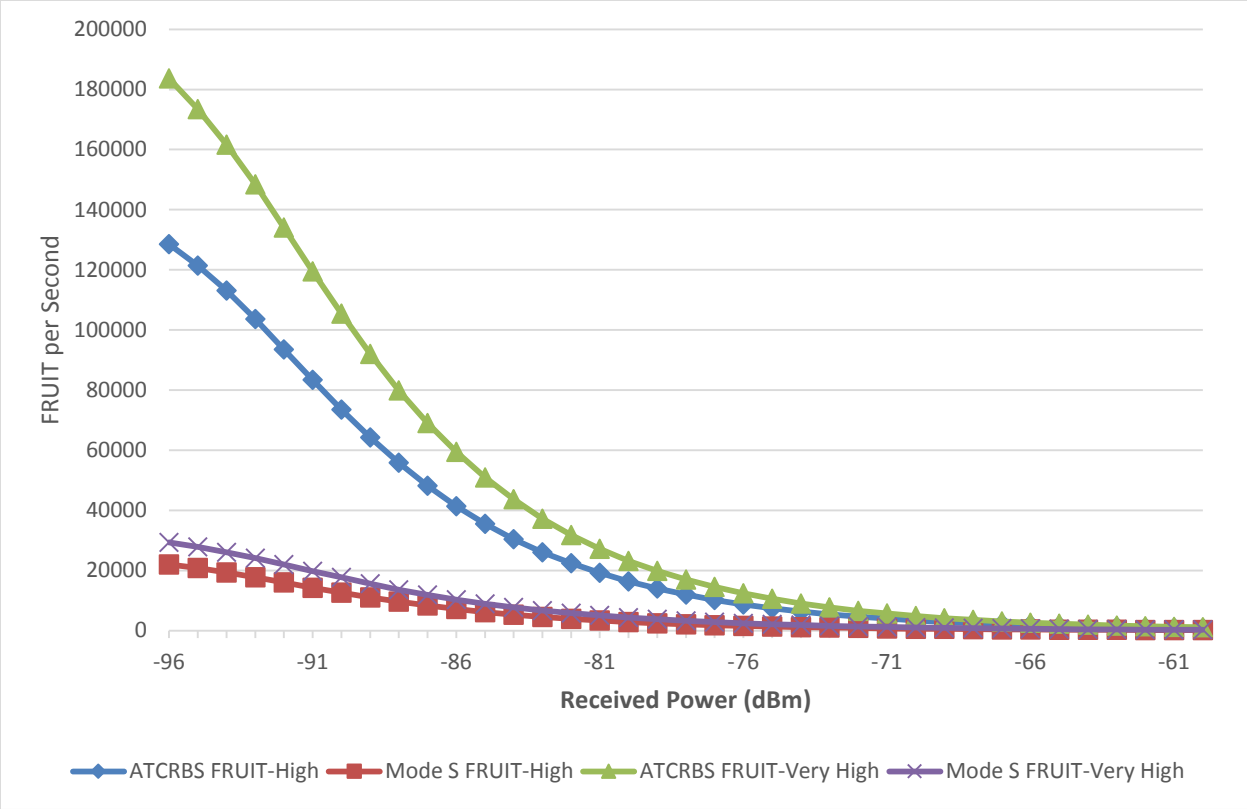

Figure 168. FRUIT per Second Distribution Injected as the Interference Source for 1090ES Detection Probability Test

The assumption of performance changing linearly with changes in FRUIT/sec should also be challenged. The same analysis for the 2.5% growth rate (i.e. larger baseline FRUIT/sec assumption), given in Table 27Table 28Table 29 and Figure 169 and Figure 170, shows larger decreases in performance for the equivalent increase in ATCRBS FRUIT/sec from the proposed AN/UPX-41(C) Stage 4 configuration.

Table 27. ADS-B Air-to-Air Performance with Mitigations for A1-to-A1 Pairs for 2035 and 2.5%/year Air Traffic Growth Rate

	10 NM	20 NM	40 NM
Requirement	3 s	7 s	12 s
2035 baseline	1.6	8	73
Monopulse SSRs	1.2	4	28
Passive WAM	1.0	2	9
Hybrid TCAS	1.4	6	47
Monopulse SSRs + Hybrid TCAS	1.1	3	17
Passive WAM + Hybrid TCAS	1.0	1.8	6

Table 28. ADS-B Air-to-Air Performance with Mitigations for A3-to-A3 Pairs for 2035 and 2.5%/year Air Traffic Growth Rate

	10 NM	20 NM	40 NM	60 NM	90 NM
Requirement	3 s	7 s	12 s	12 s	12 s
2035 baseline	0.9	1.9	7	18	72
Monopulse SSRs	0.9	1.6	5	14	31
Passive WAM	0.7	1.3	3	6	12
Hybrid TCAS	0.8	1.5	5	14	40
Monopulse SSRs + Hybrid TCAS	0.7	1.3	3	7	18
Passive WAM + Hybrid TCAS	0.7	1.1	2	4	9

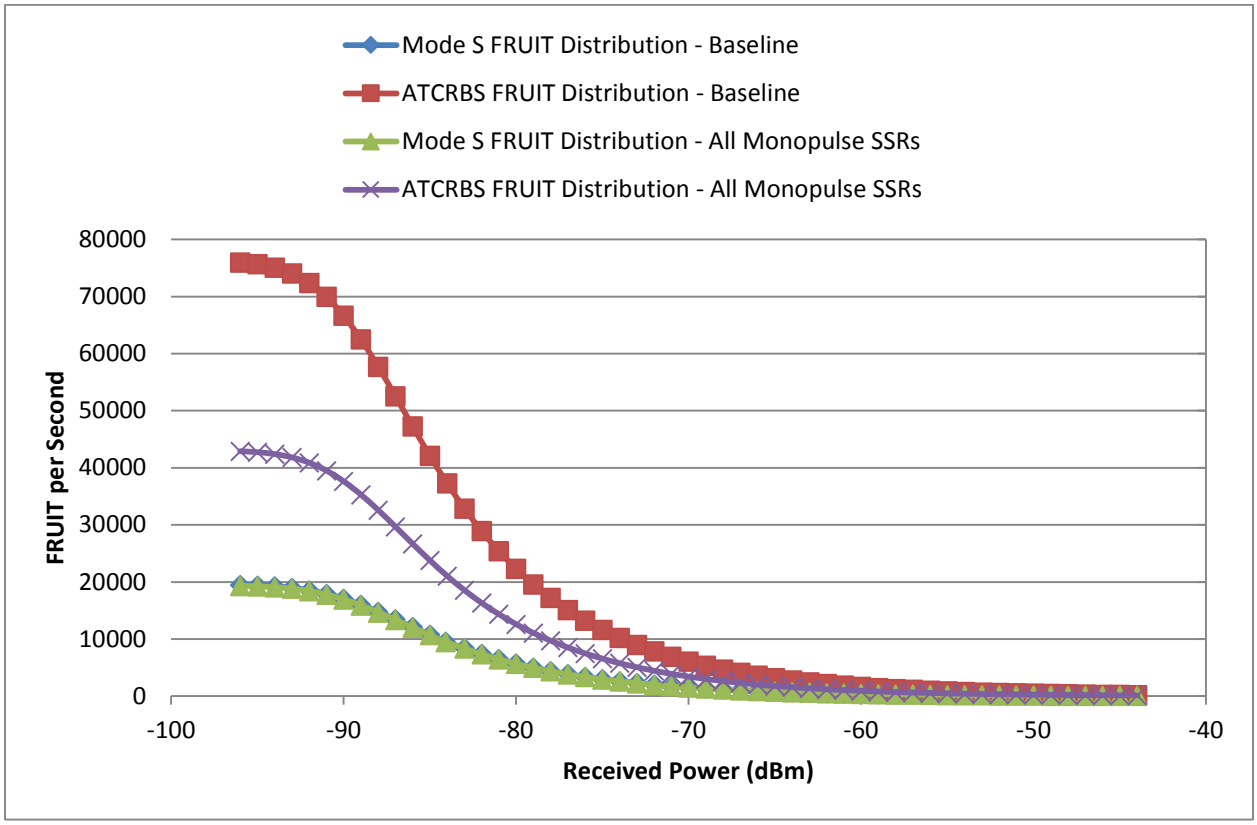

Figure 169. Effect of Monopulse SSR Mitigation on the 2035 Modeled FRUIT Distribution for the 2.5%/year Air Traffic Growth Rate

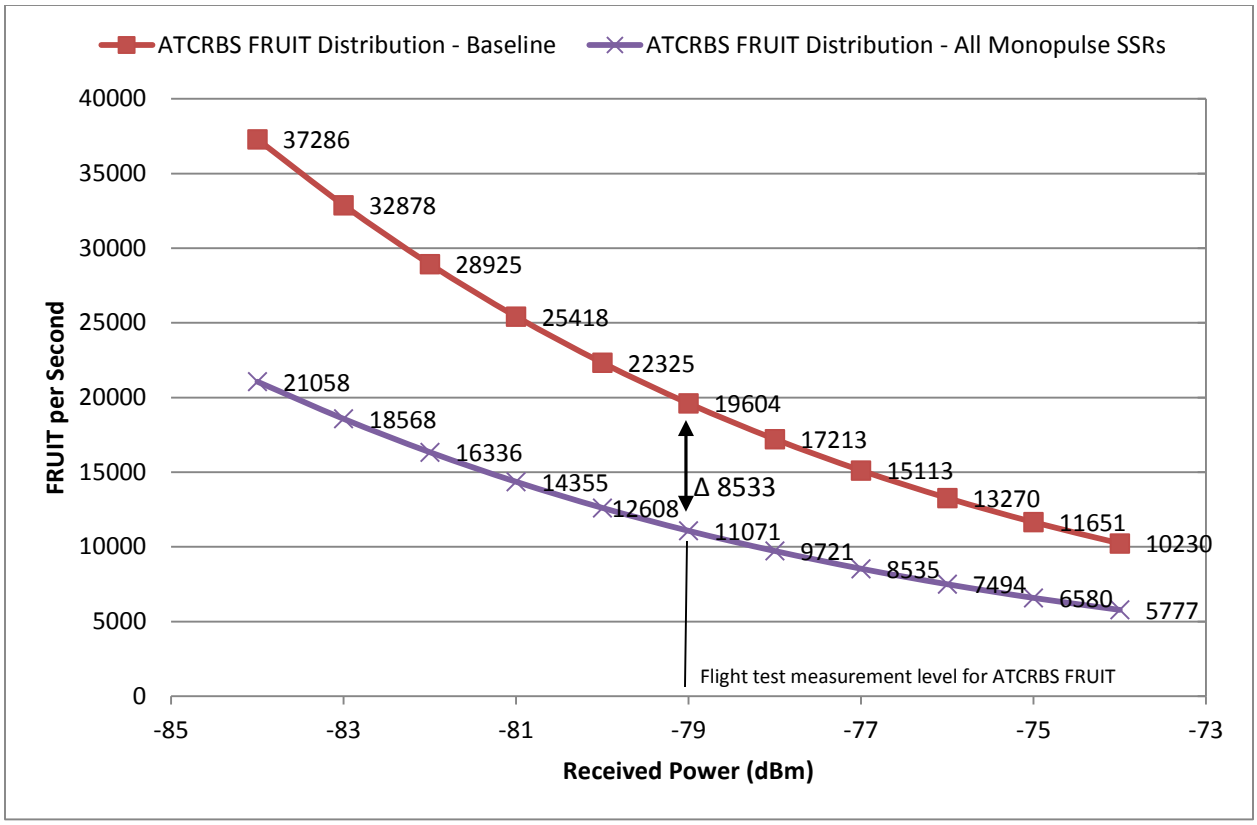

Figure 170. Effect of Monopulse SSR Mitigation on the 2035 Modeled ATCRBS FRUIT Distribution for the 2.5%/year Air Traffic Growth Rate

Table 29. Change in ADS-B Air-to-Air Performance with Monopulse SSR Mitigation and AN/UPX-41(C) Stage 4 Configuration for 2035 and 2.5%/year Air Traffic Growth Rate

	A1-to-A1			A3-to-A3				
Range	**10 nmi**	**20 nmi**	**40 nmi**	**10 nmi**	**20 nmi**	**40 nmi**	**60 nmi**	**90 nmi**
Requirement	3 s	7 s	12 s	3 s	7 s	12 s	12 s	12 s
2035 Baseline	1.6 s	8 s	73 s	0.9 s	1.9 s	7 s	18 s	72 s
Δ 2035 Baseline to Monopulse	0.4 s	4 s	45 s	0.0 s	0.3 s	2 s	4 s	41 s
Update Rate Increase with Stage 4	0.05 s	0.47 s	5.27 s	0.0 s	0.35 s	0.23 s	0.47 s	4.81 s

To explain the difference in performance change given baseline FRUIT rates for the 1.7% and 2.5% growth rates, Figure 167 shows there is a steep fall off in performance for increases in FRUIT when a certain baseline FRUIT saturation is reached. Much of this is due to a drop in error detection and correction (EDAC) performance for 1090 ES received at lower power levels. Hence, the assumption of linearity is not entirely accurate, but serves its purpose for this analysis while keeping ADS-B receiver performance degradation in mind.

The analysis given is specific to this Test and should only act as a guideline for the impact that the proposed AN/UPX-41(C) Stage 4 configuration will have in other areas of the country. In the future, this type of analysis should be conducted with FRUIT rates normalized by aircraft to account for regional differences in aircraft densities. Predicted total FRUIT rates for a region can be determined by multiplying the measured FRUIT contribution per aircraft by the number of aircraft expected to be within the line-of-sight (LOS) of a victim airborne ADS-B receiver. Finally, because the FAA considers 1090 MHz spectrum interference on post-2020 ADS-B air-to-air performance to be a high risk, this analysis should be revisited once interference mitigations have been selected by the FAA to demonstrate the update rates expected in the new baseline 1090 MHz environment.

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Appendix C. Secondary Surveillance Radar

C.1 Recording and Analysis Tools

C.1.1 Radar Beacon Analysis Tool

RBAT is used to measure overall radar system performance for all types of SSRs through the analysis of Common Digitizer Model 2 (CD-2) and All Purpose STructred Eurocontrol Radar Information EXchange (ASTERIX) target data. Disseminated target data from the eight SSRs under test was remotely recorded at the WJHTC using RT-RBAT. A queue function in RBAT can be used to automate repetitive processes.

C.1.2 Real-Time Aircraft Display System

RTADS can record and display CD-2 and ASTERIX target data in real-time where a track is updated every scan as the mainbeam sweeps past the azimuth of the target.

C.1.3 Mode S Analysis Tool

MSAT is a tool used to analyze Mode S Data Extraction (DE) files which are locally recorded in external hard drives at each Mode S SSR sites. RBAT analyzes statistics that are general to all radar systems, whereas MSAT produces statistics that asses the components of the Mode S system. Similar to RBAT, MSAT also has a queue program that allows for analysis programs to be executed autonomously after an initial setup. The queue function is beneficial if the majority of the analysis is repetitive, so by automating the process it saves time and also reduces the chance for human error.

C.1.4 Mode S Data Analysis Software

MDAS is a spinoff of MSAT used by Mode S second level engineering group to determine statistics reported by the Mode S system. In the Test Plan, MDAS had been identified as the analysis tool that was to be used for analyzing Mode S DE files. While MDAS and MSAT are similar in many ways, one important difference is the absence of the queue function in MDAS. Therefore, MSAT was used as the analysis tool for the Test to analyze Mode S DE files.

C.2 Real-time Performance Monitoring and Test Data Recordings

RT-RBAT updates performance metrics every twenty scans which in time correspond to approximately one hundred seconds and two hundred forty seconds between updates for terminal and en route SSRs, respectively. One RT-RBAT workstation monitored performance of tracks within surveillance volumes of the eight SSRs under test, and the other RT-RBAT workstation monitored performance of tracks within a hotspot region. The hotspot region was defined as the LBTS's potential sidelobe impact volume where transponder occupancy is greatest. If interference due to the LBTS was present in the NAS, it would appear more significantly in the hotspot region since there is no averaging of statistics with the entire coverage volume of the SSR. Based on modeling and simulation, an assumption of 40 nmi was made to describe the extent of the LBTS sidelobe impact range. In addition to real-time SSR performance monitoring, RT-RBAT was recording data to allow for in-depth SSR analysis after completion of the Test.

RTADS was utilized to monitor the surveillance volumes of the eight SSRs under observation during the Test. Similar to an air traffic controller's visual display, RTADS uses a graphical user interface (GUI) to provide scan-to-scan target updates which was beneficial in determining if tracks had started to coast following a change in LBTS Active/Off configuration.

If SSR performance metrics in RT-RBAT fell below the baseline recordings, the DEGRADED BUZZER procedure would go into effect. To determine if a DEGRADED BUZZER was appropriate, guidelines were setup to minimize DEGRADED BUZZER calls for interference not caused by LBTS activities.

- First, determine if any LBTS are Active. If the systems are Active, the procedure requires the analysts to check RTADS to see if there are any targets in the area.
- Second, determine through RT-RBAT, full surveillance volume and hotspot volume, if the latest updates in performance metrics have a negative trend since the beginning of the LBTS Active cycle.
- Third, in RTADS, determine if targets that highly influence performance metrics are in known poor performance coverage zones, such as low elevation angle, edge of radar coverage, etc.
- If reasons for performance metrics' downward trend is not found, the DEGRADED BUZZER goes into effect. This requires all LBTS to turn Off one at a time until either the problem goes away or all systems are Off.

A CEASE BUZZER required all Active LBTS to turn Off immediately and could only be called by FAA Air Traffic Control (ATC).

During the Test, real-time analysts did not issue a DEGRADED BUZZER, and FAA Air Traffic Control (ATC) did not issue a CEASE BUZZER.

C.3 Measurement and Analysis

C.3.1 RBAT Data Analysis

RBAT's Surveillance Analysis, Scan Summary, and Beacon False Target Summary programs were used to analyze track-level data to produce statistics for probability of detection, targets per scan, identity reliability, identity confidence, altitude reliability, altitude confidence, false target rate, and 0000 code percentage for all SSRs. For the Richmond SSR, RBAT also produced number of replies to interrogations for a beam dwell.

Probability of Detection and Targets per Scan

Probability of detection is defined as a function of uplink and downlink reliability[2]. However, RBAT uses a statistical method in which P_d for a track is defined as the percentage of track updates versus the total number of beam dwells over all tracks. There are limitations to employing statistical methods in calculation of P_d. For example, in a target population of two, both targets missing one update out of ten scans results in a P_d of 90%. While this is unacceptable by QARS blip/scan minimums, there is no knowledge of the updates that occur outside of the calculation time period. If both targets receive ten out of ten updates for the previous as well as the next ten scans, the P_d is now 96.7%.

Because of the limitations of using statistical methods for analyzing track performance, it was important to correlate number of targets per scan with probability of detection for the period of interest. A user-defined parameter in RBAT told the program the number of missed position updates it could tolerate before dropping a track. The default and optimal value, as set by the developer through sensitivity analyses, was four scans with missed updates before dropping a track. While this prevents artificial deflation of probability of detection statistics from known gaps in radar coverage (e.g. cone of silence, below LOS), it can also artificially inflate probability of detection if tracks are dropped due to extensive interference. Known as survivorship bias, this deliberate omission can be guarded against by examining the number of tracks in concert with the probability of detection for a given time interval. If the probability of detection appears stable or has moved higher relative to previous periods, but the number of targets per scan has severely dropped, this is an indication that interference is preventing track updates.

Figure 171 shows ADW's average targets per scan for all of the days using Active and Off time bins from Day 4. X-axis values that are close together are five minute periods, and values further apart are thirty minute periods. Day 1, the baseline day when the LBTS were not operating, is

[2] Stevens, C. M. *Secondary Surveillance Radar.* Artech House. Dedham, MA. 1988.

shown with the green line using Day 4's Active and Off time bins. Data from the week prior to the Test, as well as other test days are used to show the baseline statistics with greyscale lines. Lines connecting adjacent points are linear interpolations and do not necessarily reflect the actual number of targets during the time period. The points are shaded with colors that represent the different LBTS configurations.

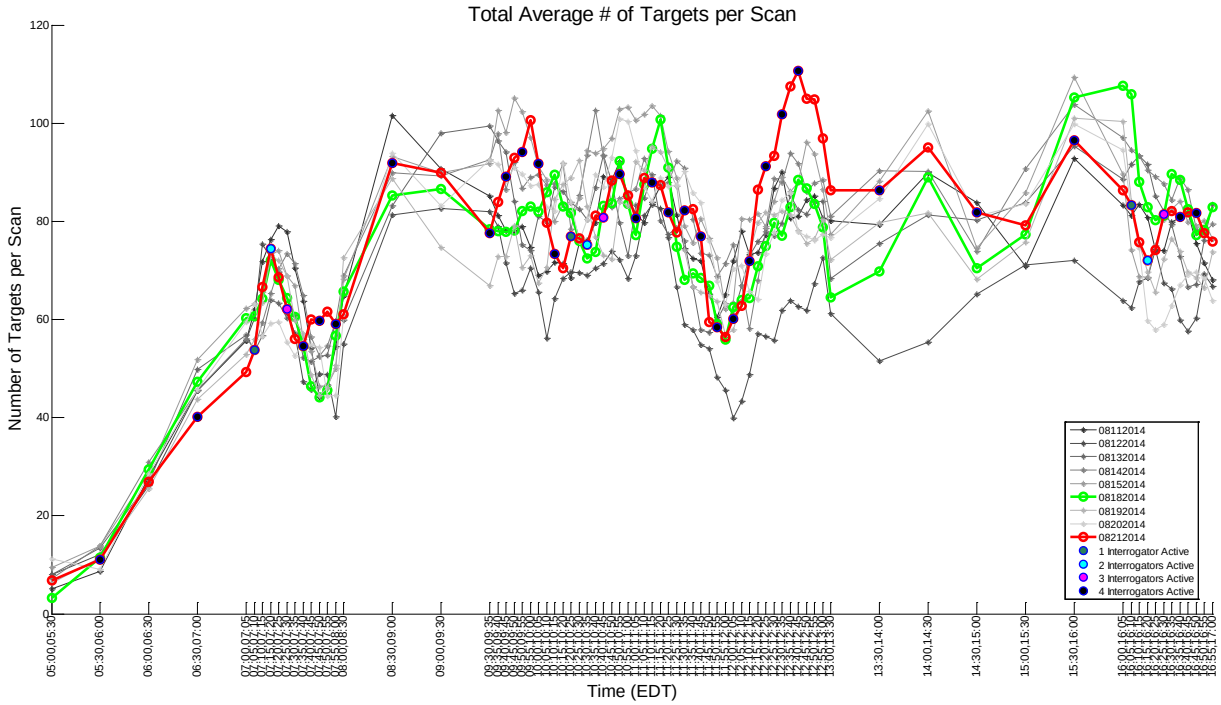

Figure 171. ADW – Day 4 – Average Number of Targets per Scan

P_d for all targets is shown in Figure 172 for ADW. Lines connecting adjacent points are linear interpolations and do not necessarily reflect actual probability of detection during the time interval. In an effort to notice interference that may not be affecting all targets, boxplots describing the P_d behavior of all targets present in the surveillance volume of ADW for each time bin are shown in Figure 173. The time bins are spaced equally for both five and thirty minute periods.

Mode S targets have a surveillance advantage over ATCRBS targets because they can be reinterrogated if a reply to a discretely addressed interrogation is not received. Therefore, Mode S-enabled SSR targets were separately analyzed as Mode S and ATCRBS targets. Figure 174 illustrates P_d for ADW ATCRBS discrete targets. Discrete targets are defined as targets that require ATC separation services with assigned beacon codes not ending in 00. For times with missing data points, there were no targets in the surveillance volume that pass the enforced filter. The P_d, in conjunction with targets per scan, showed no observable pattern of degradation in performance of the eight SSRs under test when the LBTS were Active.

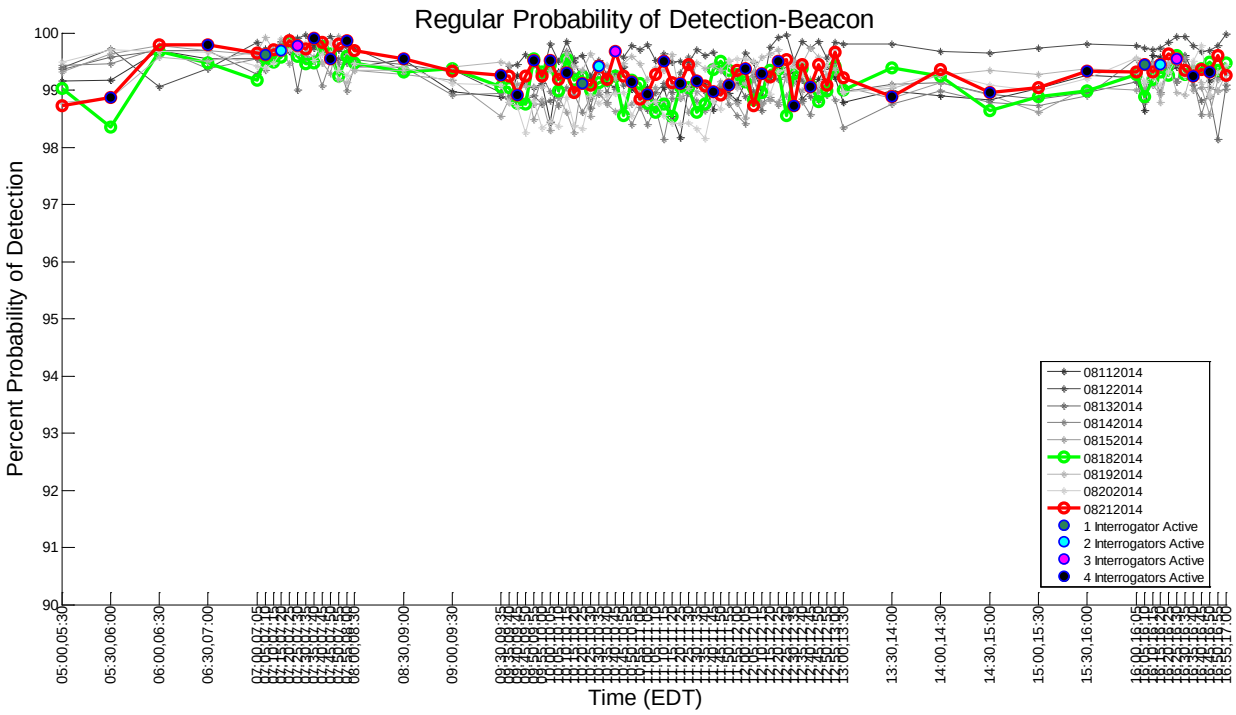

Figure 172. ADW – Day 4 – Probability of Detection

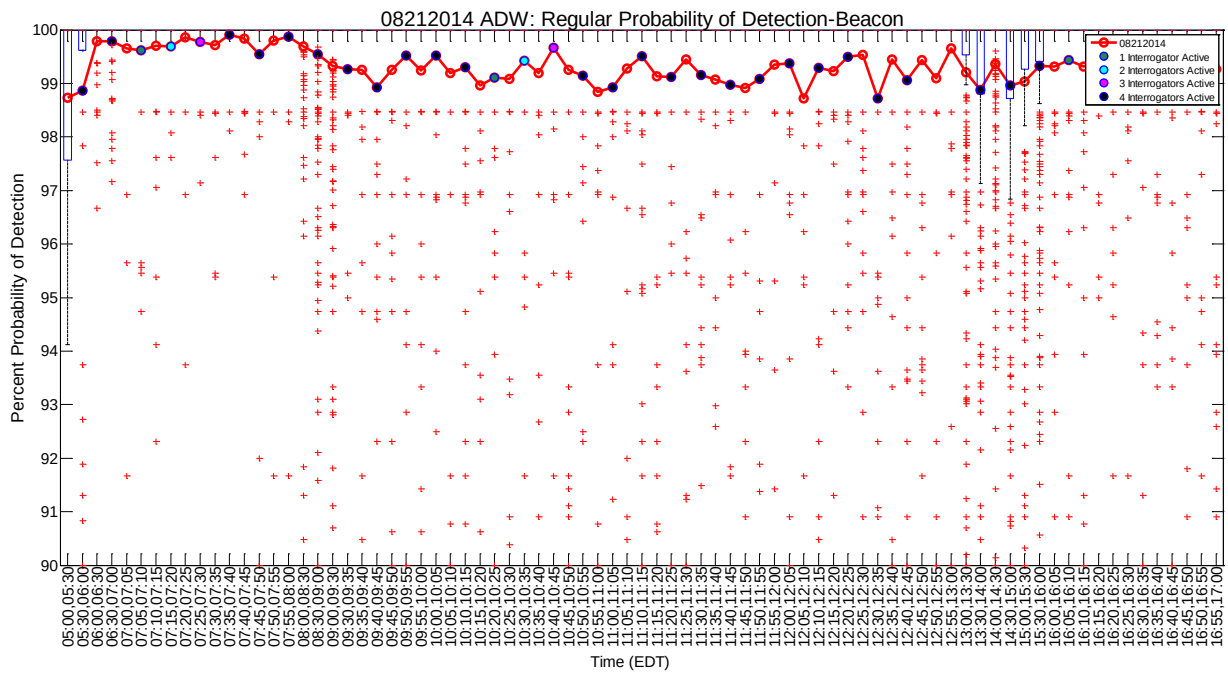

Figure 173. ADW – Day 4 – Individual Aircraft Distribution for Probability of Detection

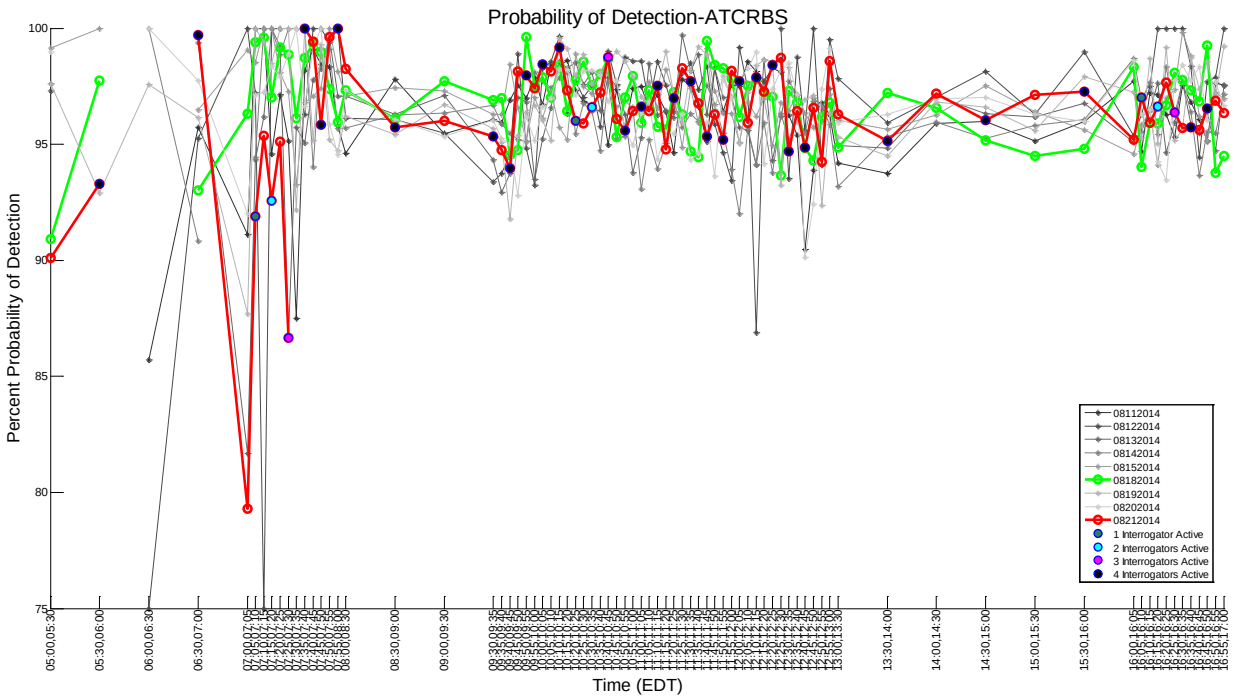

Figure 174. ADW – Day 4 – Probability of Detection – ATCRBS Discrete Targets

Mode 3/A and C Reliability and Confidence

Identity reliability is defined as the percent of times the correlated beacon message[3] Mode 3/A code with track confidence is equivalent to the track Mode 3/A code with track confidence. Identity confidence is defined as the percent of times the identity reliability is true and the correlated beacon message Mode 3/A code is high confidence. Altitude reliability is the percent of times the Mode C report is a positive altitude and the altitude is within the altitude prediction window for the correlated track. Altitude confidence is defined as the percent of times altitude reliability is true and the confidence of the correlated beacon message is high confidence. Identity reliability, identity confidence, altitude reliability, and altitude confidence parameters for ADW using Day 4's time bins are shown in Figure 175, Figure 176, Figure 177, and Figure 178, respectively. There was no observable impact from the LBTS on these parameters.

[3] Radar update correlated within a window of an existing track

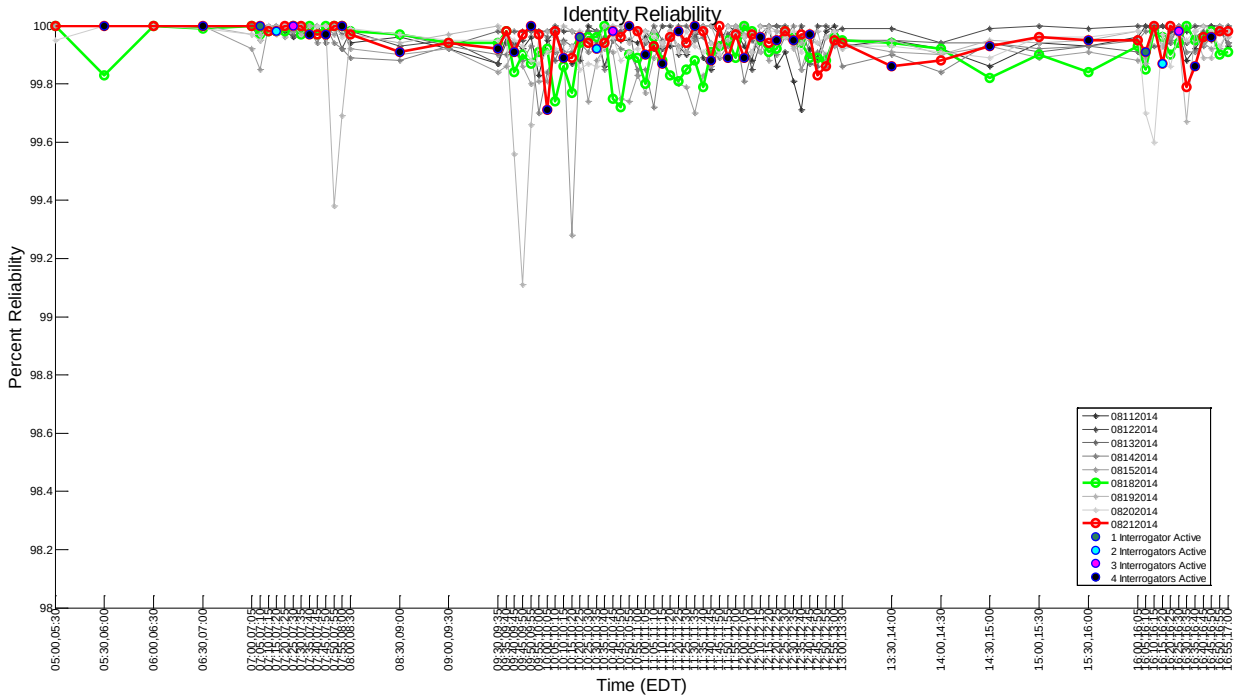

Figure 175. ADW – Day 4 – Identity Reliability

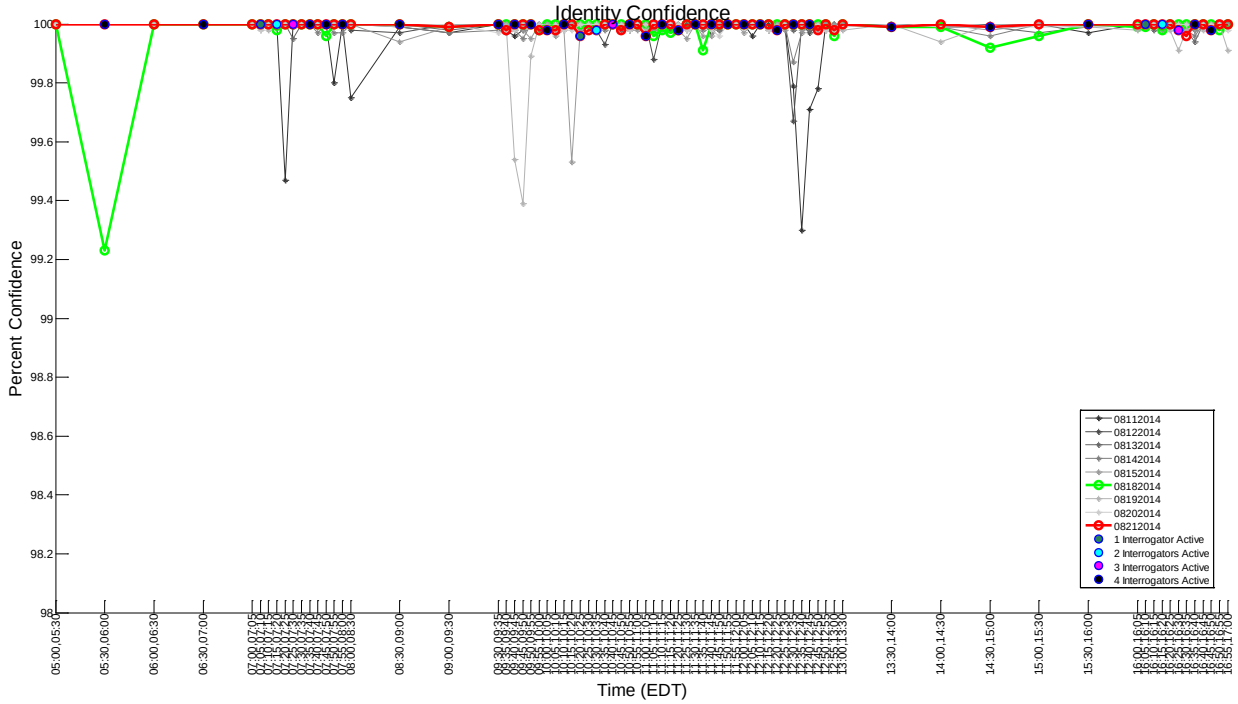

Figure 176. ADW – Day 4 – Identity Confidence

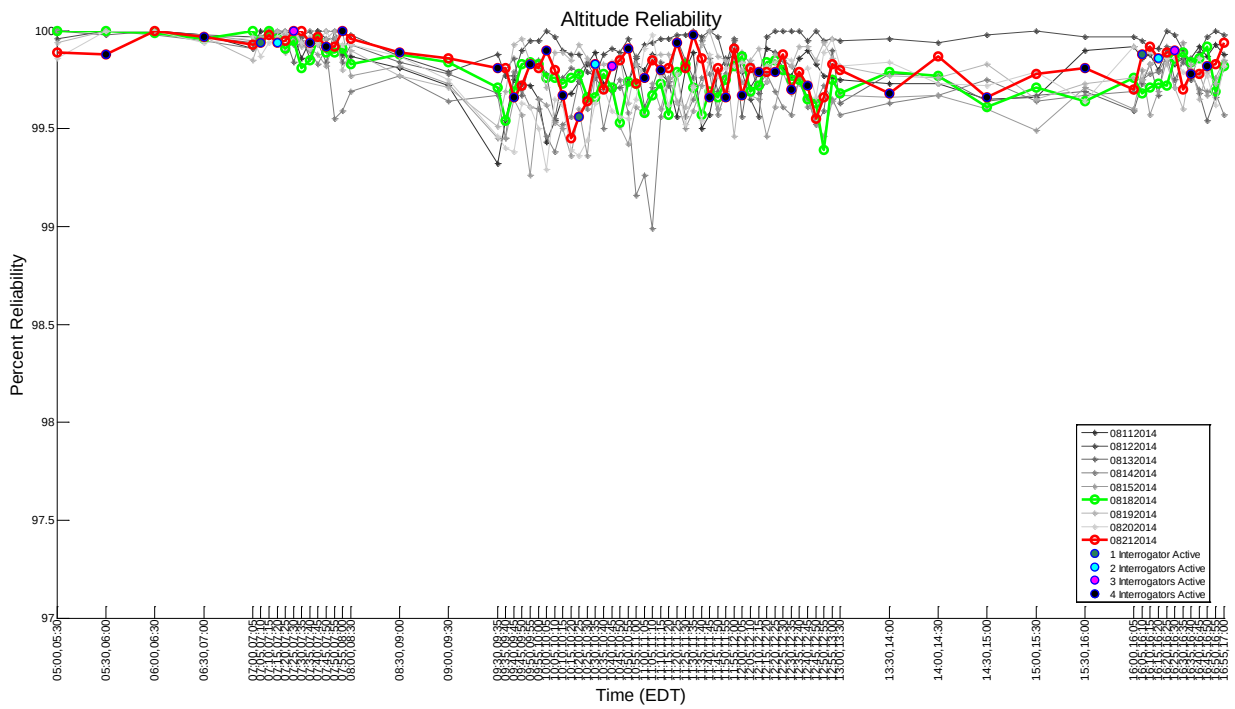

Figure 177. ADW – Day 4 – Altitude Reliability

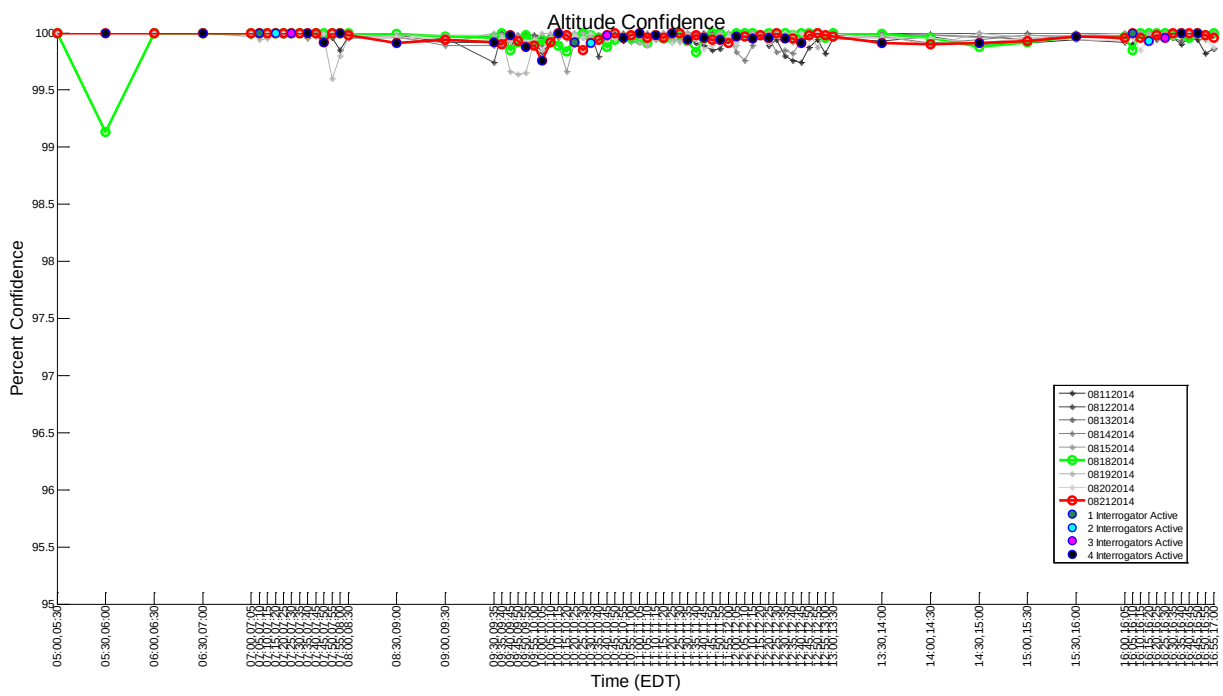

Figure 178. ADW – Day 4 – Altitude Confidence

0000 Code Percentage

When Mode A reports are so garbled that the SSR decoder does not know how to handle them, a code of 0000 is reported for a target update. Figure 179 displays 0000 code percentages seen at ADW using Day 4's time bins. As seen in the figure, the two days with an increase in 0000 code percentages occurred regardless of the LBTS Active/Off cycle. No observable impact from the LBTS was seen in 0000 code percentages at any of the eight SSR sites.

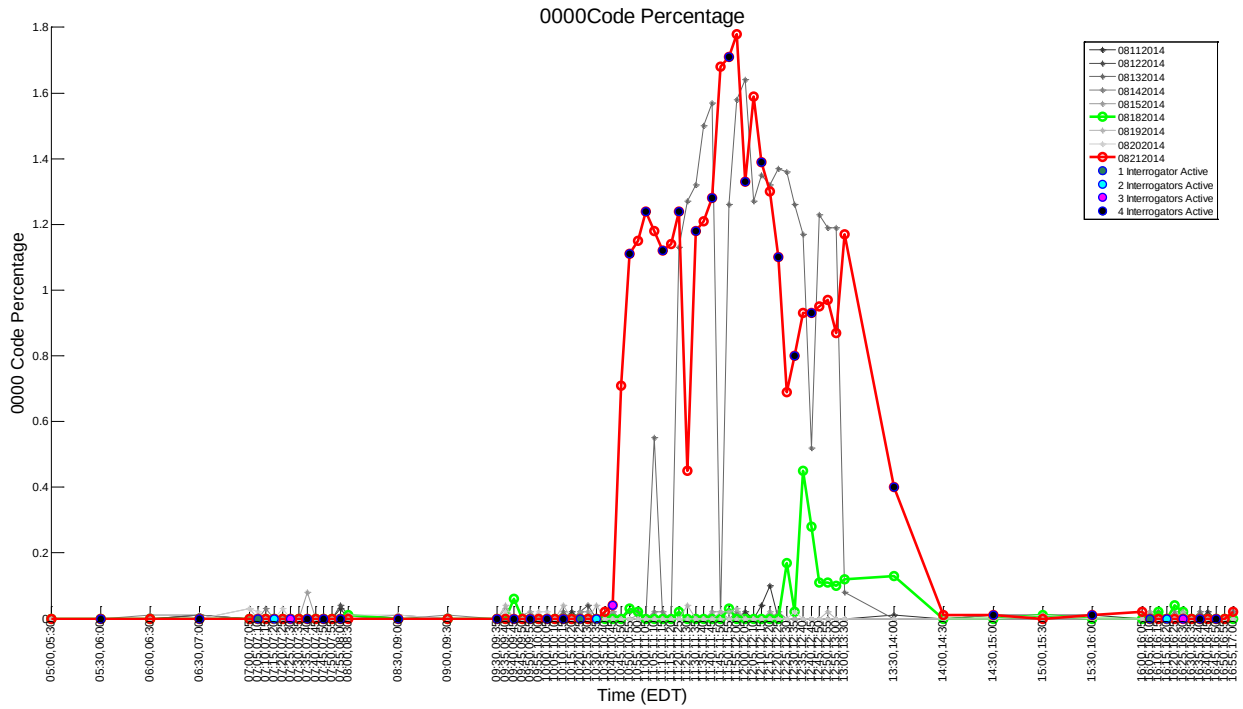

Figure 179. ADW – Day 4 – 0000 Code Percentage

Beacon False Target Rate

False targets occur due to splits, ring-a-round, uplink and downlink reflections, PRF overlaps, or lack of correlation between ATCRBS and Mode S replies. In Figure 180, percent false targets at ADW are shown with time bins from Day 4. In the morning hours, some of the SSRs had very high false target rates because there were few targets and some of the targets' beacon messages generated false target reports. Even though the false target rate was high, it was due to a small number of tracks and was not indicative of a larger problem. An increasing false target rate trend when the LBTS were Active was not observed.

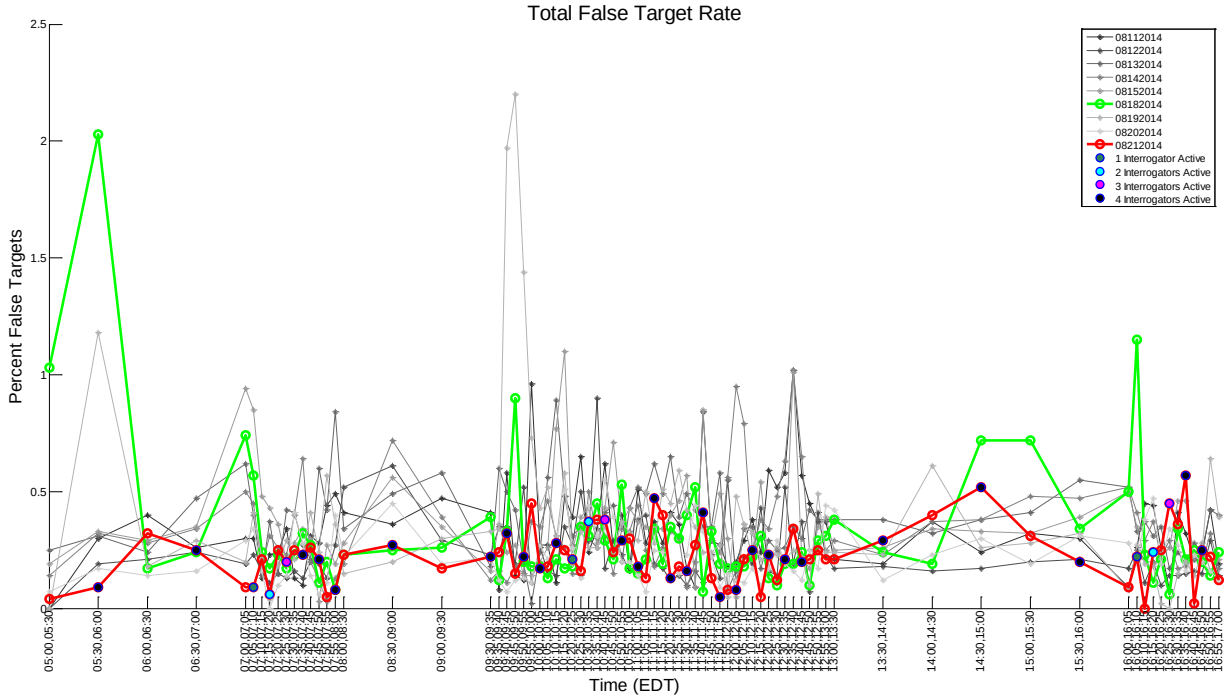

Figure 180. ADW – Day 4 – Percent False Targets

C.3.2 Mode S Data Extraction File Analysis

Mode S sites, ADW, DCA, IAD, and ORF, were analyzed further with MSAT using Mode S DE files that were recorded at the physical locations of the radar sites. The DE files store the timeline of interrogations and replies at the SSR. Using Channel Management Statistics (CMS), FRUIT Analysis, Disseminated Message Summary (DMS), and Surveillance Print in MSAT, interrogation rate, reinterrogation rate, ATCRBS FRUIT rate, Mode S FRUIT rate, and ATCRBS hit count statistics were produced. In addition, the

Due to DE file storage limitations, the Mode S system records timestamps of only the first twenty-one interrogations per aircraft per beam dwell. For aircraft that are interrogated more than twenty-one times, there is a count that totals the number of interrogations past twenty-one that were performed in that beam dwell. This is known as the retry overflow count.

Interrogation and Reinterrogation Rate Analysis

CMS determines the interrogation and reinterrogation rates for Roll-call periods by reconstructing the timeline for station times (the times at which the interrogations and replies occurred) for All-call and Roll-call interrogations and replies. Then, using All-call periods, the timeline is synched to the frame table, which contains periods and durations for interrogation and reply windows. Interrogation rate is the ratio of Roll-call interrogations per target to the number of beam dwells per target. Reinterrogation rate is the ratio of Roll-call interrogations per target

that are reinterrogations. In addition, multiple interrogations within a single beam dwell eliciting additional information for an aircraft are not counted as reinterrogations; only interrogations eliciting the same information are counted as reinterrogations. The importance of looking at CMS is that if aircraft are experiencing higher occupancy and/or there is the presence of additional FRUIT in the environment that is garbling replies at the SSR receiver, interrogation and reinterrogation rates would increase.

Interrogation and reinterrogation rates for the four Mode S SSRs under examination showed rates that were higher than anticipated. Deeper analysis uncovered that targets within ten nautical miles of a Mode S SSR were biasing average interrogation and reinterrogation rates upward. Figure 181 shows the effect range has on the reinterrogation rate as seen at ADW.

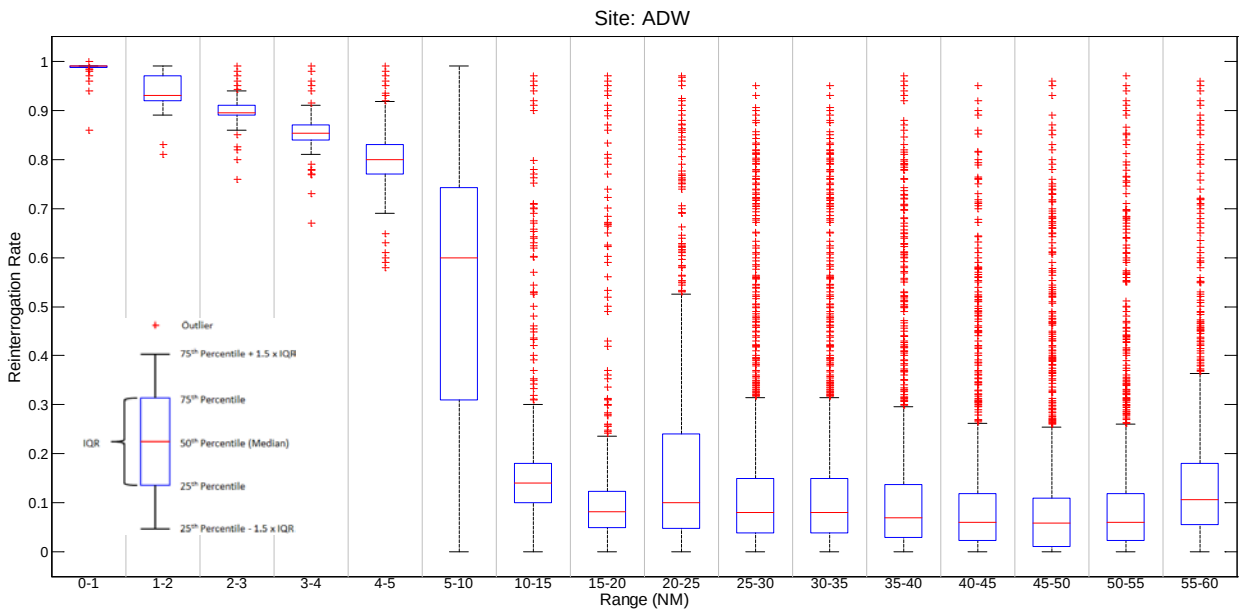

Figure 181. ADW – Day 2 – Mode S Reinterrogation Rate vs Range from SSR

Due to uncertainty in azimuth prediction for targets that are in close proximity to the SSR, the Mode S Roll-call scheduler starts interrogations many degrees before the predicted target azimuth by the surveillance processing function to ensure that unknown changes in speed and heading will not limit the ability of the Mode S system to update the position of a target. Aircraft within ten nautical miles of the SSR were the majority of the aircraft that invoked the retry overflow count within a single beam dwell. Concern that the high reinterrogation rate bias from targets within ten nautical miles would wash out interference effects prompted removal of those targets from the reinterrogation rate analysis.

After removing targets that were within ten nautical miles of the SSR, interrogation and reinterrogation rates were calculated and are shown in Figure 182 and Figure 183, respectively.

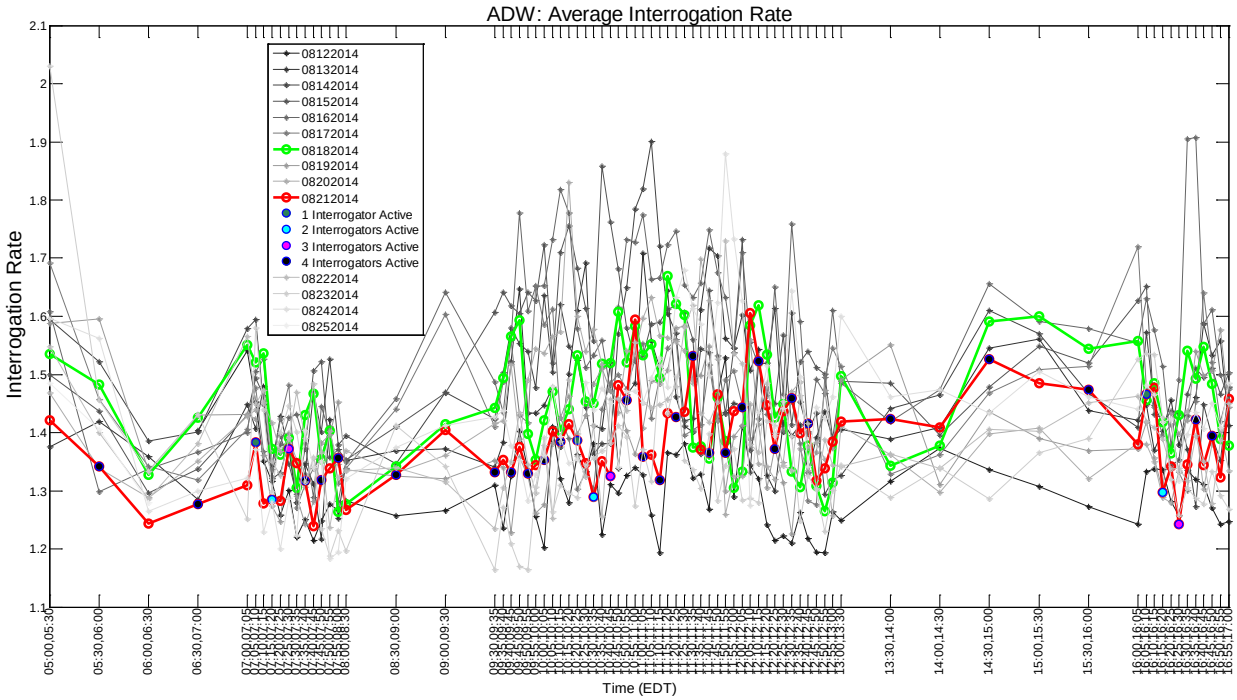

Figure 182. ADW – Day 4 – Interrogation Rate

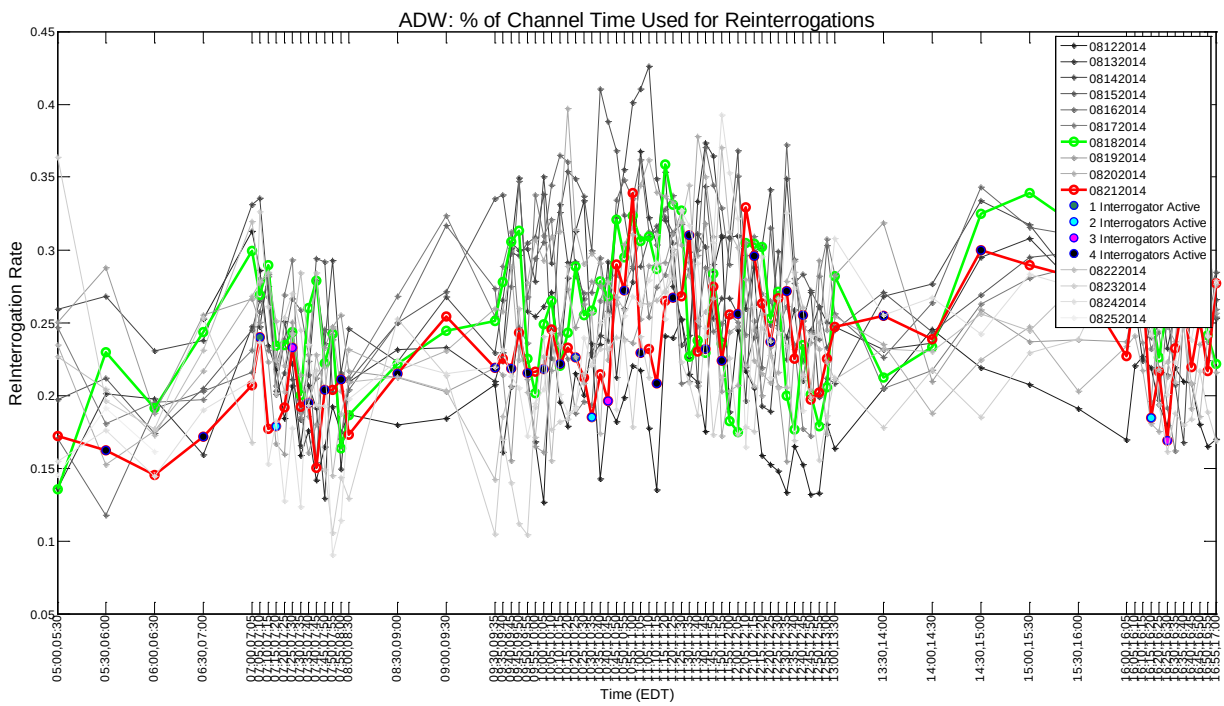

Figure 183. ADW – Day 4 – Reinterrogation Rate

While averages provide a concise description of a set of statistics, they hide outliers and anomalies that can be significant especially when determining interference to the ability of a

system to provide information used to safely separate aircraft. To step away from averages, reinterrogation rate statistics are illustrated in Figure 184 with boxplots. Since the values of reinterrogation rates are discrete, there is no useful information in showing outliers; as such, the boxplot whiskers extend to the furthest outlier.

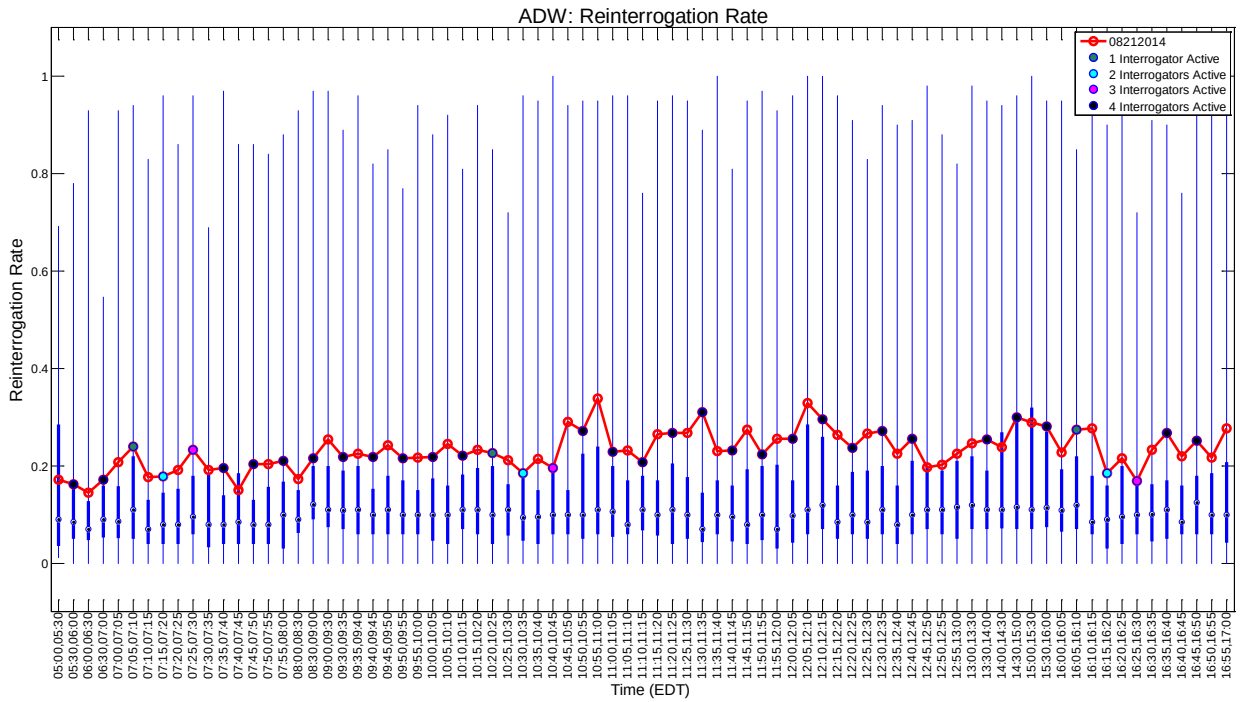

Figure 184. ADW – Day 4 – Reinterrogation Rate - Aircraft Distribution

Examination of Figure 184 shows no observable impacts to interrogation and reinterrogation rates when the LBTS were Active.

ATCRBS and Mode S FRUIT Rate Analysis

In general, FRUIT counts will increase as the number of aircraft and/or the number of interrogators that elicit replies within LOS increase. Interrogations from AN/UPX-41(C) interrogators should only elicit ATCRBS replies; therefore, ATCRBS FRUIT rates were expected to increase when the LBTS were Active and Mode S FRUIT rates would stay about the same when comparing Off and Active periods.

MSAT's FRUIT analysis was used to produce statistics for ATCRBS FRUIT rates and Mode S FRUIT rates. The FRUIT Analysis program in MSAT produces ATCRBS and Mode S FRUIT[4] rates per second separated into 32 11.25° sectors. All replies received through the mainlobe are

[4] Note that receiver sidelobe suppression (RSLS) prevents recording of FRUIT received in sidelobes.

broken down into ATCRBS or Mode S replies and assigned a sector number. In theory, FRUIT per second is the ratio of the amount of FRUIT over any given scan to the scan rate; however, as shown in Figure 185, distinct ATCRBS and Mode S listening periods do not span the entirety of any given sector. For ATCRBS FRUIT, a factor, which is the sum of the periods of all modes in the frame table divided by the sum of the ATCRBS periods in the frame table, is used to produce FRUIT that represents a sector as if the entire sector was composed of ATCRBS listening periods. Multiplying this factor by the ratio of the number of ATCRBS FRUIT to the scan rate gives ATCRBS FRUIT per second for a sector. To calculate the FRUIT rate for a 360° scan, individual sectors' FRUIT rates are multiplied by 32 and averaged together. Similarly, Mode S FRUIT is calculated by multiplying the typical definition of Mode S FRUIT per second by a factor, which is the sum of all periods in the frame table divided by the sum of all of the All-call periods in the frame table. Note that Roll-call periods are excluded when determining Mode S FRUIT rates.

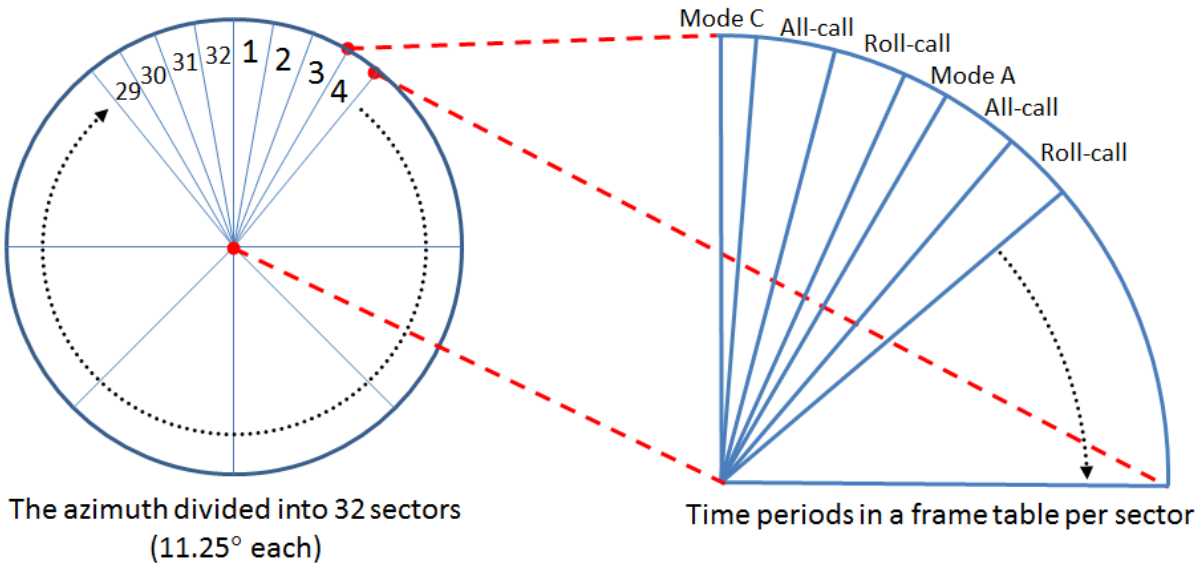

Figure 185. Mode S SSR Time Periods

The ATCRBS FRUIT rate for ADW using Day 4's time bins is shown in Figure 186. With Terra Fix enabled, all targets, including Mode S targets, responded to ATCRBS interrogations. As a result, ATCRBS-only aircraft as well as those equipped with Mode S, within the coverage volume of an SSR, were compared to the ATCRBS FRUIT rate as seen in Figure 187. Mode S FRUIT rates for ADW using Day 4's time bins is shown in Figure 188. Mode S FRUIT rate for Day 4 was compared with the number of Mode S targets within Mode S SSR coverage volume for each Active and Off periods as shown in Figure 189. Changes in FRUIT corresponded well with changes in number of targets. A correlation between an increase in ATCRBS FRUIT and Active LBTS was not observed.

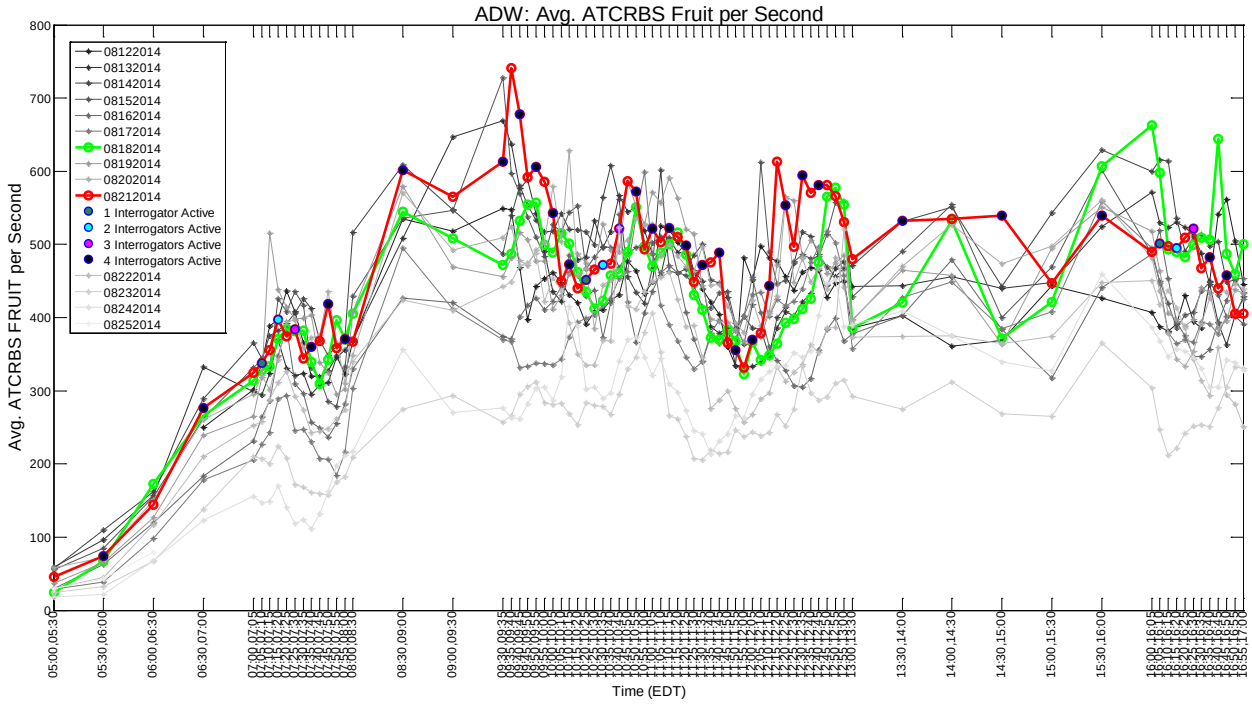

Figure 186. ADW – Day 4 – ATCRBS Fruit Rate

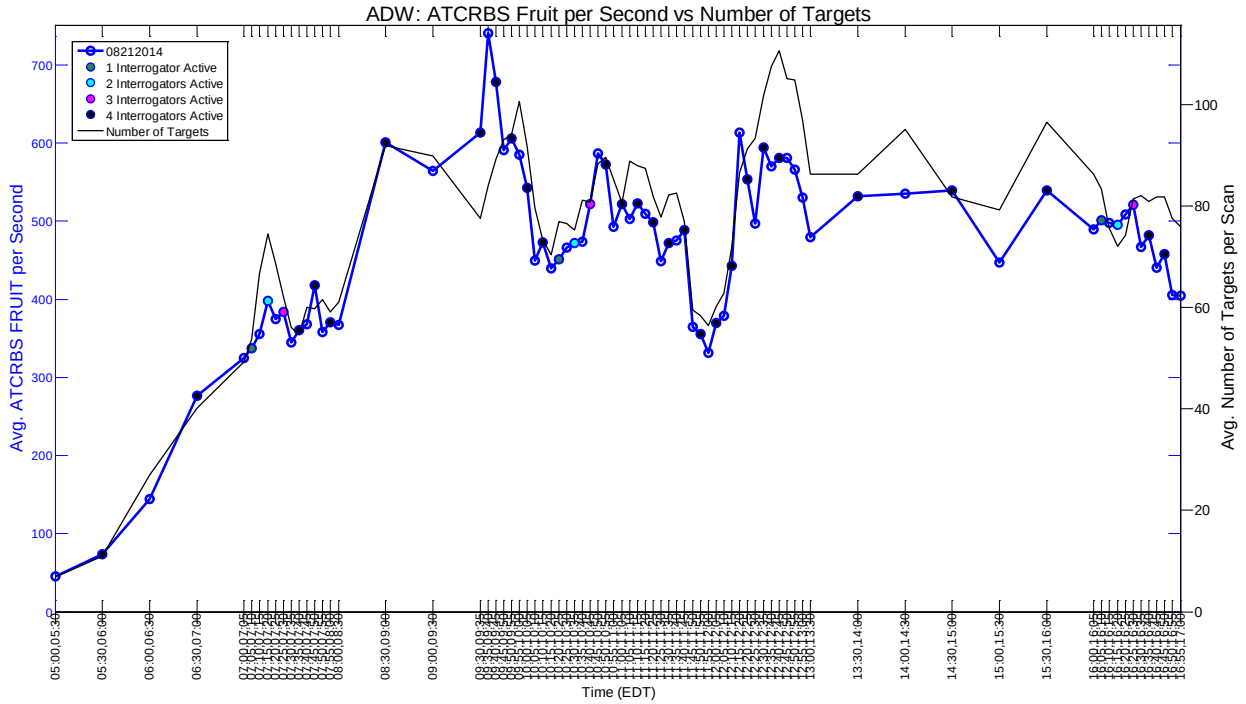

Figure 187. ADW – Day 4 – ATCRBS FRUIT Rate vs. Number of Targets

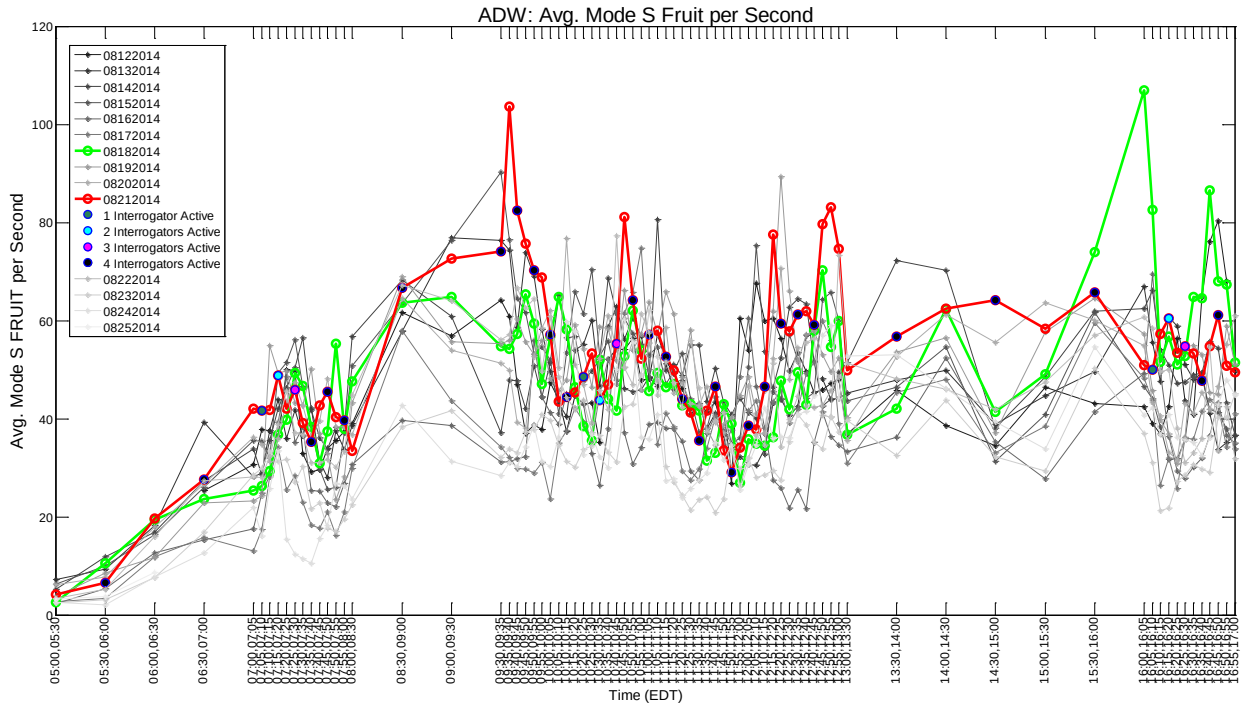

Figure 188. ADW – Day 4 – Mode S Fruit Rate

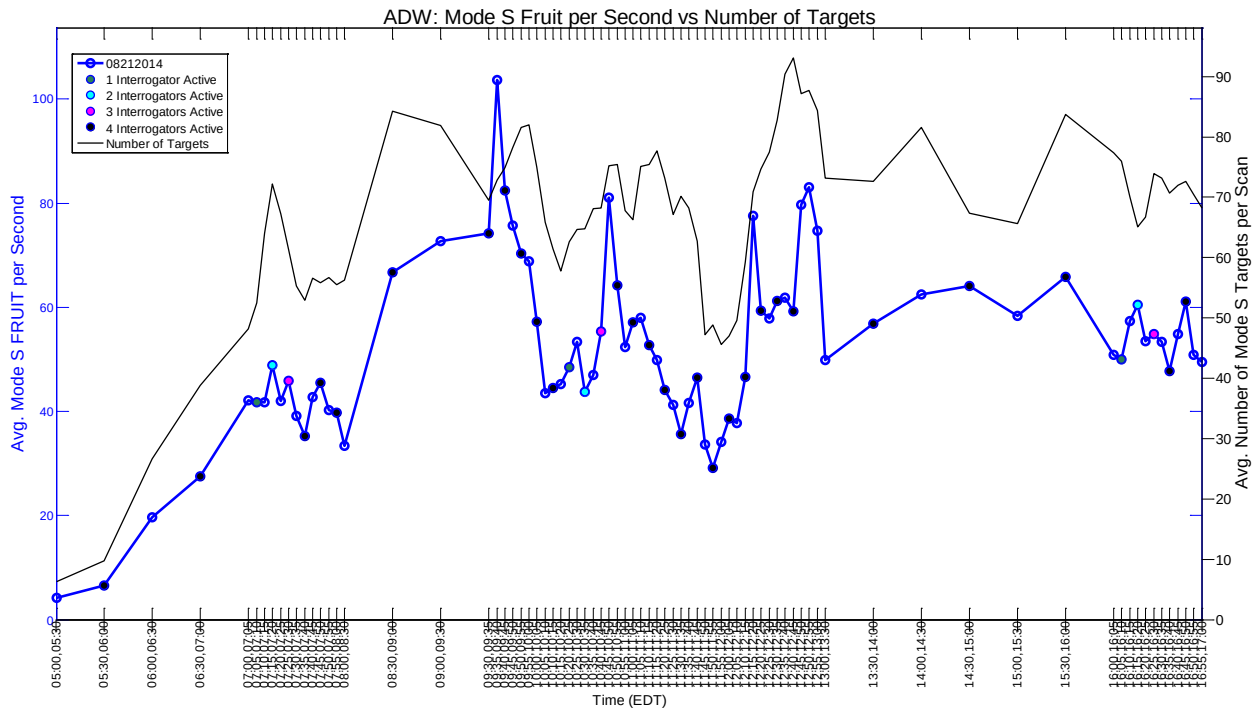

Figure 189. ADW – Day 4 – Mode S FRUIT Rate vs. Number of Mode S Targets

ATCRBS Hit Count Analysis

The performance of the ATCRBS function of a Mode S SSR is evaluated by analyzing the ATCRBS hit count, a summation of the number of replies to ATCRBS interrogations across a beam dwell. Using the DMS program in MSAT, the ATCRBS hit count was compared with Active and Off periods.

The ATCRBS hit counts had high fluctuations due to targets at extreme elevation angles. Therefore, targets below two degrees, due to poor reception at low elevation angles, and targets above eighty-five degrees, the radar's cone of silence, were excluded from the analyses. When examining data at the interrogation and reply level, many things can happen near a radar that may seem like interference in the data, such as peaks and nulls of an antenna that cause some interrogations to trigger a reply by an aircraft's transponder, but not enough to generate a target report. This causes the average number of hits to decrease as a result of antenna design limitations.

With Terra Fix enabled, all targets will respond to ATCRBS interrogations elicited by a Mode S SSR. Since a Mode S SSR's ATCRBS interrogations are not discretely carried out per aircraft, unlike Roll-calls for Mode S surveillance, it is not possible to know from DE files the total number of ATCRBS interrogations that should generate a reply.

The parameter, ATCRBS hit count, is analyzed for targets that are above an elevation angle of two degrees and below an elevation angle of eighty-five degrees. Figure 190 shows the ATCRBS hit count versus aircraft range from ADW. There is a small variation in the hit count until about fifteen nautical miles and then it tends to be constant. Figure 191 depicts how ATCRBS hit count for each time bin stack up against each other. Again, similar to P_d and reinterrogation rate, averages mask outliers. Figure 192 shows how often reports are composed with different number of hits.

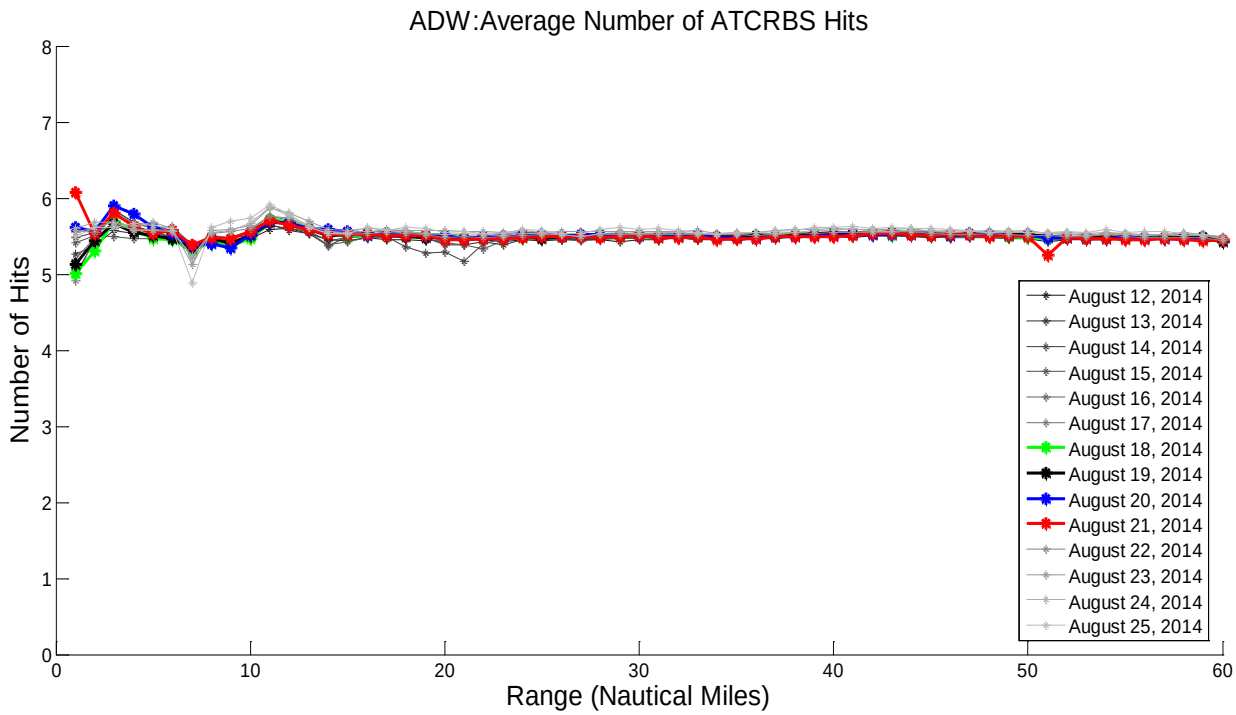

Figure 190. ADW – Average Number of ATCRBS Hits vs Range

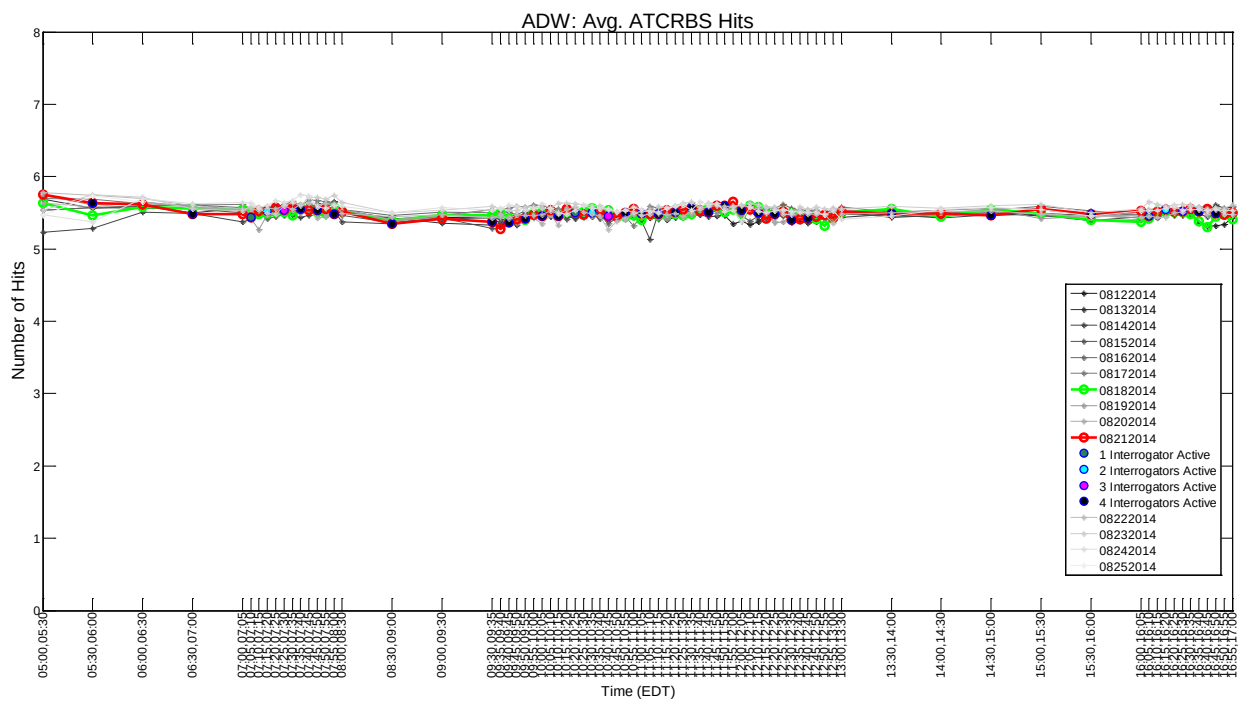

Figure 191. ADW – Day 4 – Average Number of ATCRBS Hits

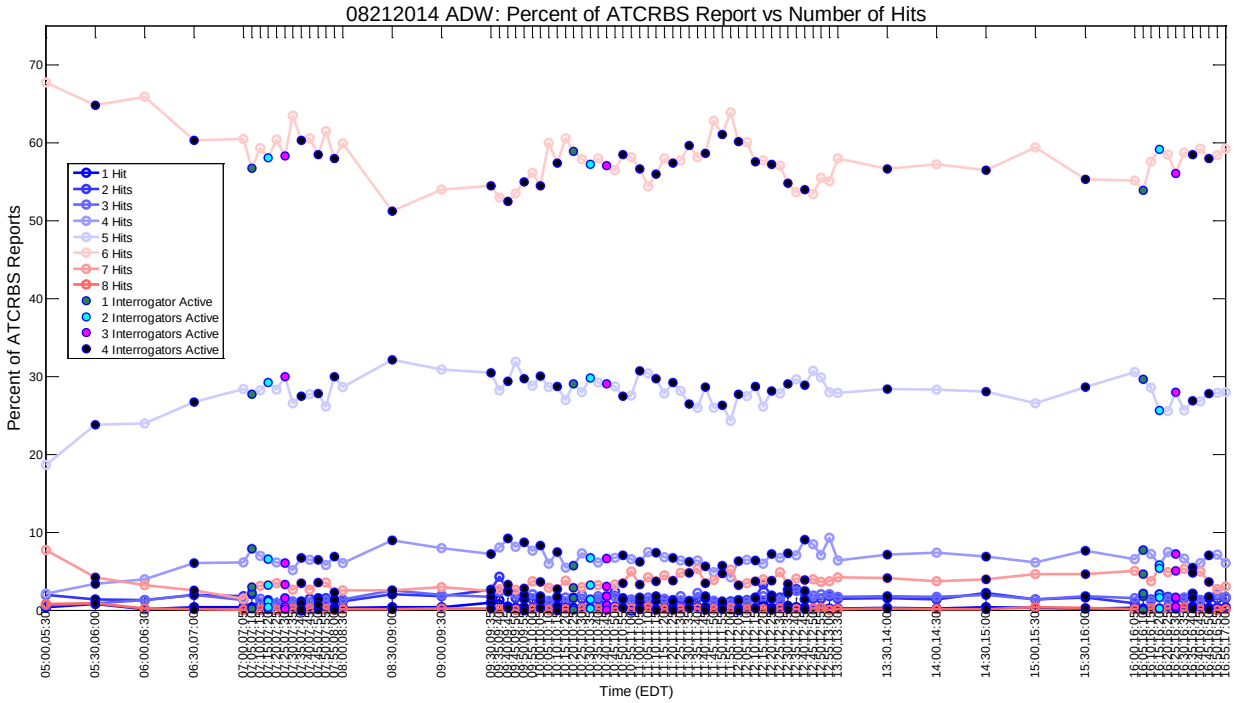

Figure 192. ADW – Day 4 – ATCRBS Number of Hits – Percent Distribution

Occupancy in the sidelobes of the LBTS has the potential to cause the ATCRBS hit count to decrease. Using the Surveillance Print program in MSAT, the ATCRBS hit count for aircraft in this area were examined further. Figure 193 shows how the average number of ATCRBS hits for aircraft within the sidelobes of the LBTS compare for Active and Off periods. Figure 194 depicts how often reports from aircraft within the sidelobes of the LBTS are composed of certain number of hits.

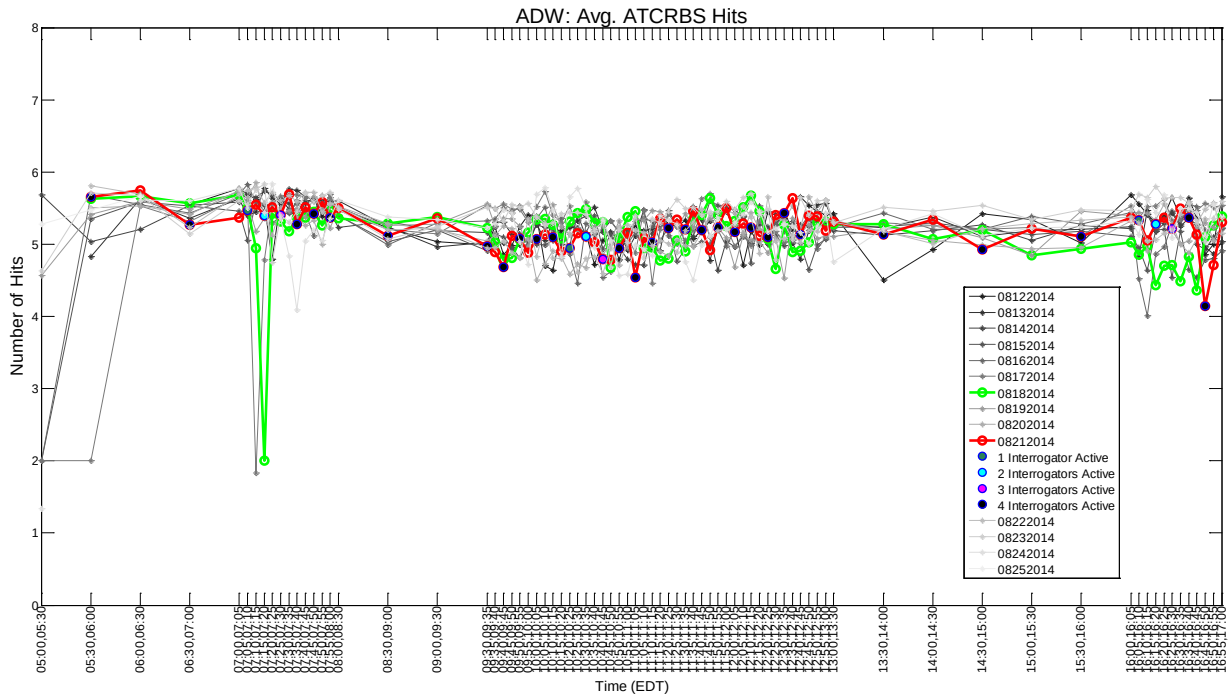

Figure 193. ADW – Day 4 – Average Number of ATCRBS Hits for Aircraft in Sidelobes of LBTS

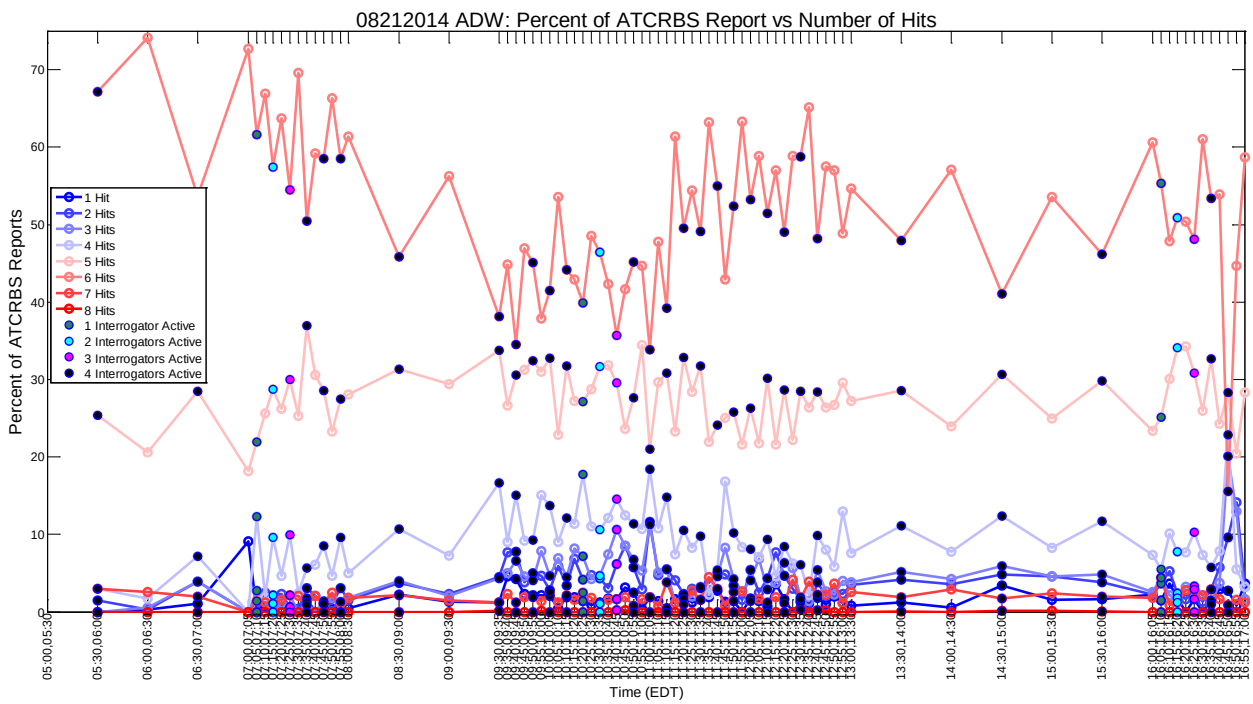

Figure 194. ADW – Day 4 – ATCRBS Number of Hits – Percent Distribution for Aircraft in Sidelobes of LBTS

This analysis showed no pattern of decrease in ATCRBS hit count when the LBTS were Active.

Mainbeam Overlap Analysis

Aircraft transponders outside of the sidelobe suppression range of an SSR only experience transponder occupancy due to the SSR when the SSR's mainbeam dwells on the aircraft. If multiple SSR mainbeams are directed at one aircraft, depending on the interlace timing of the interrogations, some interrogations may not be processed if the transponder is already in a transaction with another SSR. In this analysis, the change in interrogation rate, reinterrogation rate, and number of ATCRBS replies received is examined for times when the LBTS mainbeams were overlapping with the four Mode S SSRs under examination. Using target report data provided by three of the four LBTS, in conjunction with DE files, the changes in reinterrogation rate and ATCRBS hit count were calculated.

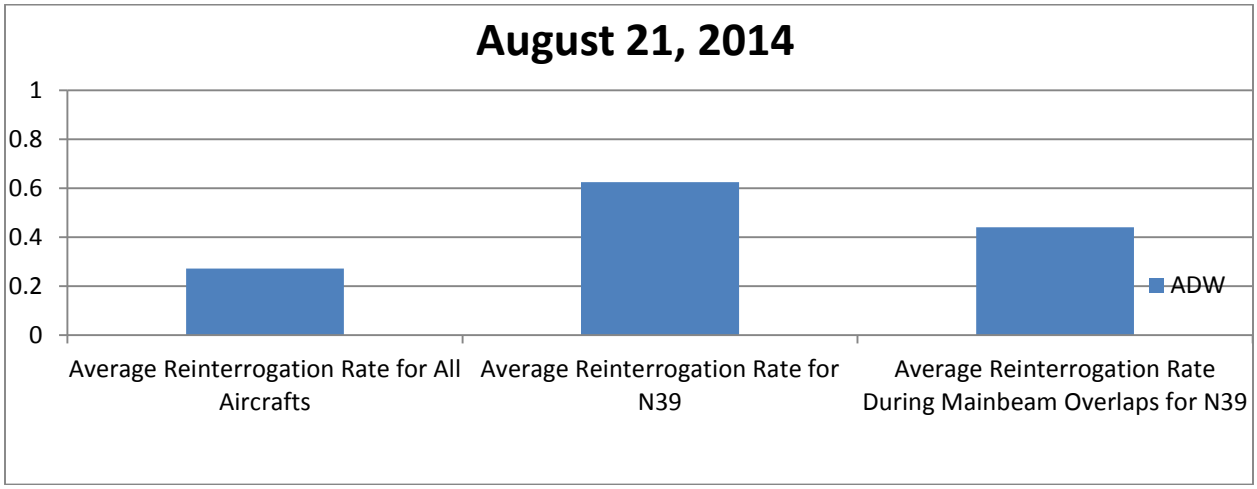

Figure 195. ADW – Day 4 – Average Reinterrogation Rate vs. Average Reinterrogation Rate with Mainbeam Overlaps

Figure 195 compares the average reinterrogation rate for all aircraft, reinterrogation rate of N39, and reinterrogation rate of N39 while the mainbeams of the LBTS were overlapping with Mode S SSR mainbeams. Reinterrogation rate for N39 was high because it flew directly over ADW where limitations in azimuth prediction cause many reinterrogations. In addition, out of the total 1424 interrogations of N39 by ADW, the timings of 367 interrogations were not recorded by the Mode S SSR during times when N39 was within ten nautical miles because of storage space limitations. Correlating target report data from the LBTS logs with target report times reported by the Mode S SSR, the times when mainbeams overlapped were computed. Since there was no time record for 367 interrogations, there was no way to check if mainbeams of the LBTS were overlapping with ADW during these specific interrogations. So, while these interrogations are used in producing overall averages, they are not considered when producing average reinterrogation rate during times when the ADW mainbeam was overlapping with the mainbeams of the LBTS. There was no observable adverse effect to reinterrogation rate while the LBTS were operating.

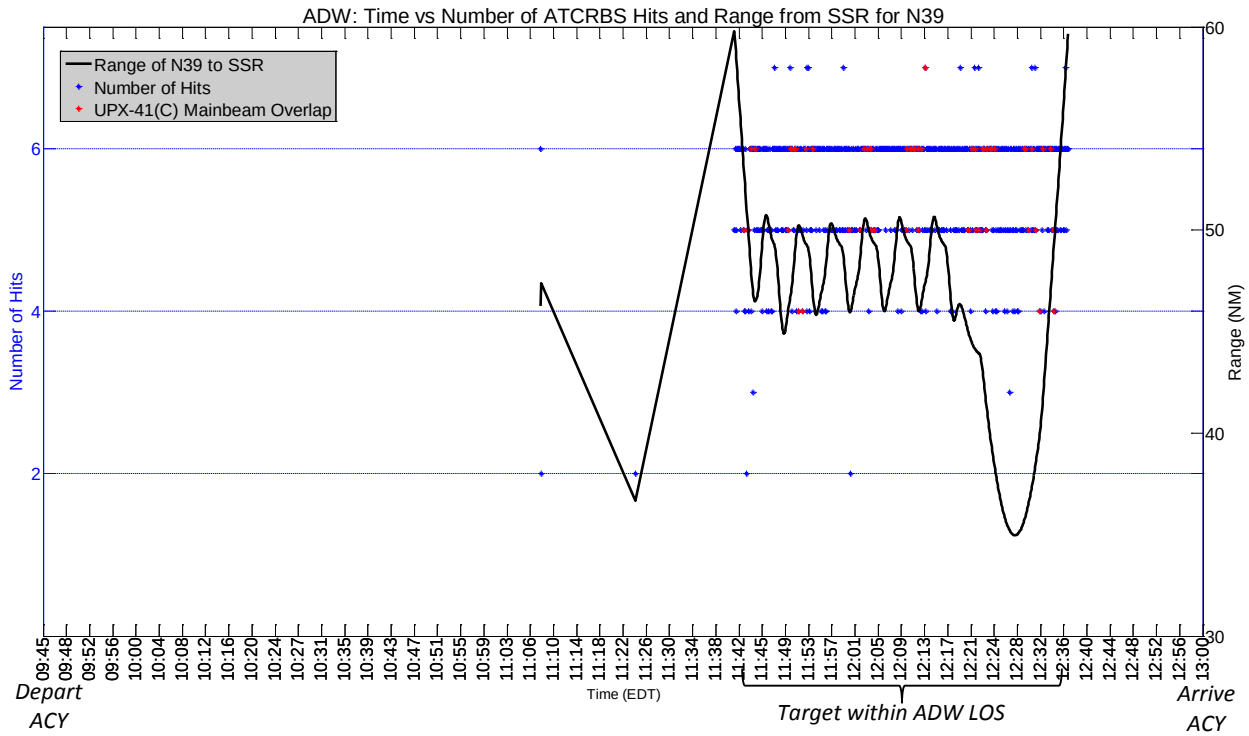

Figure 196. ADW – Day 3 – Time vs N39's Range to ADW and Number of ATCRBS Hits on N39

The ATCRBS hit count per target report disseminated by ADW for N39 is shown in Figure 196. Hit counts in red denote times when the ADW and LBTS mainbeams were overlapping. ATCRBS hit counts with respect to N39's range to ADW show little variation. If interference from LBTS mainbeam overlaps was present, this would reduce ATCRBS hit counts when comparing to periods of no LBTS mainbeam overlap of the same range. There was no observable impact to ATCRBS hit count when LBTS mainbeams were overlapping with the mainbeams of the Mode S SSRs under test.

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Appendix D. ADS-B Ground Radio Analysis

D.1 Radio ADS-B Ground Radio Measurement Analysis

Figure 197 shows boxplots that represent 60-second moving average target report update rate distributions for aircraft seen by radio SV017-01 on Day 2 of the Test from 0900 to 0930 EDT when no LBTS were operating. The x-axis contains ICAO addresses of aircraft seen and the y-axis shows the 60-second moving average update rate for each of the aircraft. None of the aircraft shown have all 60-second average update rates close to once per second because of the aforementioned throttling.

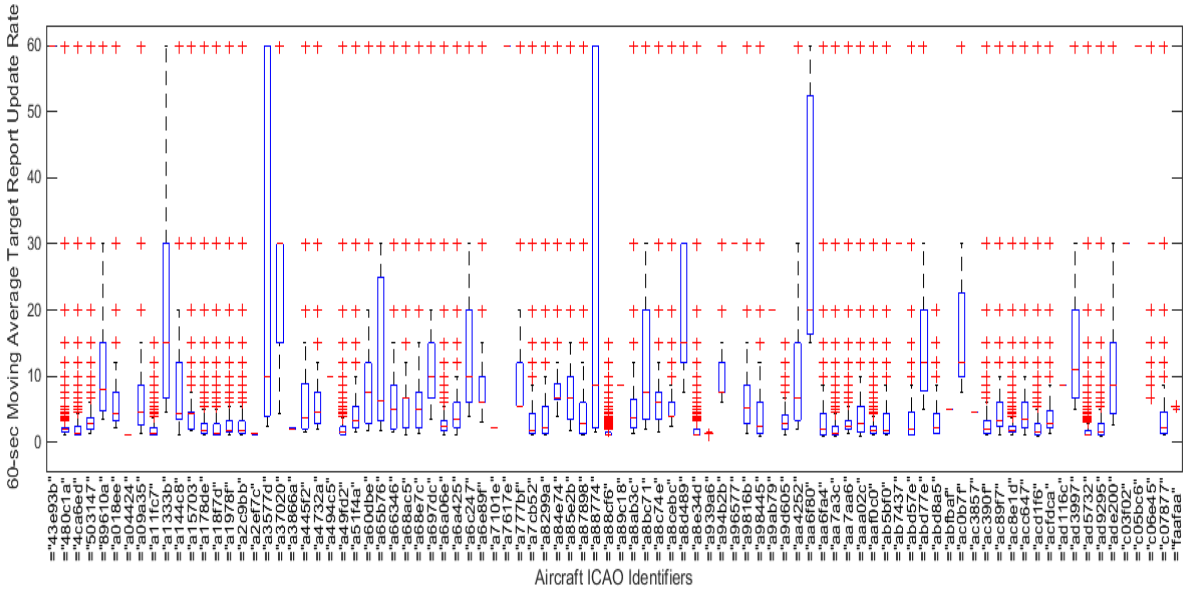


Figure 197. SV017-01 – Day 2 – 0900, 0930 EDT – Aircraft 60 second Average Message Reception Rate

Targets within twenty nautical miles of a radio site were more likely to have reports sent to SDPs since the high quality reports are usually from radios with the shortest distance to the aircraft. Figure 198 shows update rates for targets within twenty nautical miles of radio SV017-01 as reported by radio SV017-01. The black line strings together the configurations of LBTS depicted by shading of the points for each of the time bins listed on the x-axis. Outliers in this plot are not shown due to the discretization of update rates and lack of boxplots show that there are no targets within twenty nautical miles for a given time interval. Even with the condition of twenty nautical miles around a radio site enforced, the average update rates still exceeded the expected once per second update rate for many targets.

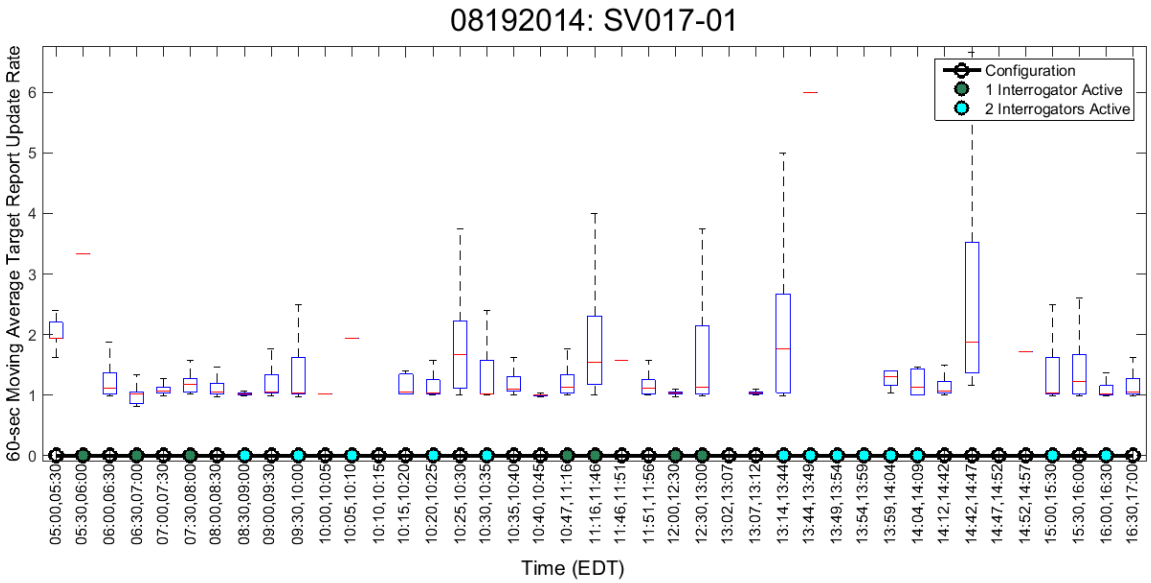


Figure 198. SV017-01 – Day 2 – Targets within 20 nmi – 60 Second Moving Average Update Rate

To illustrate that the ADS-B system is functioning correctly, update rates for three aircraft from Day 2 were assessed. Using the best CAT033 reports over the entirety of the ADS-B network (Figure 199), all 60-second moving average update rates for the three aircraft were within 5% of the expected one-second update rate. As intended, the network of all ADS-B ground radios achieves 60-second moving average update rate of once per second.

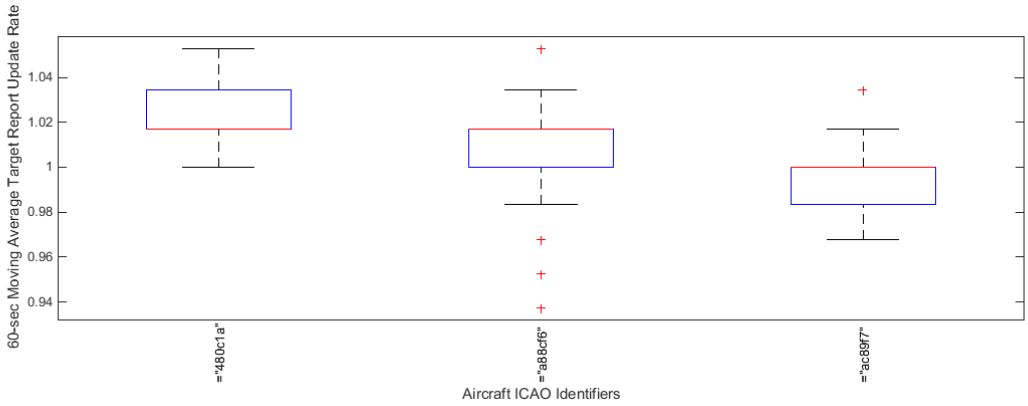


Figure 199. Day 2 – 0900, 0930 EDT – Aircraft 60 second Average Message Reception Rate

For any new live test intending to analyze interference to ADS-B ground radios, it is recommended that DF17s are recorded at ADS-B ground radios.

D.2 Radio ADS-B Ground Radio Simulation Analysis Supplement

D.2.1 Radio SV036-01

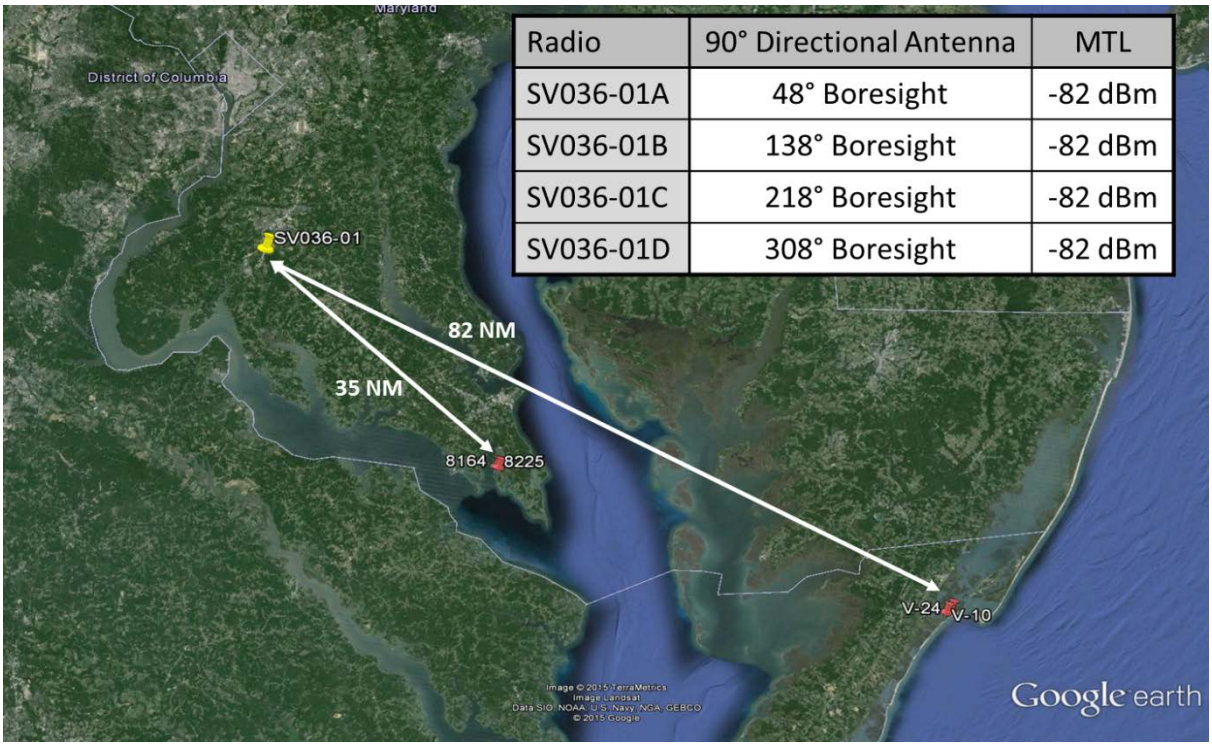


Figure 200. SV036-01 Location and Properties

Table 30. SV036-01 – ADS-B Squitter Reception Overlaps and Failures

SV036-01	Off			Active		
Boresight	**Squitter per second**	**Overlaps per second**	**Failures per second (%)**	**Squitter per second**	**Overlaps per second**	**Failures per second (%)**
48°	391.81	977.82	186.98(47.72%)	382.67	1058.52	187.19(48.92%)
138°	187.29	306.64	56.36(30.09%)	186.04	352.36	59.19(31.81%)
218°	245.43	439.28	85.17(34.70%)	244.70	486.43	88.00(35.96%)
308°	323.97	831.26	134.35(41.47%)	317.38	876.36	133.58(42.09%)

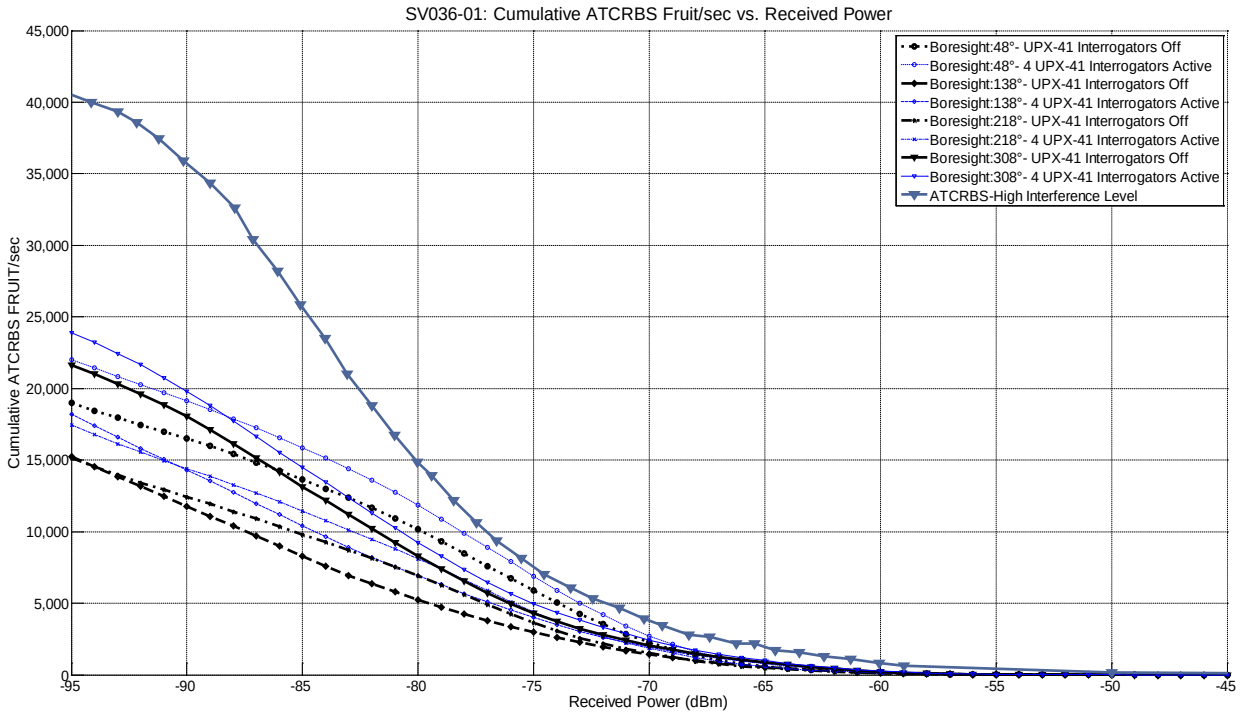


Figure 201. SV036-01 – Cumulative ATCRBS FRUIT/sec vs. Receiver Power Level (dBm)

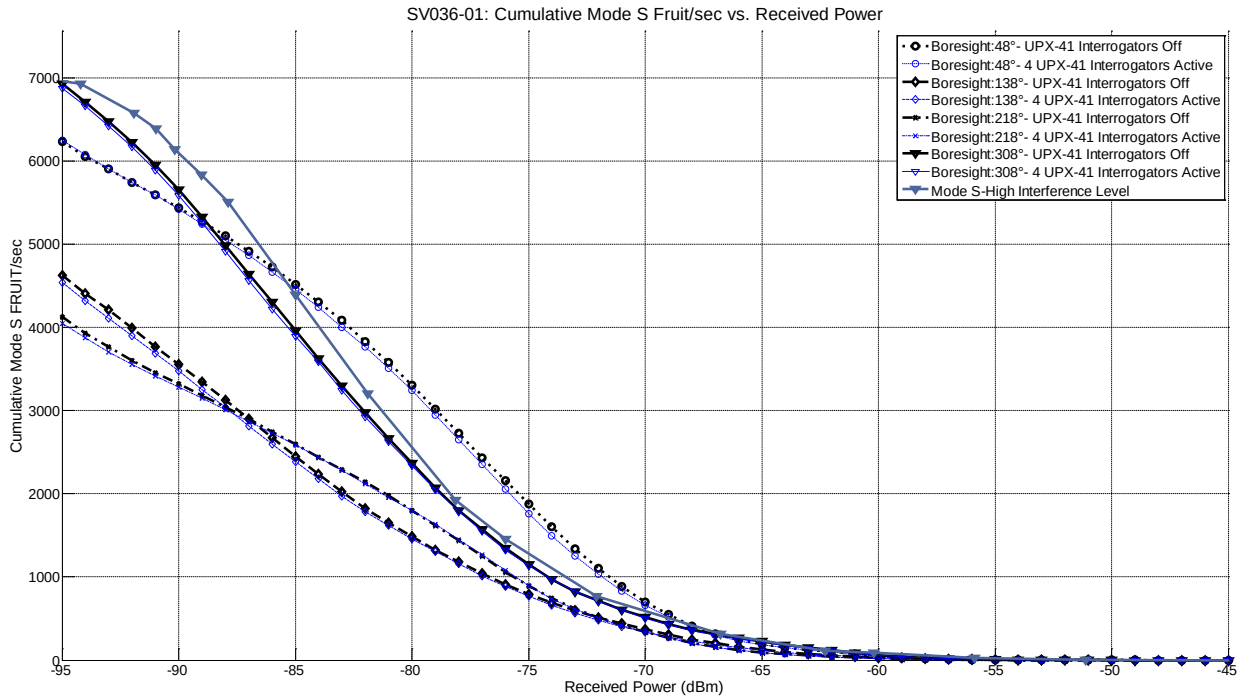


Figure 202. SV036-01 – Cumulative Mode S FRUIT/sec vs. Received Power Level (dBm)

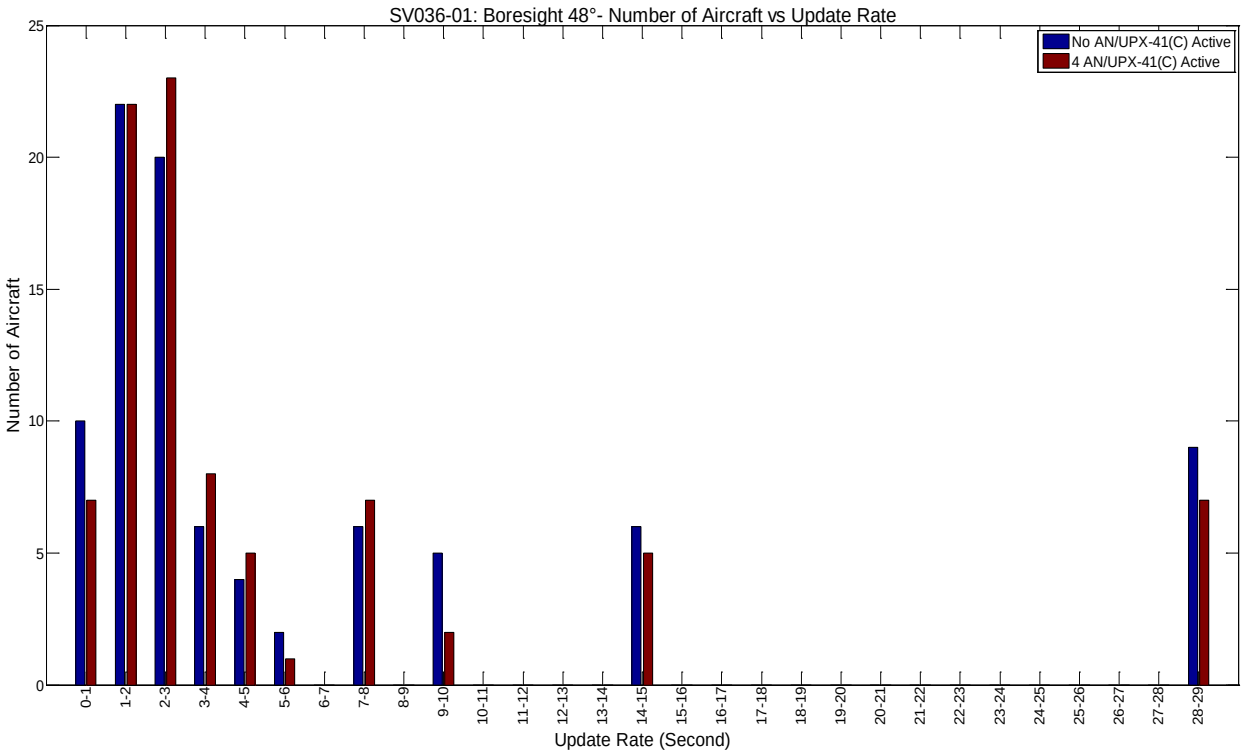


Figure 203. SV036-01 - Boresight 48° - Number of Aircraft vs. Update Rate

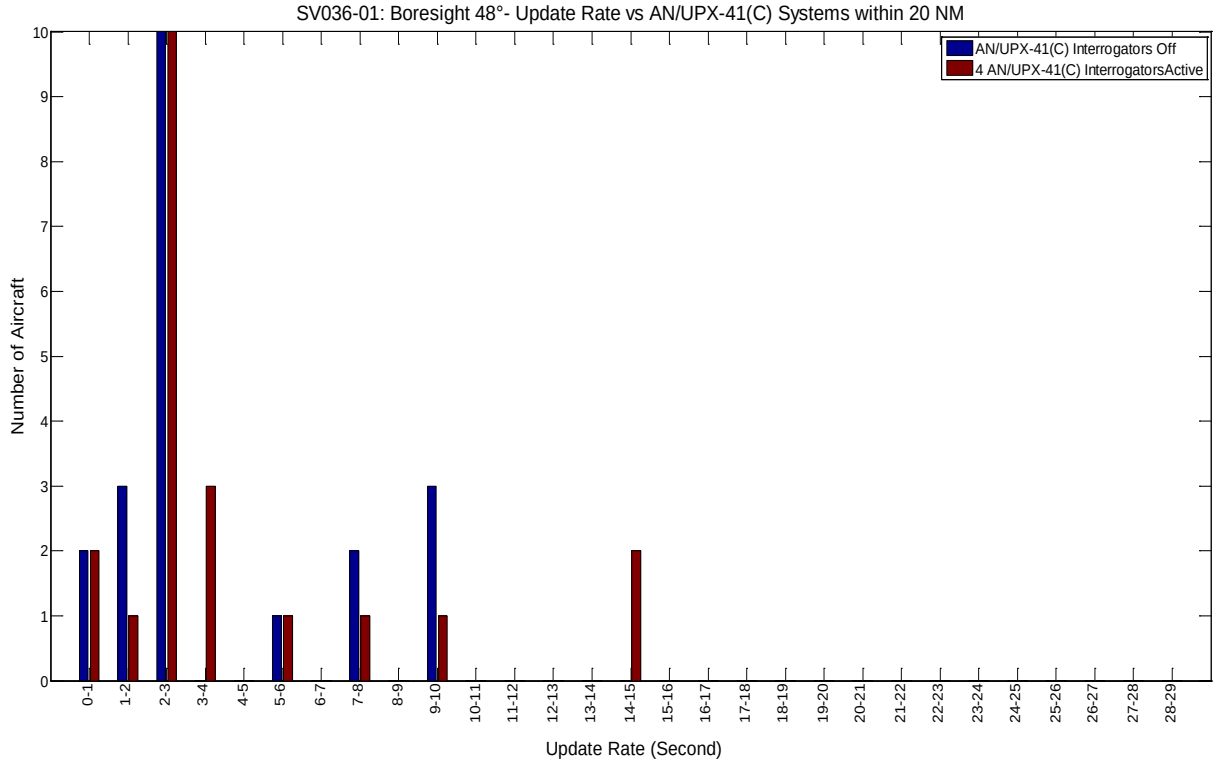


Figure 204. SV036-01 – Boresight 48° – Number of Aircraft within 20 nmi vs. Update Rate

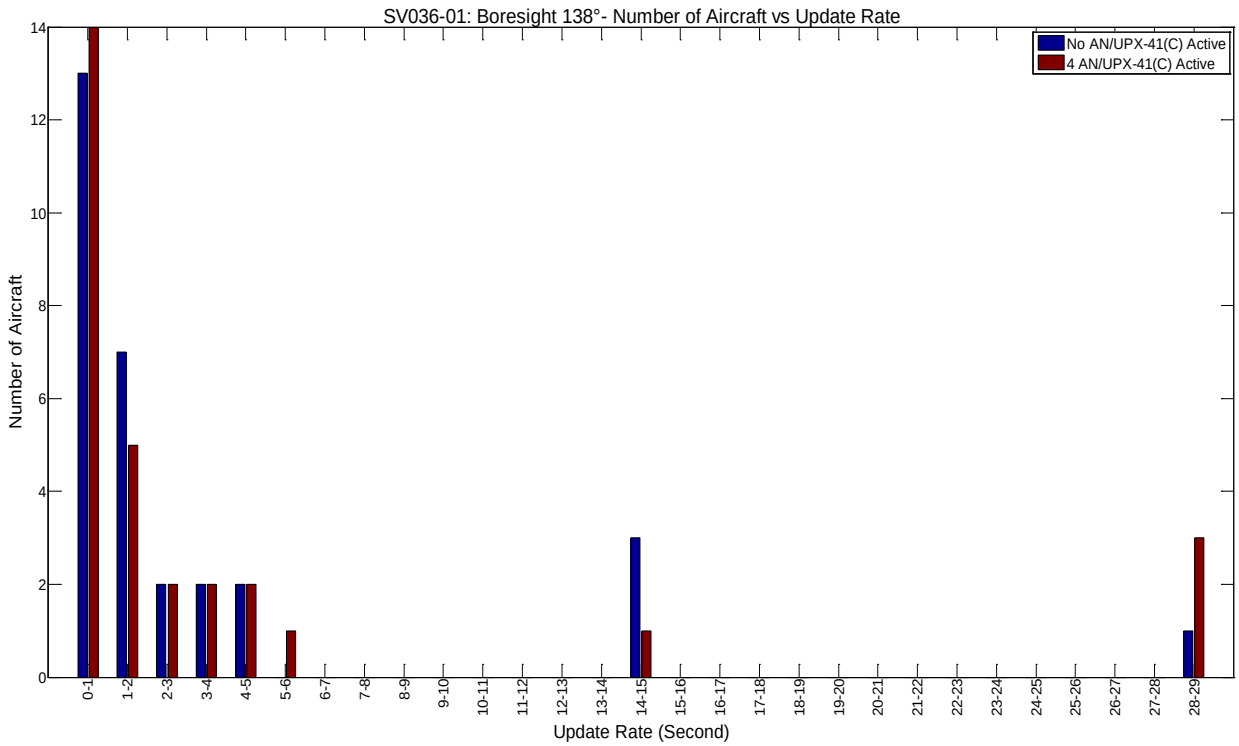


Figure 205. SV036-01 – Boresight 138° – Number of Aircraft vs. Update Rate

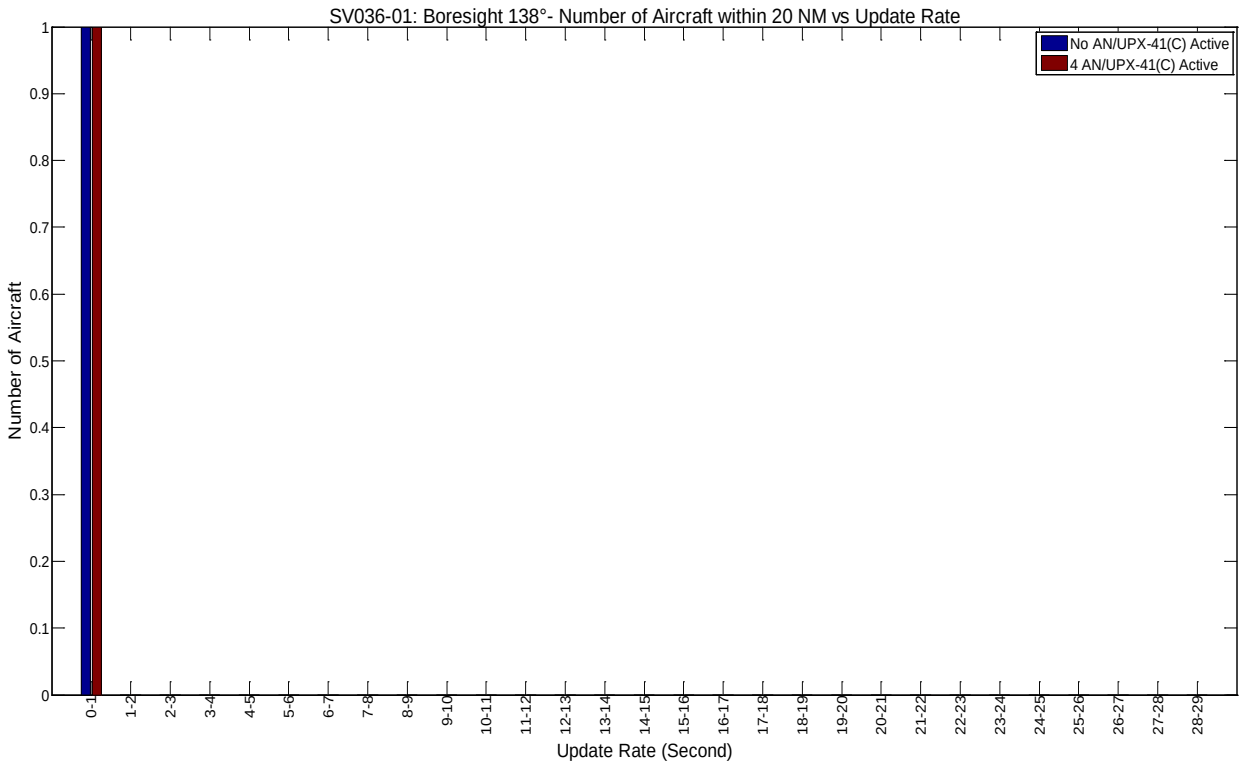


Figure 206. SV036-01 – Boresight 138° – Number of Aircraft within 20 nmi vs. Update Rate

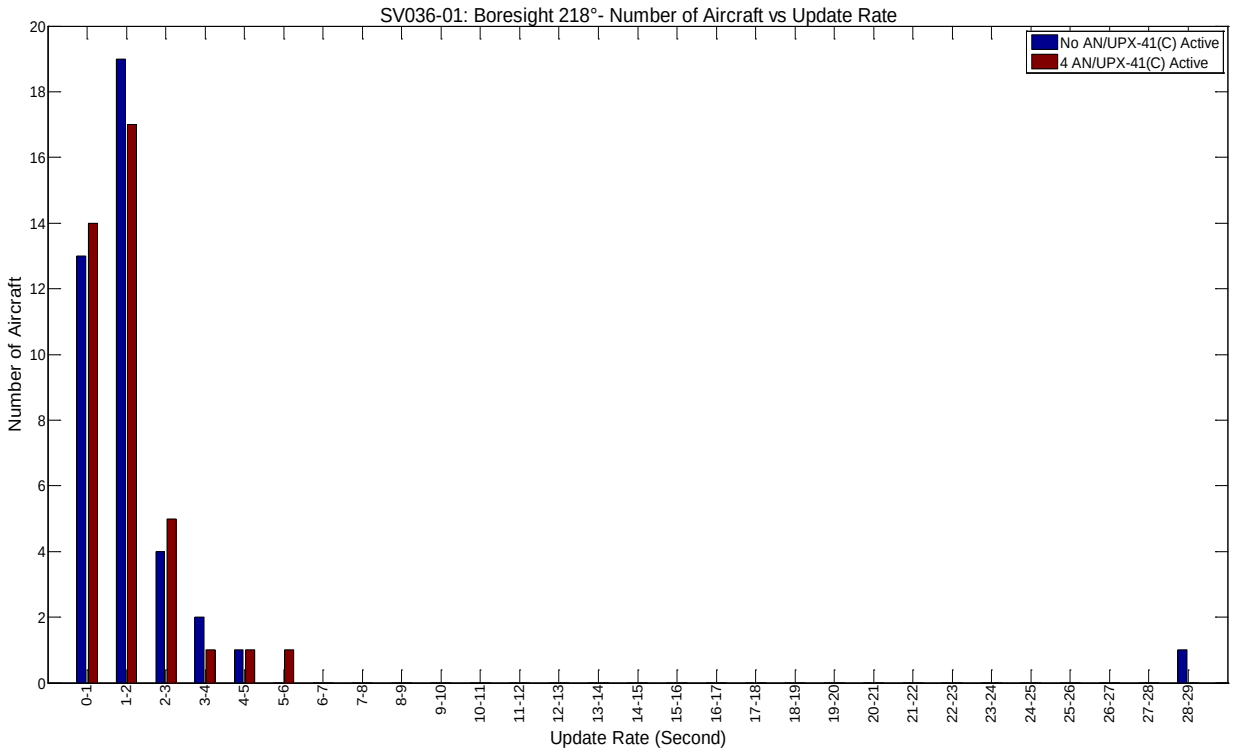


Figure 207. SV036-01 – Boresight 218° – Number of Aircraft vs. Update Rate

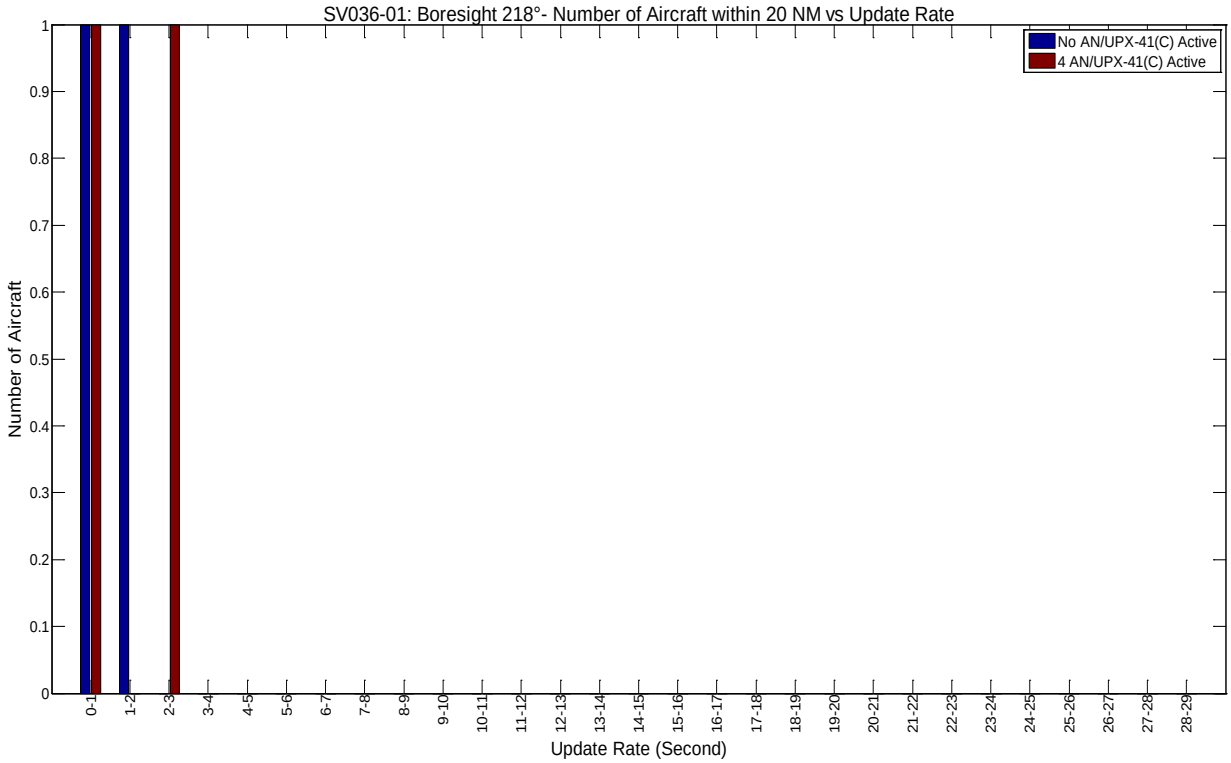


Figure 208. SV036-01 – Boresight 218° – Number of Aircraft within 20 nmi vs. Update Rate

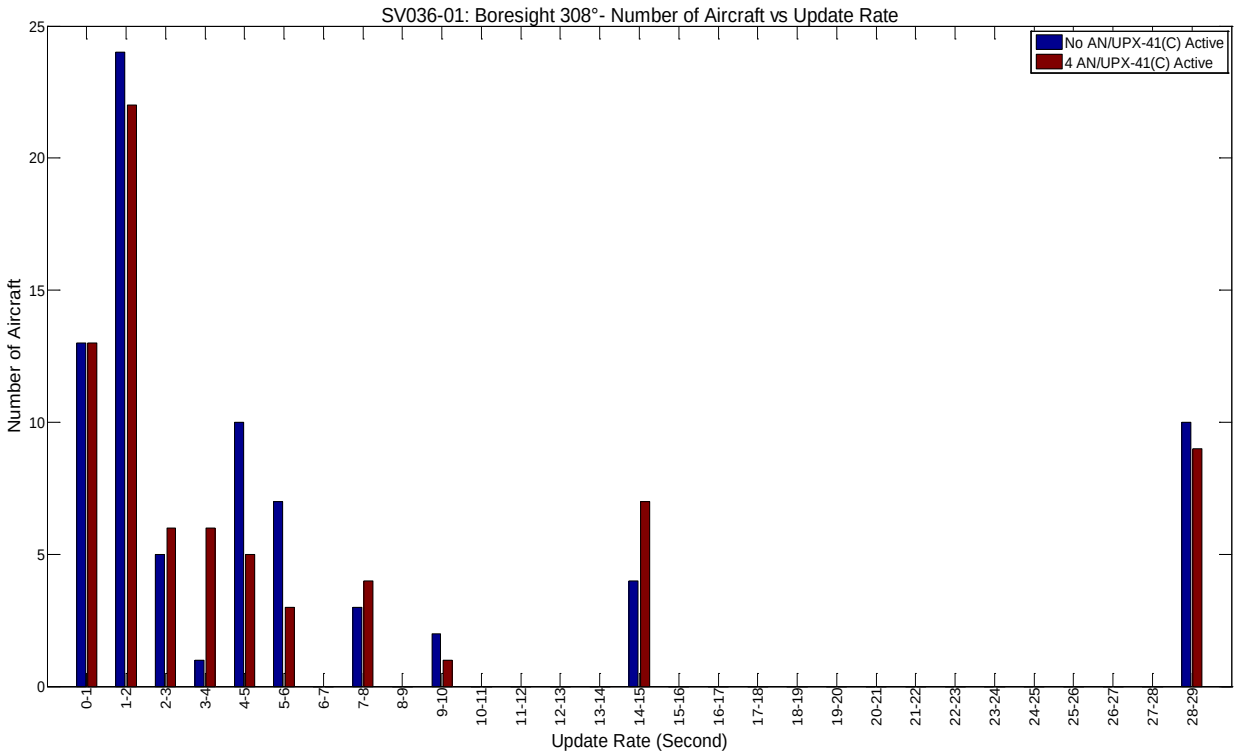


Figure 209. SV036-01 – Boresight 308° – Number of Aircraft vs. Update Rate

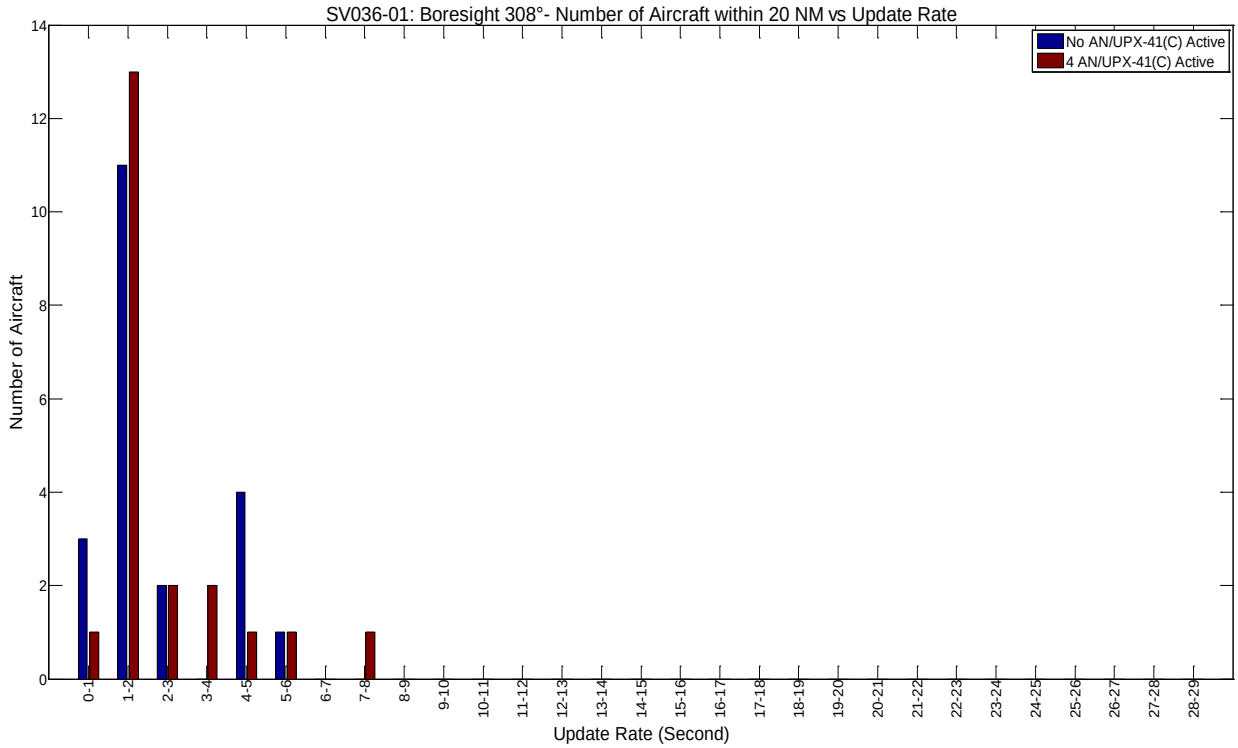
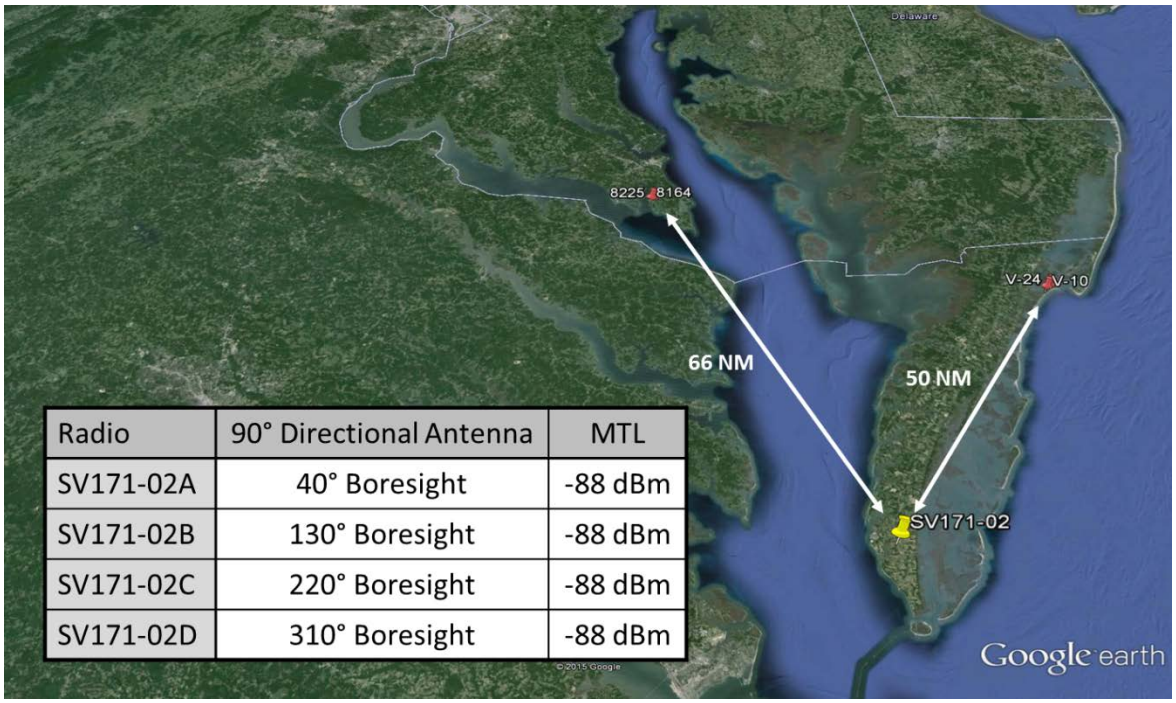


Figure 210. SV036-01 – Boresight 308° – Number of Aircraft within 20 nmi vs. Update Rate

D.2.2 Radio SV171-02



Radio	90° Directional Antenna	MTL
SV171-02A	40° Boresight	-88 dBm
SV171-02B	130° Boresight	-88 dBm
SV171-02C	220° Boresight	-88 dBm
SV171-02D	310° Boresight	-88 dBm

Figure 211. SV171-02 Location and Properties

Table 31. SV171-02 – ADS-B Squitter Reception Overlaps and Failures

SV171-02	Off			Active		
Boresight	**Squitter per second**	**Overlaps per second**	**Failures per second (%)**	**Squitter per second**	**Overlaps per second**	**Failures per second (%)**
40°	280.38	550.82	104.95(37.43%)	281.77	638.81	111.57(39.60%)
130°	94.06	75.09	15.14(16.09%)	96.68	89.46	16.08(16.63%)
220°	181.05	250.14	43.95(24.27%)	181.61	281.91	46.56(25.64%)
310°	374.65	938.44	166.82(44.53%)	371.02	1041.89	172.19(46.41%)

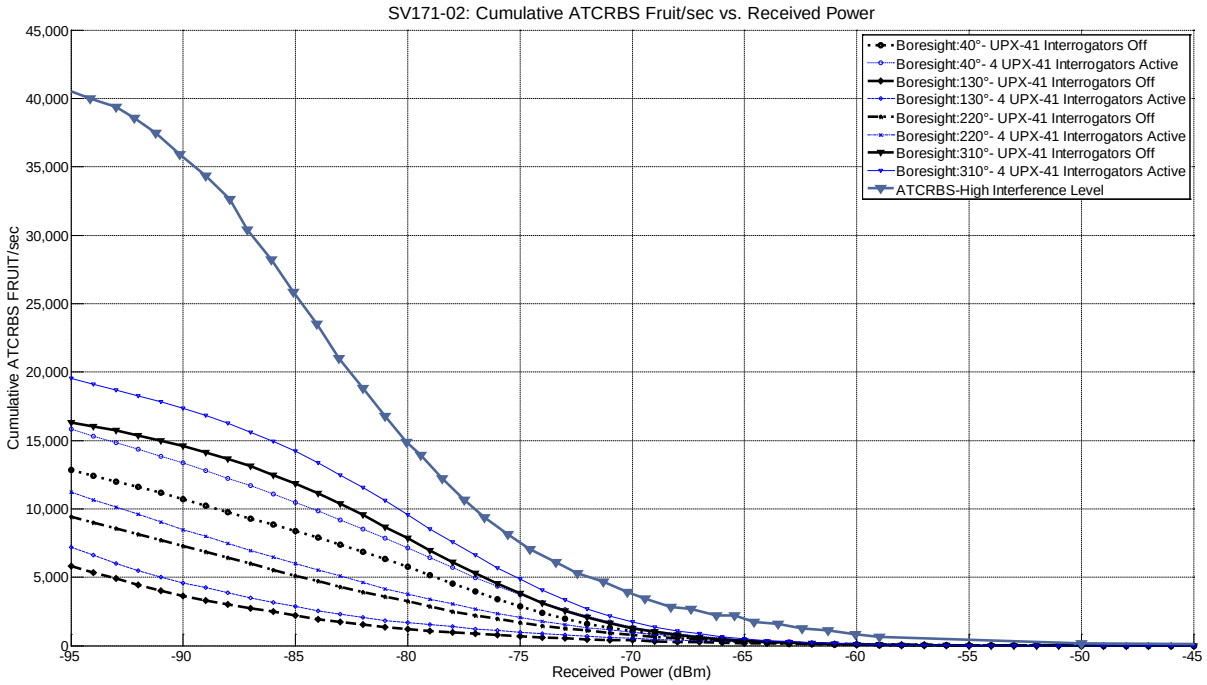


Figure 212. SV171-02 – Cumulative ATCRBS FRUIT/sec vs. Receiver Power Level (dBm)

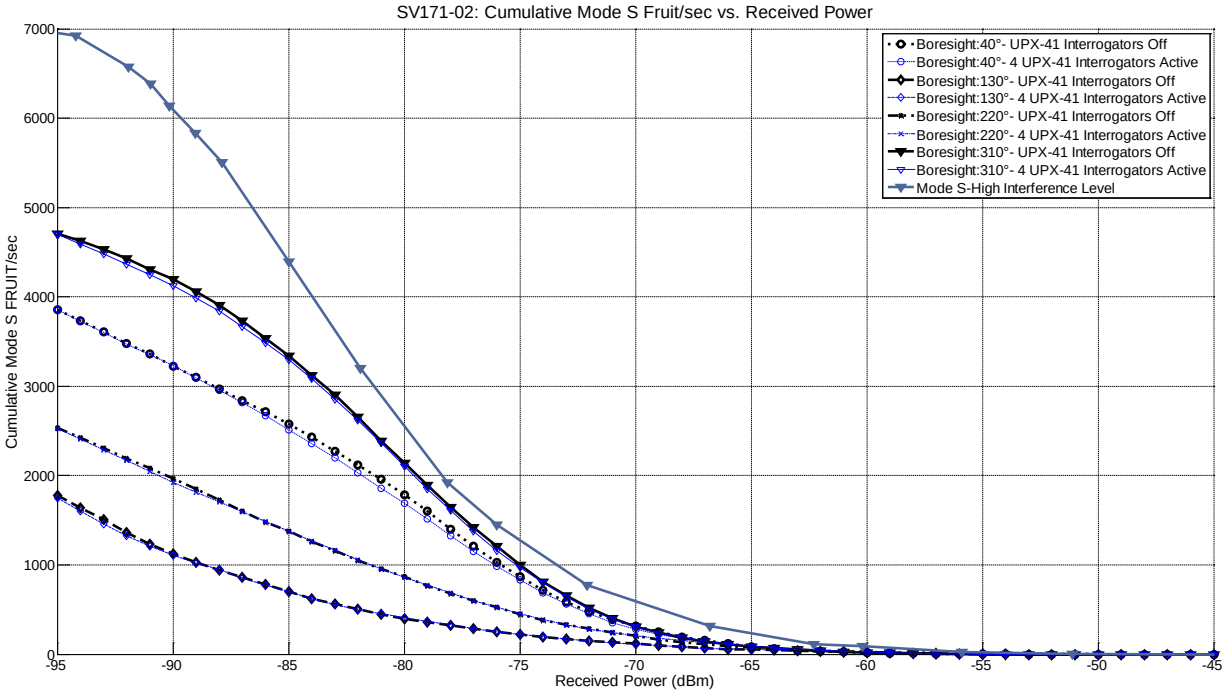


Figure 213. SV171-02 – Cumulative Mode S FRUIT/sec vs. Receiver Power Level (dBm)

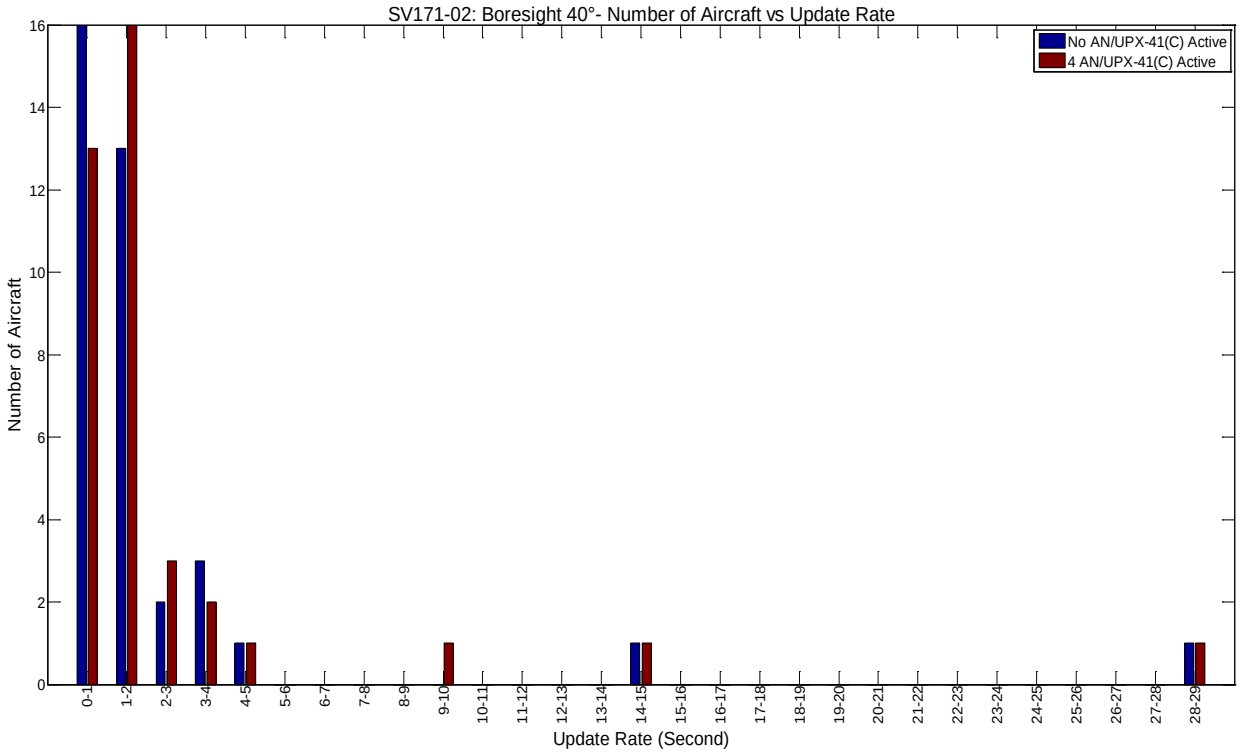


Figure 214. SV171-02 – Boresight 40° – Number of Aircraft vs. Update Rate

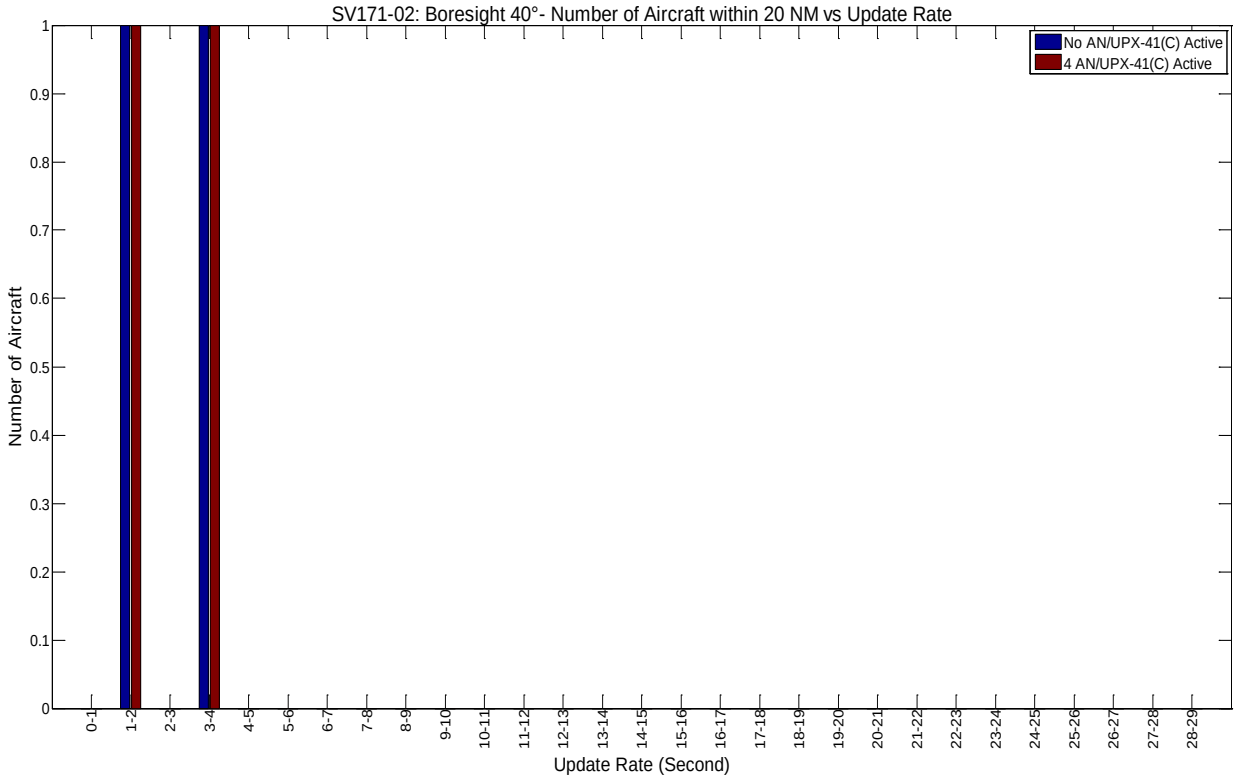


Figure 215. SV171-02 – Boresight 40° – Number of Aircraft within 20 nmi vs. Update Rate

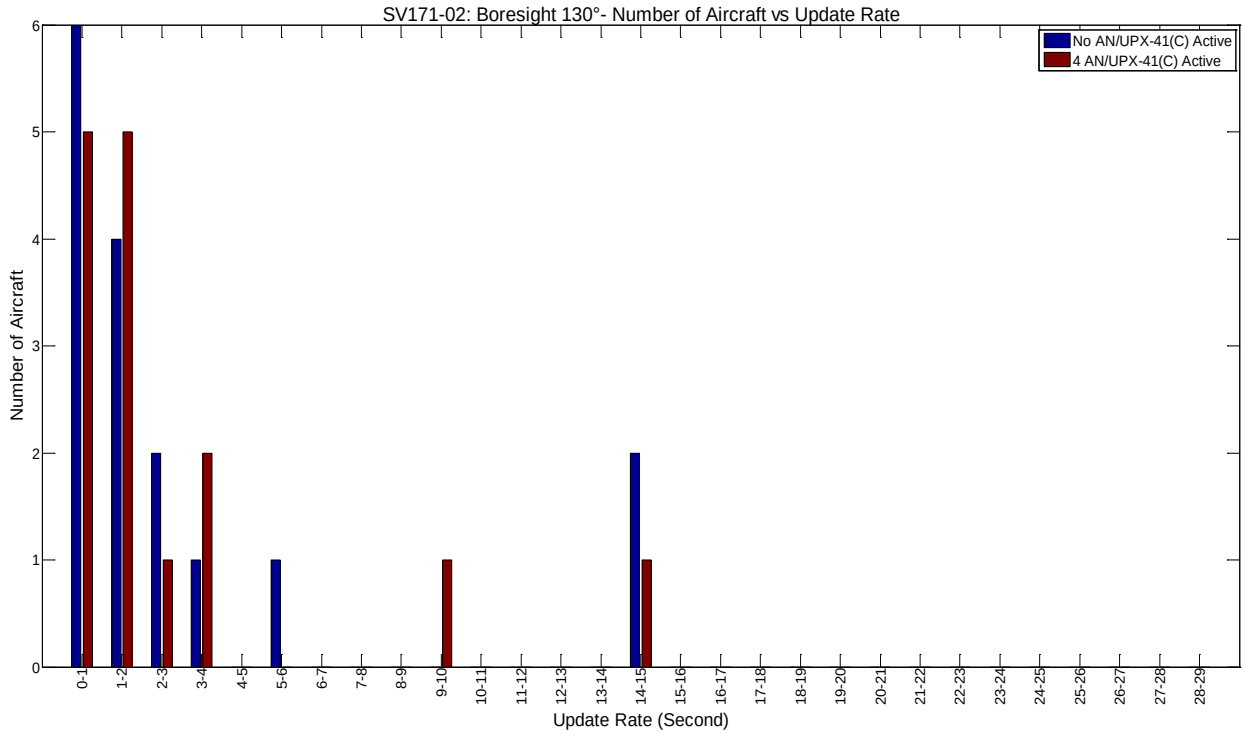


Figure 216. SV171-02 – Boresight 130° – Number of Aircraft vs. Update Rate

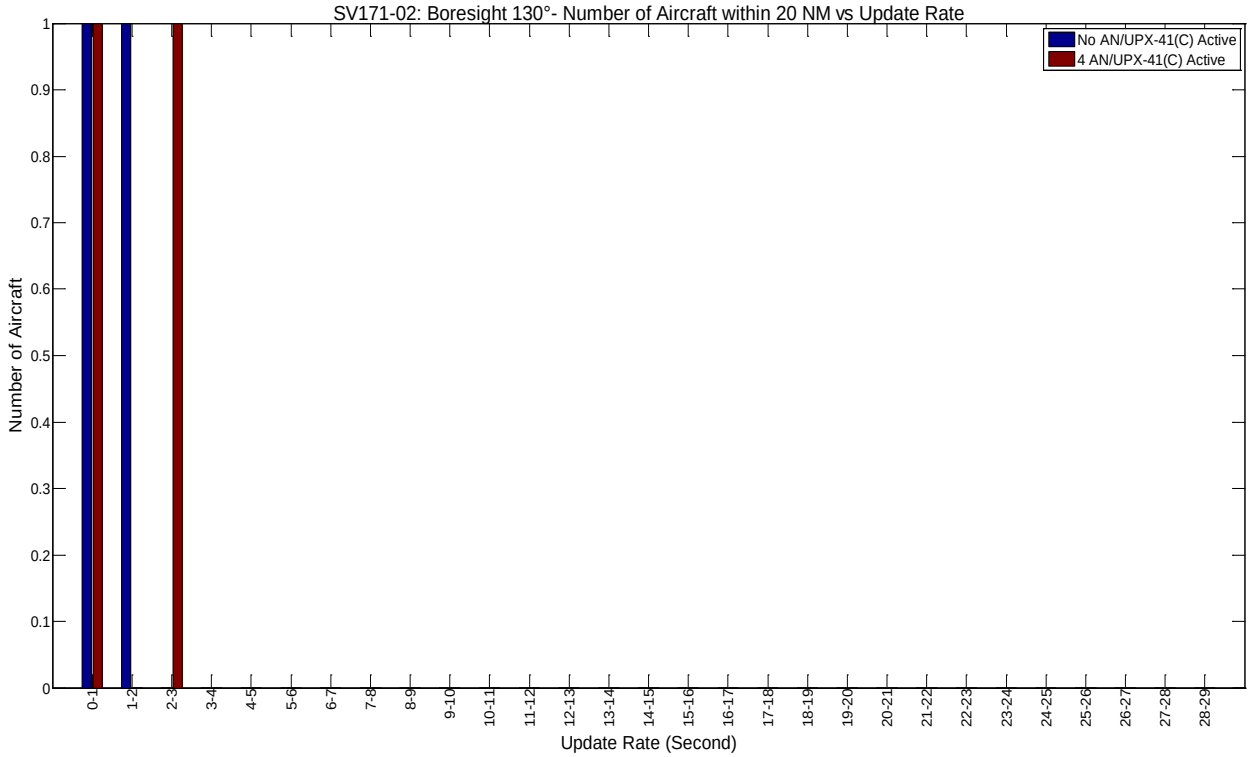


Figure 217. SV171-02 – Boresight 130° – Number of Aircraft within 20 nmi vs. Update Rate

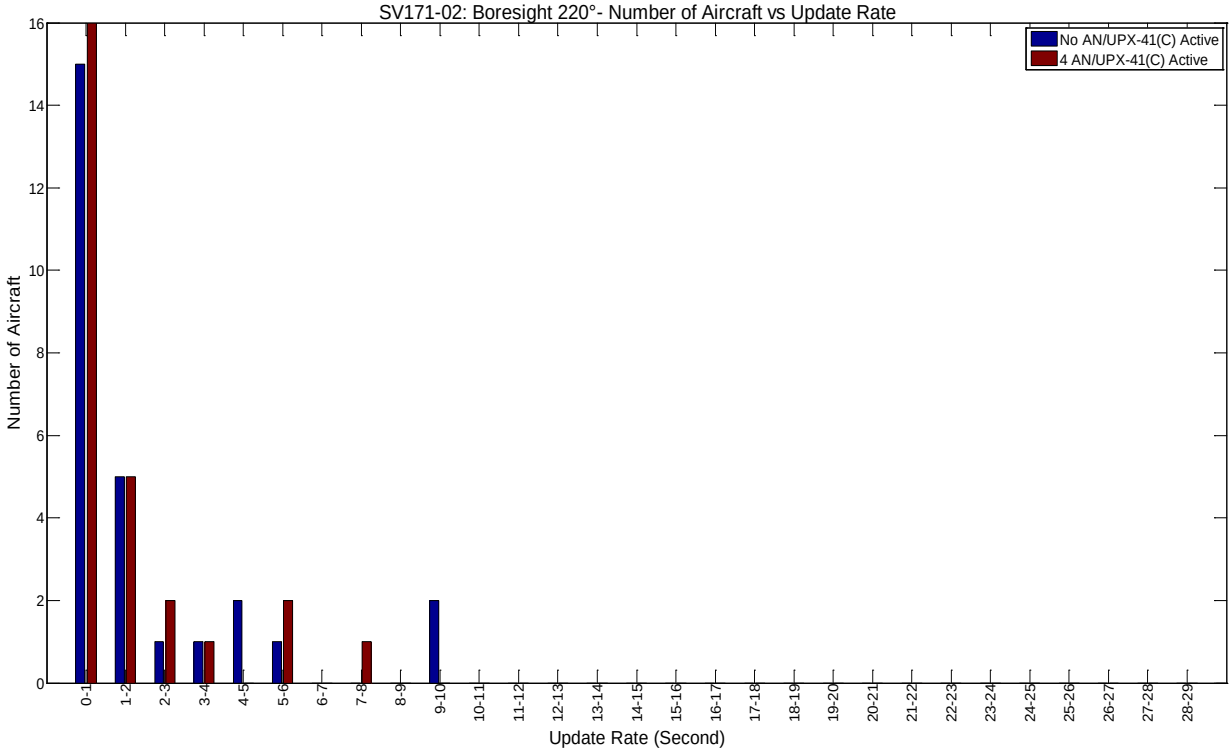


Figure 218. SV171-02 – Boresight 220° – Number of Aircraft vs. Update Rate

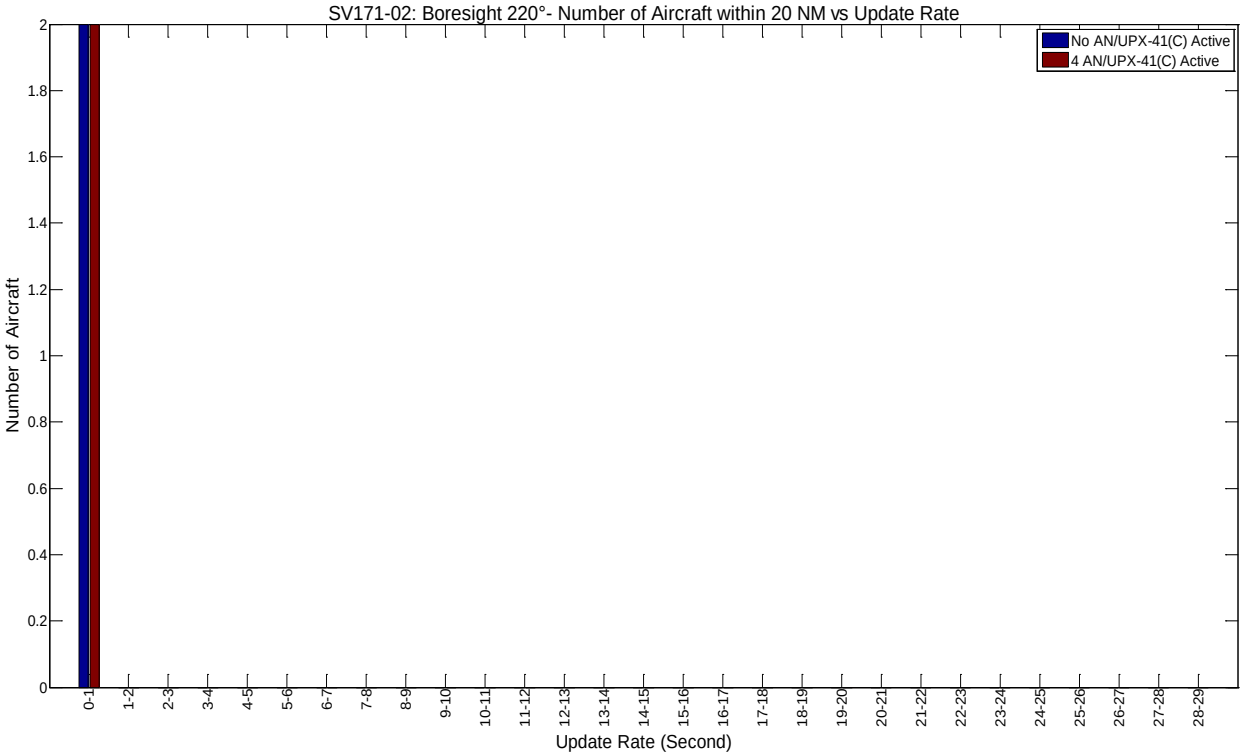


Figure 219. SV171-02 – Boresight 220° – Number of Aircraft within 20 nmi vs. Update Rate

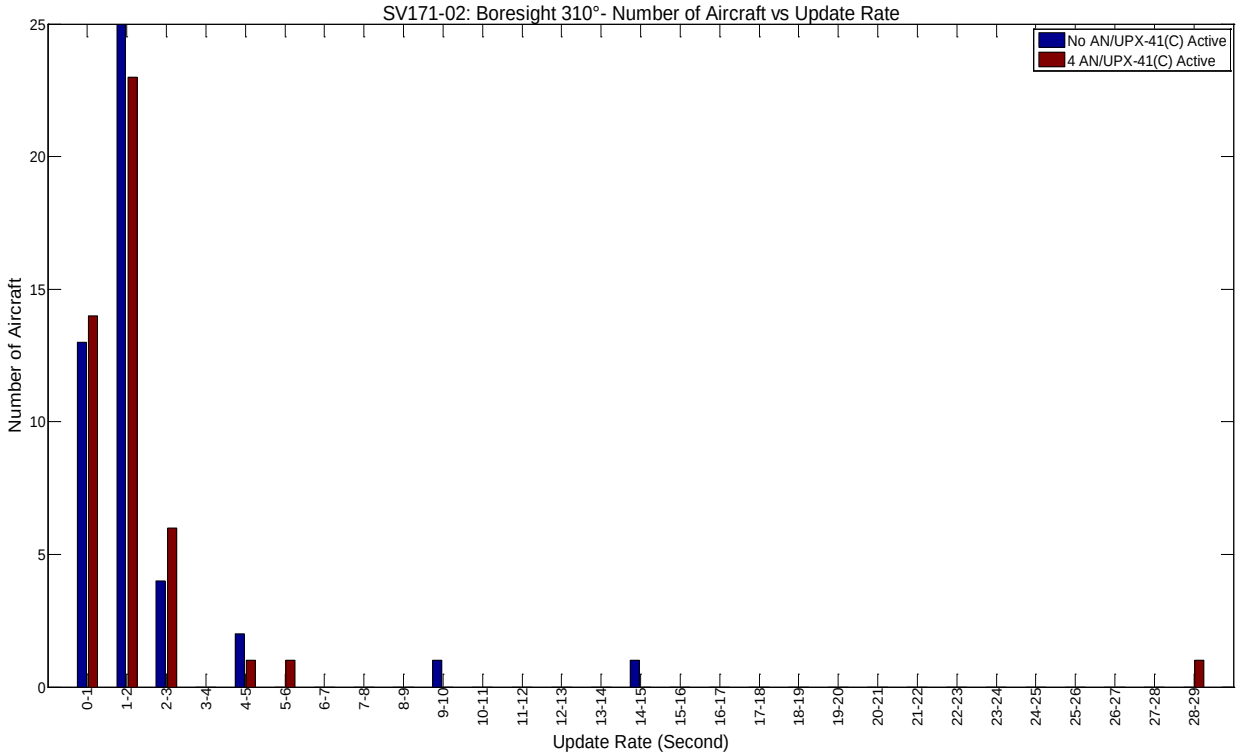


Figure 220. SV171-02 – Boresight 310° – Number of Aircraft vs. Update Rate

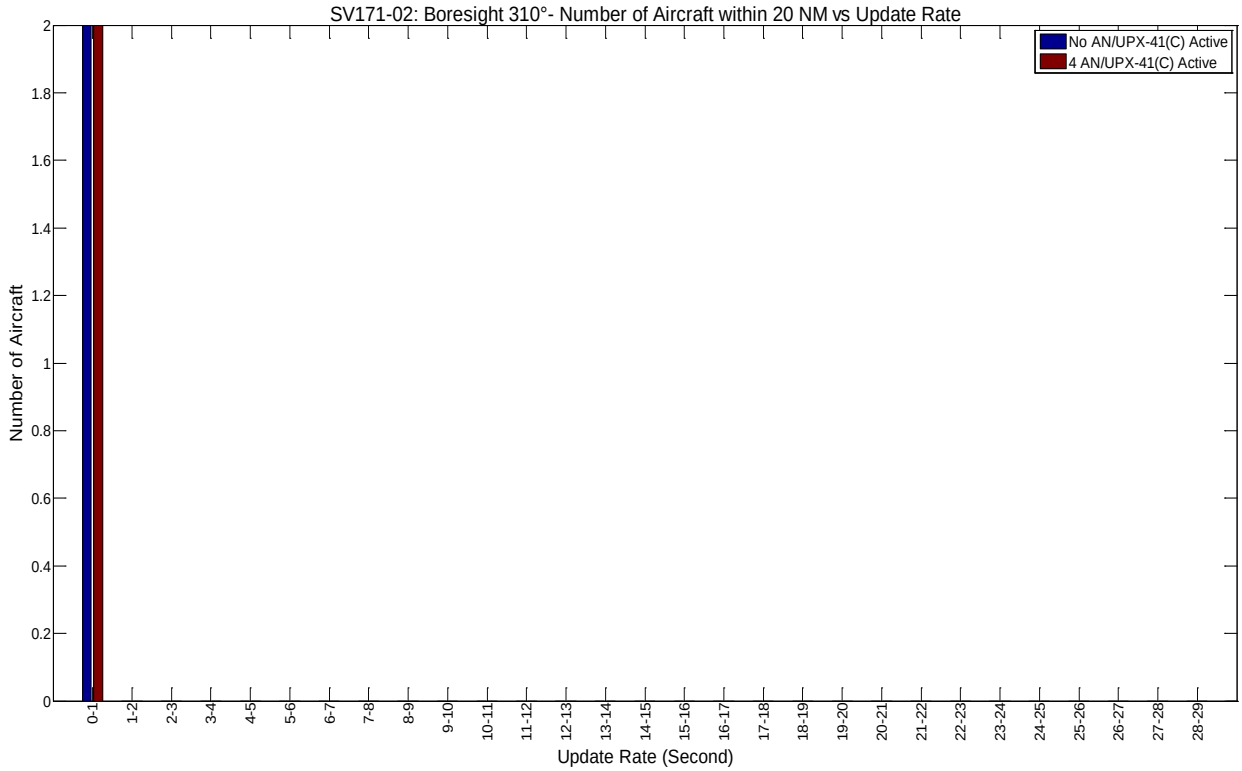


Figure 221. SV171-02 – Boresight 310° – Number of Aircraft within 20 nmi vs. Update Rate

D.2.3 Radio SV186-02

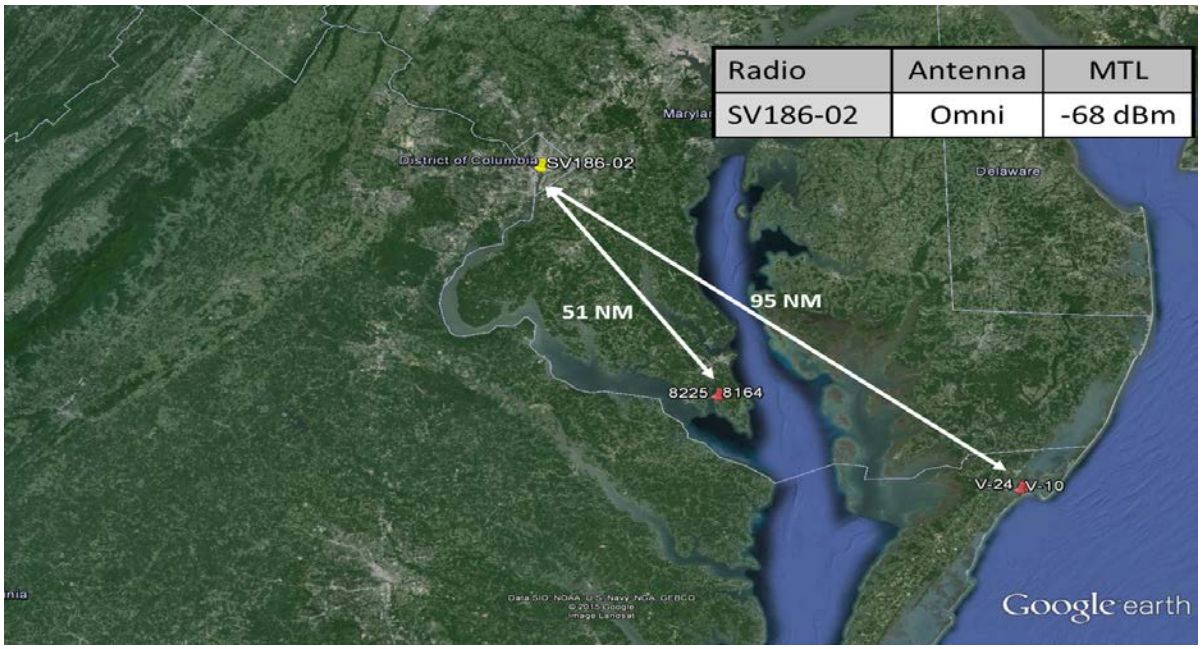


Figure 222. SV186-02 Location and Properties

Table 32. SV186-02 – ADS-B Squitter Reception Overlaps and Failures

SV186-02	Off			Active		
Boresight	**Squitter per second**	**Overlaps per second**	**Failures per second (%)**	**Squitter per second**	**Overlaps per second**	**Failures per second (%)**
Omni-directional	74.92	21.69	**2.27(3.03%)**	73.35	21.21	**2.06(2.81%)**

In Table 32, the failures per second decrease slightly due to variations in antenna gain from one scenario to the next. This effect averages out when the sample size is larger.

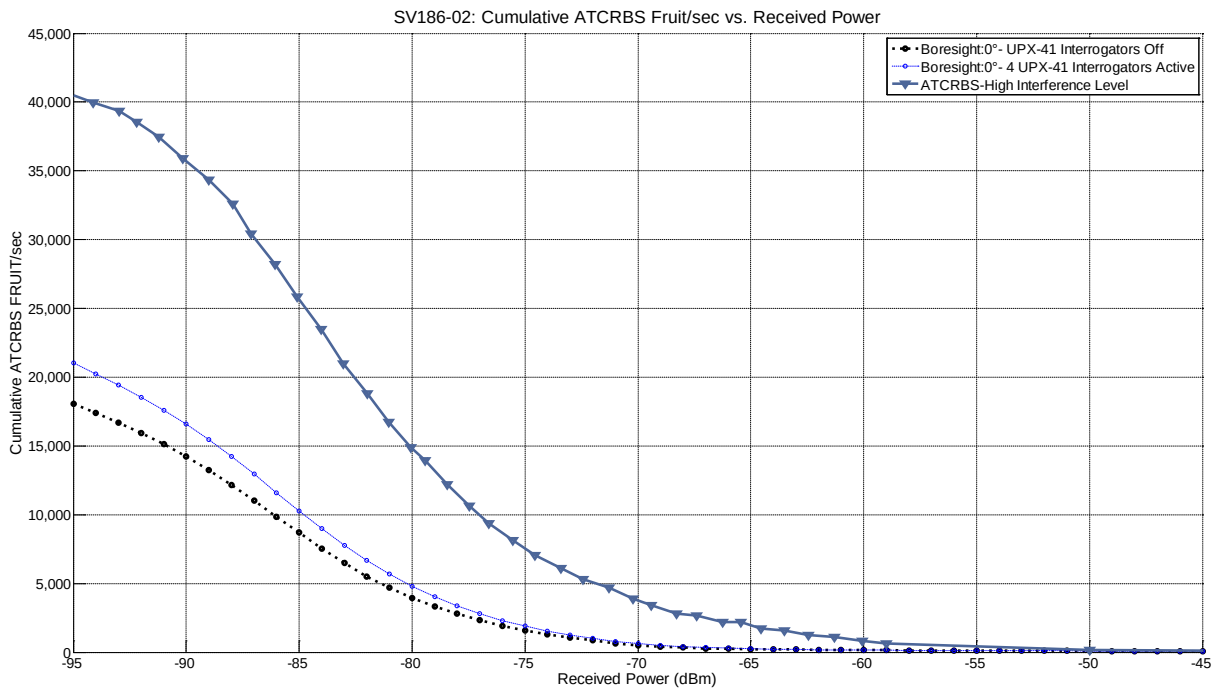


Figure 223. SV186-02 – Cumulative ATCRBS FRUIT/sec vs. Receiver Power Level (dBm)

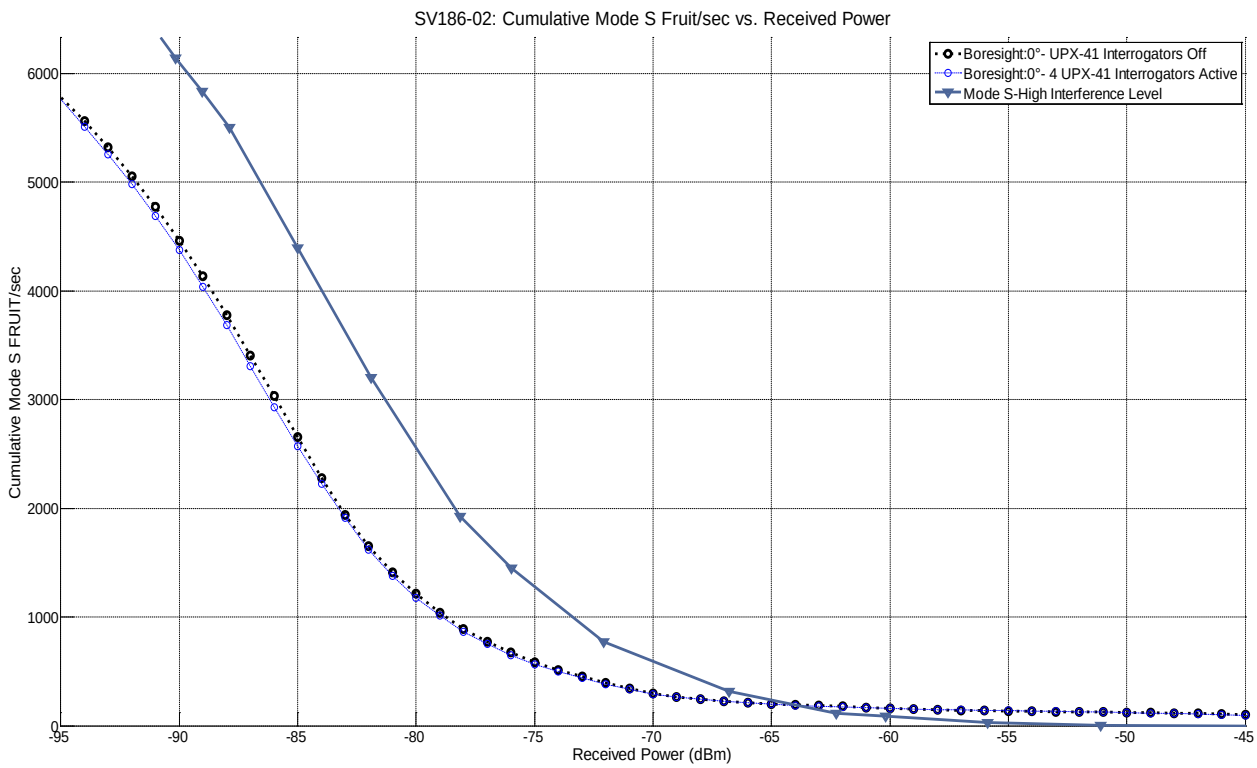


Figure 224. SV186-02 – Cumulative Mode S FRUIT/sec vs. Receiver Power Level (dBm)

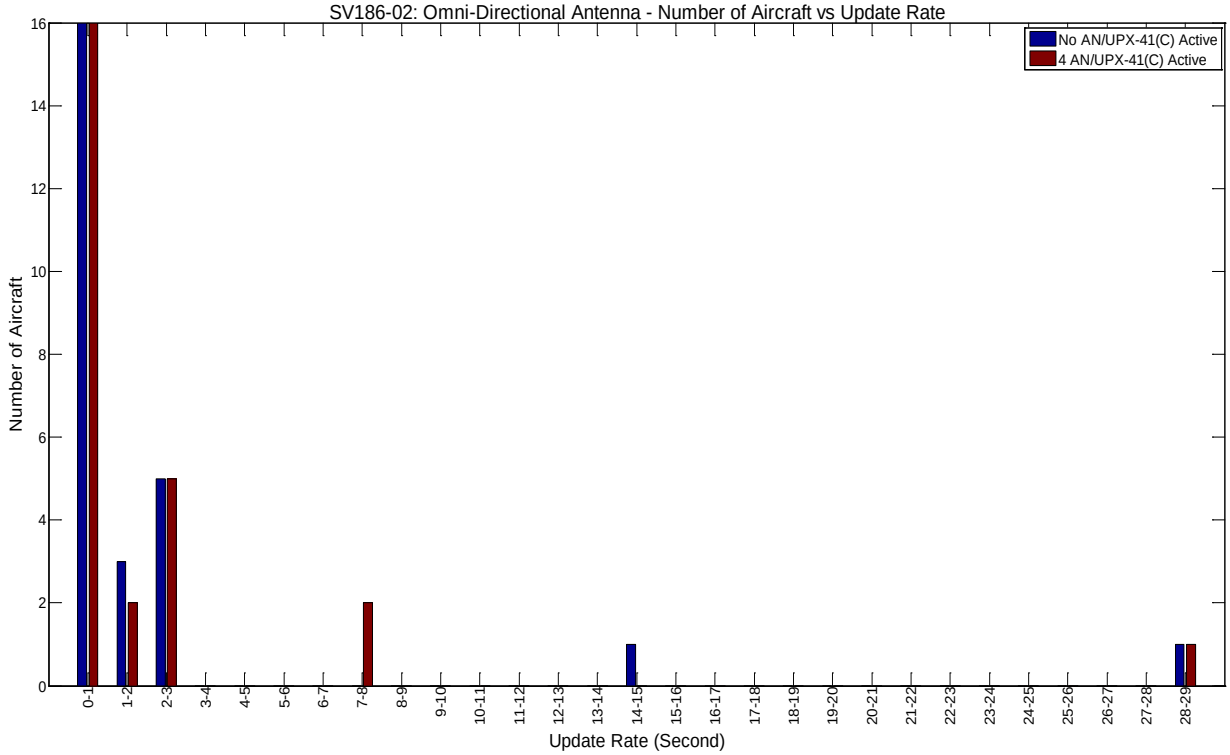


Figure 225. SV186-02 – Omni-Directional Antenna – Number of Aircraft vs. Update Rate

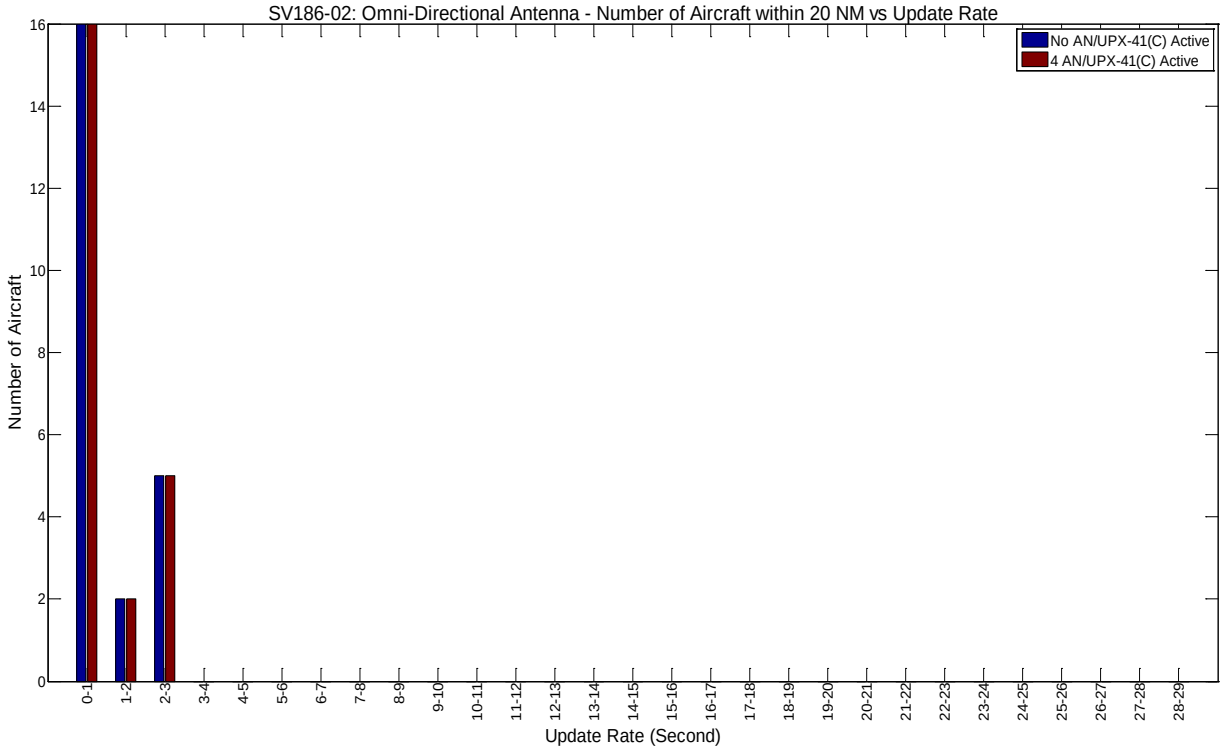


Figure 226. SV186-02 – Omni-Directional Antenna – Number of Aircraft within 20 nmi vs. Update Rate

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Appendix E. Military Interrogators

Table 33. Military Interrogators Not Active During Test

Branch	Interrogator	Location
AF	TCAS	McGuire AFB, NJ
AF	GPN-30	McGuire AFB, NJ
AF	TCAS/AMP-480	Andrews AFB, MD
AF	GPN-30	Dover, DE
AF	GPN-30	Johnstown, PA
AF	APM-480	Seymour-Johnson, NC
AF	UPX-37	Orange, CT
AF	GPN-30	Seymour-Johnson, NC
AF	RT-1853C	PAX NAS
AF	APX-100	Stewart, NY
AF	APM-123	Langley, VA
AF	TPX-49	Johnstown, PA
AF	TPX-56	McGuire AFB, NJ
AF	APX-100	Martinsburg, WV
AR	UPX-37	Tobyhanna, PA
AR	TPX-56	Edgewood, MD
AR	GPN-30	Ft. Bragg, NC
AR	TPX-56	Ft. Indiantown, PA
AR	TPX-56	Ft. Indiantown, PA
AR	MSTTIA	Tobyhanna, PA
AR	TPX-56	Tobyhanna, PA
AR	TPX-56	Tobyhanna, PA
AR	TPX-46	Aberdeen, MD
AR	TPX-56	Ft. Bragg, NC
CG	UPX-28 & T/E	Atlantic Beach, NC
CG	UPX-28 & T/E	Bayonne, NJ
CG	UPX-28 & T/E	Cape May, NJ
CG	UPX-28 & T/E	Sandy Hook, NJ
CG	UPX-28 & T/E	Portsmouth, VA
CG	UPX-28 & T/E	Curtis Bay, MD
MC	UPX-37	Camp Jejeune, NC
MC	UPX-37	Oak Grove, NC
MC	UPX-37	Cherry Pt, NC
MC	TPS-73	New River, NC
MC	GPN-30	Cherry Pt, NC

Branch	Interrogator	Location
MC	TPX-566	Bogue Field, NC
MC	UPX-37	Dam Neck, VA
MC	UPX-37	Bogue Field, NC
MC	TPS-73	Bogue Field, NC
MC	UPX-37	Bogue Field, NC
MC	UPX-27	Atlantic Field, NC
MC	UPX-27	Camp Lejeune, NC
MC	GPN-30	New River, NC
MC	UPX-27	Quantico, VA
N	TPX-56	Wallops Is, VA
N	RAYMK2D	Oceana, VA
N	UPX-27	Wallops Is, VA
N	GPN-30	PAX NAS
N	TIET-47N	Ridley Park, PA
N	UPX-41C	PAX NAS
N	UPX-27	Ft. Story, VA
N	UPX-27	Ft. Story, VA
N	MILACAS	Ridley Park, PA
N	USM-719	PAX NAS
N	USM-719	PAX NAS
N	USM-719	Kinsale, VA
N	USM-719	Westover, MD
N	USM-719	Seaford, DE
N	USM-719	Bishops Head, MD
N	APX-122	PAX NAS
N	UPX-41C	PAX NAS
N	UPX-41C	PAX NAS
N	UPX-41C	Wallops Is, VA
N	UPX-41C	Wallops Is, VA
N	APX-122	PAX NAS
N	TPX-57	Ft. Story, VA
N	TPX-57	Ft. Story, VA
N	USM-708	PAX NAS
N	USM-708	PAX NAS
N	APX-122	PAX NAS
N	TPX-56	PAX NAS
N	UPX-27 & 29	Wallops Is, VA
NG	TPS-70/78/703	Elkridge, MD
NG	APX-113	Greenlawn, MD

Branch	Interrogator	Location
NG	MSSR	Linthicum, MD
NG	ASR-12	Linthicum, MD

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Appendix F. Volpe 1030/1090 MHz Simulator Validation

F.1 Simulator Background

Results produced by the Simulator for high-density scenarios are only credible if those produced in smaller scenarios are consistent with what is actually observed in a real-world environment. When the Simulator was developed, a major portion of the development effort went towards adjusting the Simulator parameters to ensure that it closely tracked actual ATC radar system operation. This "tuning" occurred over the first decade of its use as more and more measured data became available. Initially, the tuning involved one-on-one or few-on-few situations whose behavior could be predicted accurately from MOPS and other known system characteristics[5]. More recently, the focus has shifted to large-scale system performance data gathered in connection with ADS-B and military spectrum compatibility testing.

The last major validation effort was in 2007 when the Simulator was compared to a July WJHTC flight test in the New York City area[6]. The outcome showed good agreement for the Mode S environment, but predictions for ATCRBS FRUIT from the simulator were 2.5 times less than what was measured. WJHTC believed that much of this discrepancy arose from a mechanism where Mode S transponders misinterpreted low-level Mode S interrogations, responding ATCRBS instead of Mode S or no reply. A similar mechanism applies to ATCRBS transponders but in this case the suppression from the low-level Mode S interrogation is missed resulting in additional ATCRBS FRUIT from ATCRBS transponders as well. The comparison between simulated and measured data also showed a distinct difference between the ways the TCAS units were interrogating. The TCAS unit in the WJHTC aircraft was generating nearly five times more interrogations than what the simulator produced, creating a large difference in total interference attributable to TCAS. In a thorough investigation of what the WJHTC aircraft TCAS unit was doing, it was found that nearly 80% of its interrogations were attempts to acquire new targets, some more than 100 nmi away. WJHTC attributed the behavior to a couple of potential factors. The impact of acquisition squitters occurring more than the nominal once per second increases the acquisition range of TCAS. This was shown to be related to the low-level Mode S interrogation issue mentioned above but at times instead of misinterpreting an ATCRBS interrogation, an ATCRBS/Mode S All-call is falsely decoded resulting in a reply that is identical to the acquisition squitter. Also, TCAS range is also a consequence of manufacturers

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[5] Cameron, Alan. Mabius, Lawrence. Schaefer, Jacqueline. *The 1030-1090 MHz Interference Simulator Technical Description and Initial Results*, TR-9454-02-01, April 27, 2001.

[6] Volpe Center. *AWACS Interference Analysis Summary*. Briefing to FAA Spectrum Management Office. December 16, 2008. PowerPoint presentation.

trying to make their TCAS units as sensitive as possible. Regardless, if the interrogations were over directional beams, this type of operation appeared to be consistent with interference limiting constraints and several manufacturers are doing it this way now. To accommodate the higher rate of interrogations, major modifications were made to the Simulator TCAS model and this made Mode S TCAS FRUIT from simulations agree closely with measurements.

With the August 2014 flight test data, Volpe has conducted a validation effort that closely mimics the effort from 2007. First, a comparison between measured and simulated 1030 MHz uplink data was made for Day 3 to find discrepancies between interrogation and suppression rates with select parts of Day 4 used to illustrate interesting observations. Second, a comparison between simulated and measured 1090 MHz downlink data was made for Day 3 and Day 4 to determine if there were discrepancies in FRUIT rates seen by an airborne receiver.

F.2 Simulation Setup

As part of the validation effort, it is important to understand how simulation scenarios were created to get a sense of the accuracy to which the environment was modeled. This section, however, does not describe each model. Ref. 5 provides a description of how each object works.

Scenarios were created for Day 3 at 12:26 p.m. EDT and Day 4 at 10:15 a.m. EDT. To create aircraft snapshot scenarios, a new method was implemented where aircraft tracks were pulled from the FAA's SBS network. The old method relied on stitching together tracks from multiple radars – a cumbersome process. Recorded as a Wireshark capture file, the SBS data was extracted using SAT to get CAT033 data. While CAT033 contains numerous data fields with information about an aircraft's vector and avionics, the setup of the Simulator scenarios only pulled the fields shown in Table 34.

Table 34. CAT033 Data Fields Used to Derive Simulation Aircraft Setup

Field
ICAO address
Equipage
Latitude
Longitude
Altitude
Beacon Code
Velocity (x-component)
Velocity (y-component)
Surveillance Volume ID

A set of scripts, written in MATLAB, used these parameters to create a set of unique aircraft that mimicked the actual aircraft flying during the time in question. The aircraft are defined only by

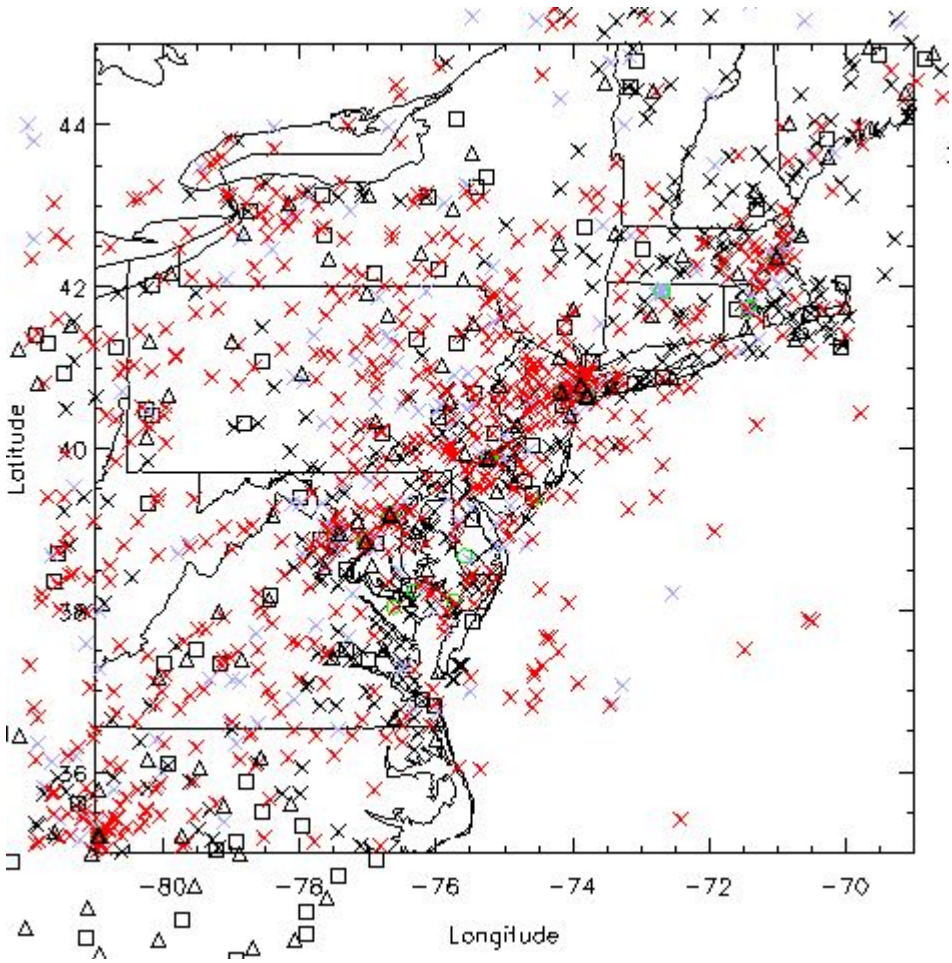
their position, altitude, speed, and heading. The scripts also used these parameters to make assumptions about transponder equipage (ATCRBS or Mode S) and whether or not a Mode S-equipped aircraft had a TCAS unit. The validity of the assumptions and their impact on simulated 1030 MHz and 1090 MHz activity will be discussed later. The equipage profile of Day 3 is given in Table 35 with transponder parameters given in Table 36. A snapshot of the aircraft setup is shown in Figure 227. As expected, the densest areas of aircraft activity were between New York City and Washington, D.C. Day 4 followed a similar geographical and equipage pattern.

Table 35. Day 3 Number of Aircraft and Equipage

	Equipage					**Total**
	Mode A/C-only	**Mode A/C/S**				
		TCAS II on		**No ACAS system or TCAS II off**		
		ADS-B-equipped	*No ADS-B*	*ADS-B-equipped*	*No ADS-B*	
Transponder Count	347	89	563	47	401	1447
Percent of Total	24%	6%	39%	3%	28%	100%

Table 36. Transponder Parameters

Parameter	Mode A/C-only	Mode A/C/S
MTL*†	-73 dBm ± 4 dB	-74 dBm ± 3 dB
Transmit Power*	125 – 500 W 21 – 27 dBW 51 – 57 dBm	
ISLS Threshold*	0 dB – 9 dB	0 dB – 9 dB
Cable Loss	0 dB	
Antenna Pattern	Probabilistic gain model (Ref. 5)	
Squitter Rate	N/A	6.2/sec
Transponder Occupancy Times	Transponders modeled with Typical occupancy times as described in the Transponder Occupancy Model section	



Legend

X : ATCRBS aircraft X : TCAS/Mode S/ATCRBS aircraft X : Mode S/ATCRBS aircraft

+ : MLAT receiver O : MLAT transmitter + : Victim receiver

□ : SSR Δ : ADS-B ground station

Figure 227. Day 3 Scenario Setup

Figure 227 also shows the ground-based surveillance systems included in the simulation. Locations and system operation specifications for SSRs, ADS-B ground stations, and MLAT systems were provided by the FAA. Table 37

Table 38,Table 39 detail the equipment modeled for each site. Additionally, the four LBTS were added to the simulation for the runs when the sites were Active. Each LBTS boresight antenna azimuth was staggered 90° apart from each other.

Table 37. Secondary Surveillance Radar Parameters

Modeled Parameters		Mode S	ASR-11	BI-5	BI-6*	BI-6M
Count	Terminal	44	29	20	0	0
	En-route	0	0	0	19	9
Interrogation Modes		A/C/S	A/C	A/C	A/C/S	2/4/A/C/S
Receiver/Plot Extractor		Monopulse	Monopulse	Sliding Window	Monopulse	Monopulse
PRF		Varies	Varies	Varies	Varies	Varies
Transmit Power (dBm)		50-60			59-62	
Cable Loss (dB)		0				
Peak Antenna Gain (dBi)		Varies	Varies	Varies	Varies	Varies
3dB Beam Width		2.62°				
Mode S roll-call coverage (nmi)		60			200	250
Rotation Time (sec)		4.8			12	
Receiver MTL (dBm)		-79				

Table 38. ADS-B Ground Radio Parameters

Parameters	Airport Surface	Terminal and En-route
Number of Antennas and Types	4 Dual 180° ground plane 27 omni-directional	91 Quadruple 90° ground plane
Transmit Power (dBm)	40-46	58-61
Receiver MTL (dBm)	-68	-88

Table 39. Multilateration System Parameters

Parameter		ASDE	WAM
Sites		BOS, BDL, PVD, LGA, JFK, EWR, PHL, BWI, DCA, IAD, CLT	PAX
Receiver MTL (dBm)		-72 to -68	-85 to -80
Max Transmit Power (dBm)		52	57
Antenna Gain (dBi)	**Omni**	0 to 2.8	2.8
	Sector (ground plane)	3 to 6.9	6 (180°)
Mode A/C Interrogations*		Whisper-shout Mode A – 80 int/sec Mode C – 40 int/sec	Whisper-shout Mode A – 36 int/sec Mode C – 36 int/sec
Mode S Interrogations		UF4 – 1 int / 3.3 sec UF5 – 1 int / 3.7 sec	UF4 – 1 int / 3.3 sec UF5 – 1 int / 5.5 sec

To validate simulated signal activity against measurements, the WJHTC aircraft was modeled in the simulation as a 1030 MHz and 1090 MHz victim at 38 different points, corresponding to the central position of each five minute Active and Off period. While using only one aircraft snapshot for all victim positions was not entirely accurate in terms of the other aircraft positions relative to SSR, MLAT and TCAS interrogators and the WJHTC aircraft, it was strategically easier than creating different scenarios for each five minute interval. For each of the victim positions, the simulation was run for 28.672 seconds which corresponds to seven full rotations of the AN/UPX-41(C) antenna beam. This allows collection of signal statistics for both the 1-6 scan 1 2 3/A C interlace pattern and the 7th scan 1 4 2 4 3/A 4 C 4 interlace pattern. Since aircraft are static in the simulation, the signal statistics are averaged over the duration of the simulation run time to give an approximate picture of the amount of transponder occupancy, replies, suppressions, and FRUIT that would be seen at the victim for the moment in time in which the snapshot of aircraft was taken.

F.3 AN/UPX-41(C) Model

Using the AN/UPX-41(C) system specifications provided by the Navy, Volpe developed an initial simulation to estimate the 1030 MHz impact. Using the August 2014 data, 1090 MHz impact was determined through the differences in the FRUIT rates between Off and Active periods.

All things equal, transponder occupancy varies with range, altitude, and link budget performance in respect to the simulated AN/UPX-41(C) system. Aircraft are simulated from zero to 250 nmi to determine the change in occupancy with respect to range. Figure 228 shows the variance in occupancy versus range from one simulated AN/UPX-41(C) system for a Mode A/C/S transponder equipped aircraft.

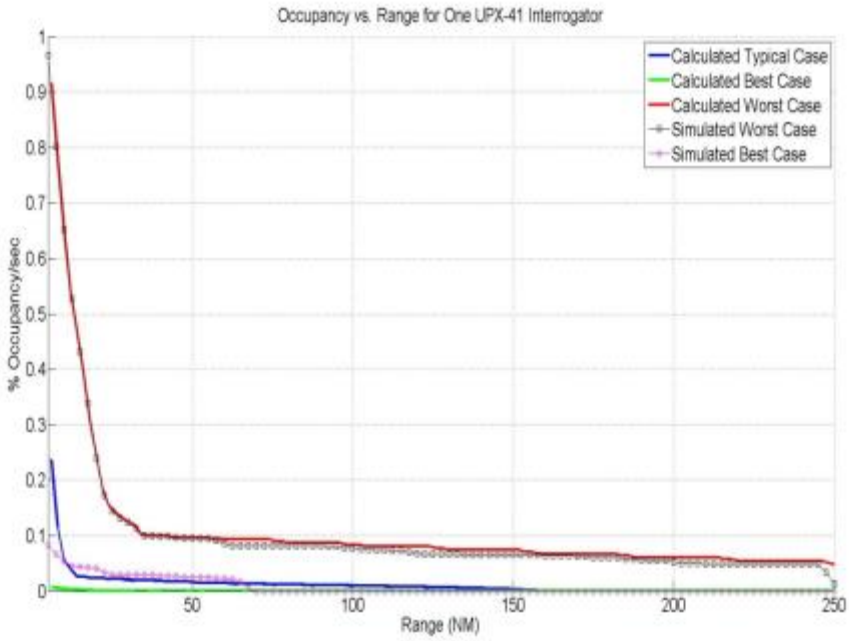


Figure 228. Simulated Occupancy vs. Range (Mode A/C/S Transponder)

The 1090 MHz contribution due to simulated AN/UPX-41(C) was determined by using Day 3's Active/Off periods. F.2 describes the setup of the simulation files used for this analysis.

Table 40. Summary of Simulated LBTS Impact on 1090 MHz FRUIT – Day 3

Day 3	Mode S					ATCRBS			
Time	LBTS Off	Time	LBTS Active	Delta	Time	LBTS Off	Time	LBTS Active	Delta
'13:57:31'	3218.018	'14:02:30'	3093.784877	-124.233	'13:57:31'	3068.604	'14:02:30'	3555.17578	486.5723
'14:07:31'	2839.565	'14:12:30'	2376.918248	-462.646	'14:07:31'	2602.713	'14:12:30'	3121.4774	518.764
'14:17:31'	2186.105	'14:22:30'	1906.354632	-279.75	'14:17:31'	2071.394	'14:22:30'	2624.6861	553.2924
'14:27:30'	2043.666	'14:32:30'	2050.327846	6.661551	'14:27:30'	1944.754	'14:32:30'	2854.03878	909.2843
'14:37:28'	1952.846	'14:42:29'	2132.8125	179.9665	'14:37:28'	1776.995	'14:42:29'	2909.59821	1132.603
'14:47:28'	1910.052	'14:52:29'	2041.294643	131.243	'14:47:28'	1888.009	'14:52:29'	2675.851	787.8418
'14:57:30'	1728.306	'15:02:30'	1472.900391	-255.406	'14:57:30'	1637.172	'15:02:30'	2098.24916	461.077
'15:07:30'	1095.668	'15:12:29'	818.4640067	-277.204	'15:07:30'	1164.446	'15:12:29'	1060.9654	-103.481
'15:17:29'	961.2165	'15:22:29'	1169.991629	208.7751	'15:17:29'	1090.89	'15:22:29'	1752.99944	662.1094
'15:27:31'	1539.655	'15:32:34'	1926.060268	386.4049	'15:27:31'	1707.31	'15:32:34'	2547.81669	840.5064
'15:37:33'	2206.717	'15:42:34'	2586.914063	380.1967	'15:37:33'	2242.955	'15:42:34'	3466.20396	1223.249
'15:47:36'	2655.518	'15:52:37'	2683.558873	28.04129	'15:47:36'	2824.602	'15:52:37'	3625.87193	801.2695
'15:57:39'	2674.491	'16:02:41'	2695.94029	21.4495	'15:57:39'	2760.638	'16:02:41'	3723.07478	962.4372
'16:07:41'	2645.02	'16:12:41'	2738.420759	93.40123	'16:07:41'	2839.774	'16:12:41'	3683.62863	843.8546
'16:17:42'	2729.109	'16:22:41'	2791.608538	62.5	'16:17:42'	2853.83	'16:22:41'	3981.41044	1127.581
'16:27:41'	3160.889	'16:32:41'	3480.608259	319.7196	'16:27:41'	3352.051	'16:32:41'	4868.05943	1516.009
'16:37:39'	3665.492	'16:42:40'	3323.904855	-341.588	'16:37:39'	3808.419	'16:42:40'	4271.55413	463.1348
Average	2306.608		2311.16851	4.560711		2331.444		3107.09772	775.6532

Similar to Table 6 which shows the impact of four LBTS on 1090 MHz, the impact seen from the four simulated LBTS was tabulated in Table 40. However, the impact of the four simulated LBTS was derived through comparison of all Active/Off periods and not just periods where the traffic density was determined to be similar. Even with this variable, as seen in the table above, the Mode S FRUIT has a small increase of only 4.5 FRUIT per second. This is very close to zero. The ATCRBS FRUIT, on average, increases about 775 FRUIT per second, which is larger than what was measured in the environment as seen in Table 6. Regardless, the range of values of deltas that make up the average ATCRBS FRUIT have similar fluctuations to what is seen in Table 6.

F.4 1030 MHz – Transponder Occupancy and Interrogation/Reply Rates

Moving the victim aircraft around the test circuit, the interrogation pulses collected at the victim give the Mode A/C/S transponder ATCRBS function occupancy shown in Figure 229. This was calculated based on Typical occupancy times that came from ICAO Doc 9924[7], Aeronautical Surveillance Manual, Appendix M, which will be amended to incorporate the characteristic tables (M-1, M-2, and M-3) in ICAO ASP TSG WP15-11R1[8]. Transponder occupancy for the Mode A/C/S Mode S function as well as both functions with MOPS Standard times are given in Figure 231, Figure 232, Figure 233, respectively.

In Figure 229, the red and yellow dots are the transponder occupancy calculated from the measured 1030 MHz activity, using sliding window averages of one second and 10 seconds, respectively. The larger green and magenta dots give the simulated transponder occupancy for the times when the LBTS were Off and Active, respectively. Figure 230 gives the transponder occupancy plotted in Google Earth for geospatial reference.

There are three general observations from Figure 229. First, the trend of the simulated transponder occupancy compared to the measured transponder occupancy matches well with respect to time and positon of the victim. Second, the measured and simulated data have a general discrepancy in terms of the transponder occupancy magnitude across the whole flight test. On average, this difference is about 1%; however, the areas around Atlantic City, Norfolk, and Richmond differ by more than this. Finally, while the simulated points show a clear increase in transponder occupancy when the LBTS were Active, the change in occupancy from Off to

[7] International Civil Aviation Organization (ICAO). *Aeronautical Surveillance Manual*. Doc 9924-AN/474, March 15, 2010.

[8] International Civil Aviation Organization (ICAO) Aeronautical Surveillance Panel (ASP) Technical Subgroup (TSG). *Typical Transponder Occupancy*. WP15-11R1. Paris, France. June 24-28, 2013.

Active is larger in the measured data. The following sub-sections discuss the reasons behind these differences and the ways they can be reconciled.

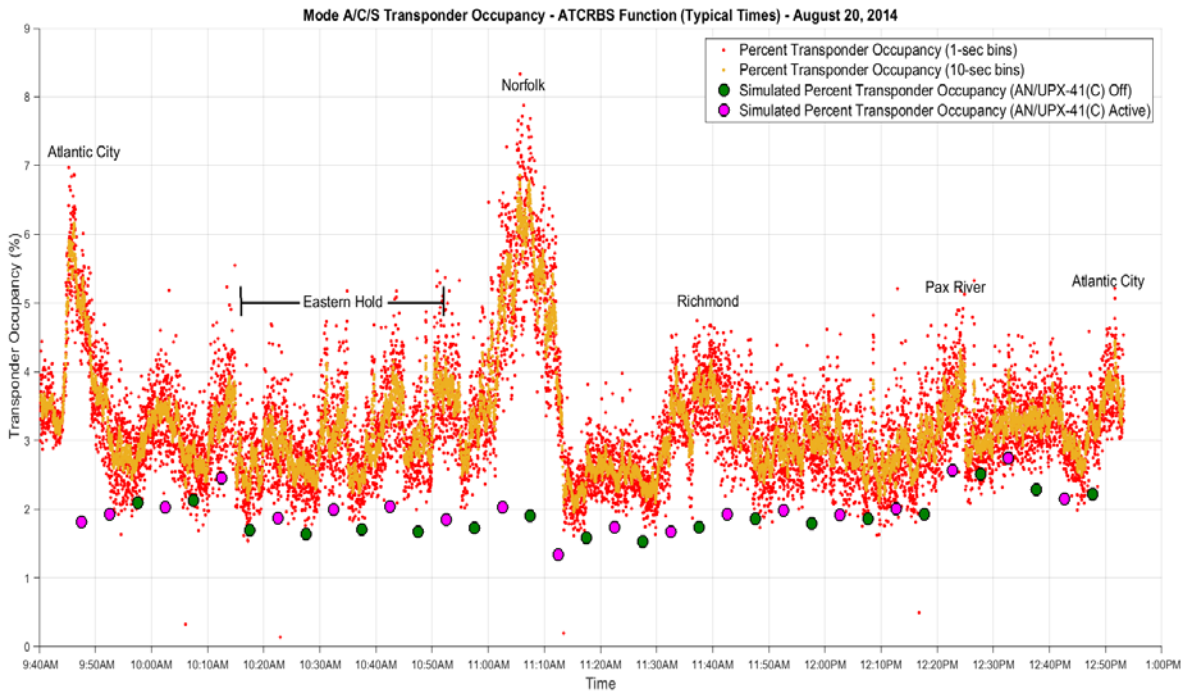


Figure 229. Mode A/C/S Transponder Occupancy for the ATCRBS Function using Typical Transponder Occupancy Times for Day 3

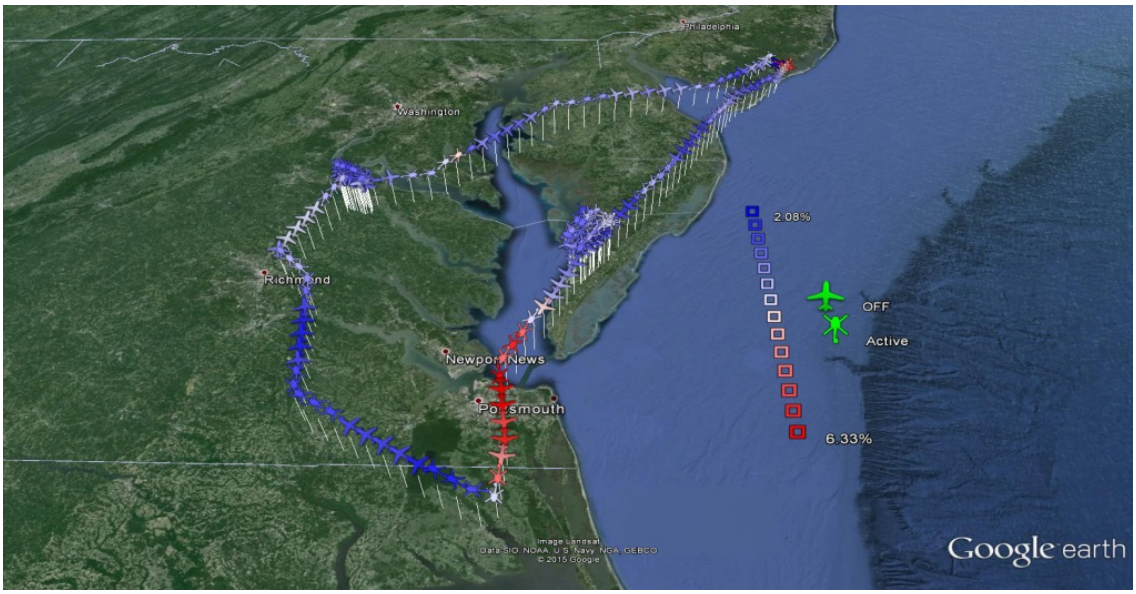


Figure 230. Geospatial Plot of Mode A/C/S Transponder Occupancy for the ATCRBS Function using Typical Transponder Occupancy Times for Day 3

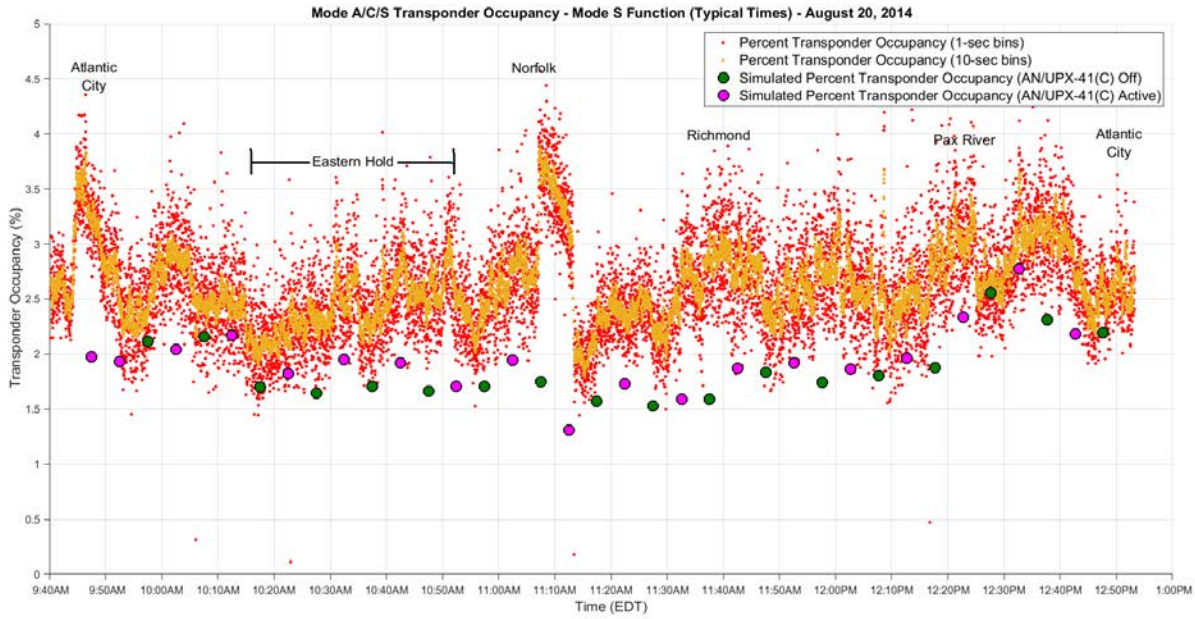


Figure 231. Mode A/C/S Transponder Occupancy for the Mode S Function using Typical Transponder Occupancy Times for Day 3

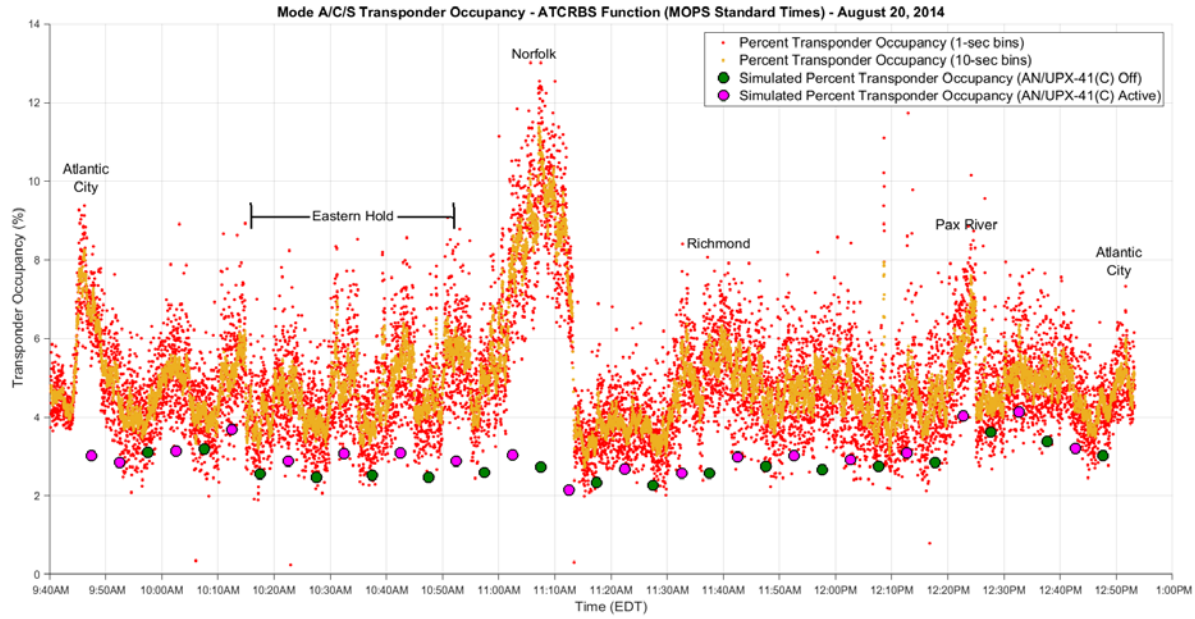


Figure 232. Mode A/C/S Transponder Occupancy for the ATCRBS Function using MOPS Standard Transponder Occupancy Times for Day 3

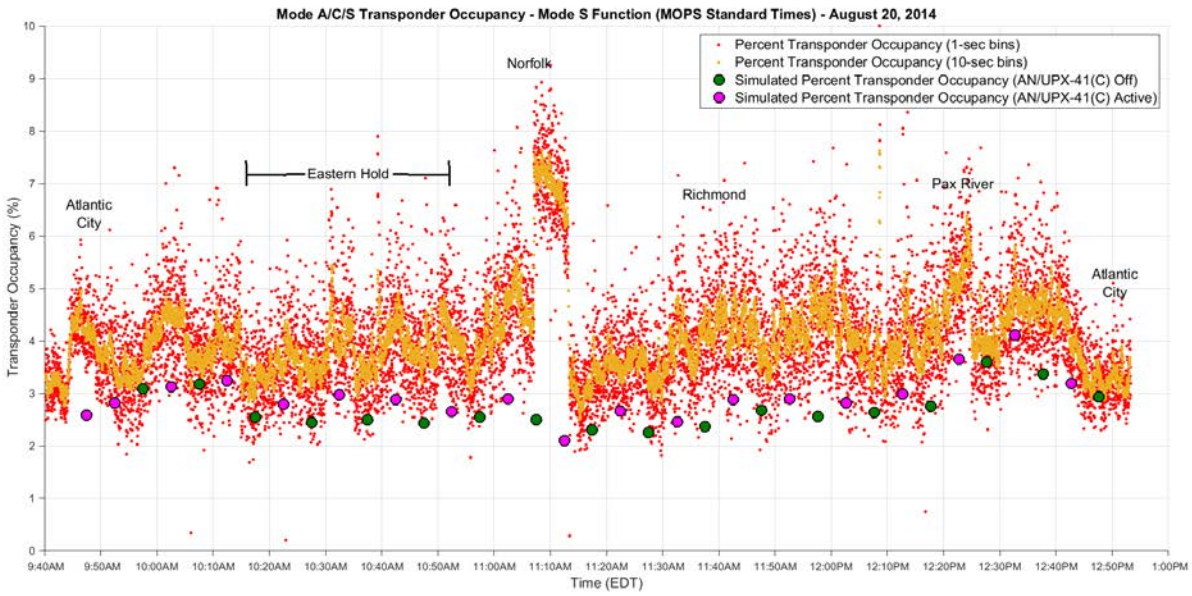


Figure 233. Mode A/C/S Transponder Occupancy for the Mode S Function using MOPS Standard Transponder Occupancy Times for Day 3

F.4.1 Transponder Occupancy Broken Down by Event

To further analyze the transponder occupancy discrepancies between measurements and simulation, Figure 234 breaks down measured transponder occupancy by event: Mode A and C reply, suppression bus events (from TCAS ownship interrogations), P1-P2 suppression, and Mode S reply. The majority of the occupancy is due to P1-P2 suppressions and suppression bus events. While the latter stays relatively constant, the former increases dramatically during peak periods near Atlantic City, Norfolk, and Richmond. This pushes transponder occupancy well above simulated values. Mode S replies occupy the transponder by the least amount and Mode A and C reply occupancy holds constant except for the Norfolk area where measured ATCRBS interrogations increased threefold. It should be noted that these trends also were observed on Day 1 and Day 4 so this was not an anomaly seen on only one day. Examples will be given in Sections F.4.2 and F.4.4.

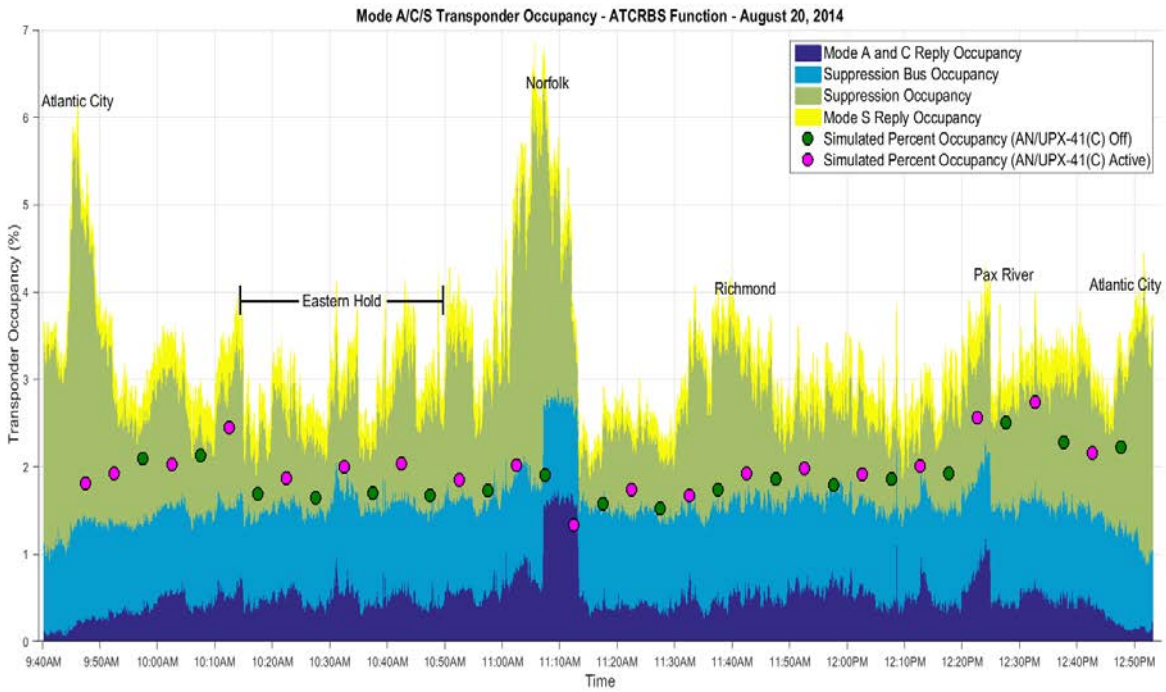


Figure 234. Mode A/C/S Transponder Occupancy for the ATCRBS Function using Typical Transponder Occupancy Times for Day 3 – Breakdown by Event (Stacked Bar Plot with 10-sec Sliding Window Average)

F.4.2 Transponder Suppression Rate

As observed in F.4.1, P1-P2 suppressions create the greatest differences between measured and simulated transponder occupancy. To understand why this is occurring, Figure 235 breaks down the different suppression types. From top to bottom in the legend, there are 13 types of suppressions: ATCRBS/Mode S all-call with a long P4, P1-P2 with no P3, S1-P1-P3-shortP4 Mode A, S1-P1-P3-shortP4 Mode C, P1-P3-shortP4 Mode A, P1-P3-shortP4 Mode C, Mode S, Mode S near MTL, Mode 4, Mode 1, Mode 2, Mode A, and Mode C. The vertical axis gives the suppression rate per second with the rate of each type of suppression stacked on top of each other (stacked bar plot) while the horizontal axis tracks the time of the WJHTC aircraft circuit. The line plot above the bar plot gives the transponder occupancy over the circuit time period that is due exclusively to the P1-P2 suppressions. Overall, Mode S interrogations dominate the suppressions, but this is expected because every Mode S interrogation contains a preamble that purposely suppresses the ATCRBS function of the Mode A/C/S transponder. The simulated suppression rate tracks well with the measured suppression rate except for the areas near Atlantic City, Norfolk, and Richmond – consistent with the discrepancies seen in the overall transponder occupancy.

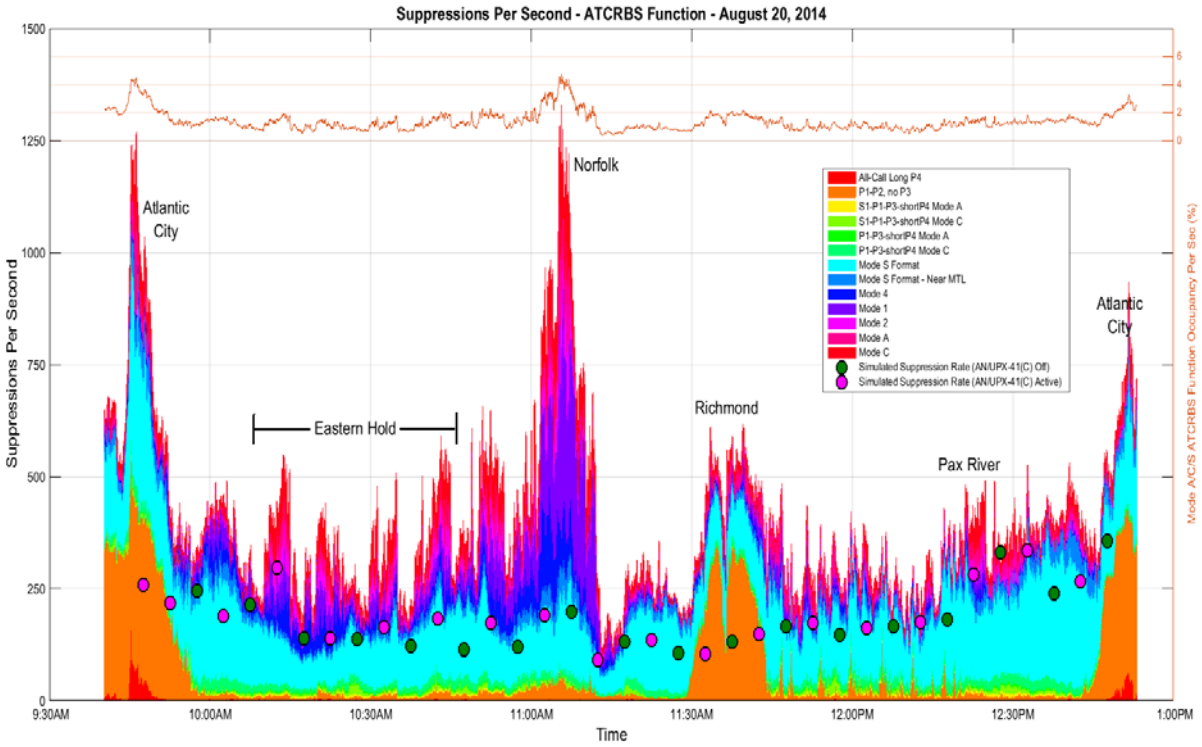


Figure 235. Mode A/C/S Transponder ATCRBS Function Suppression Rate and Occupancy for Day 3 – Breakdown by Event (Stacked Bar Plot with 10-sec Sliding Window Average)

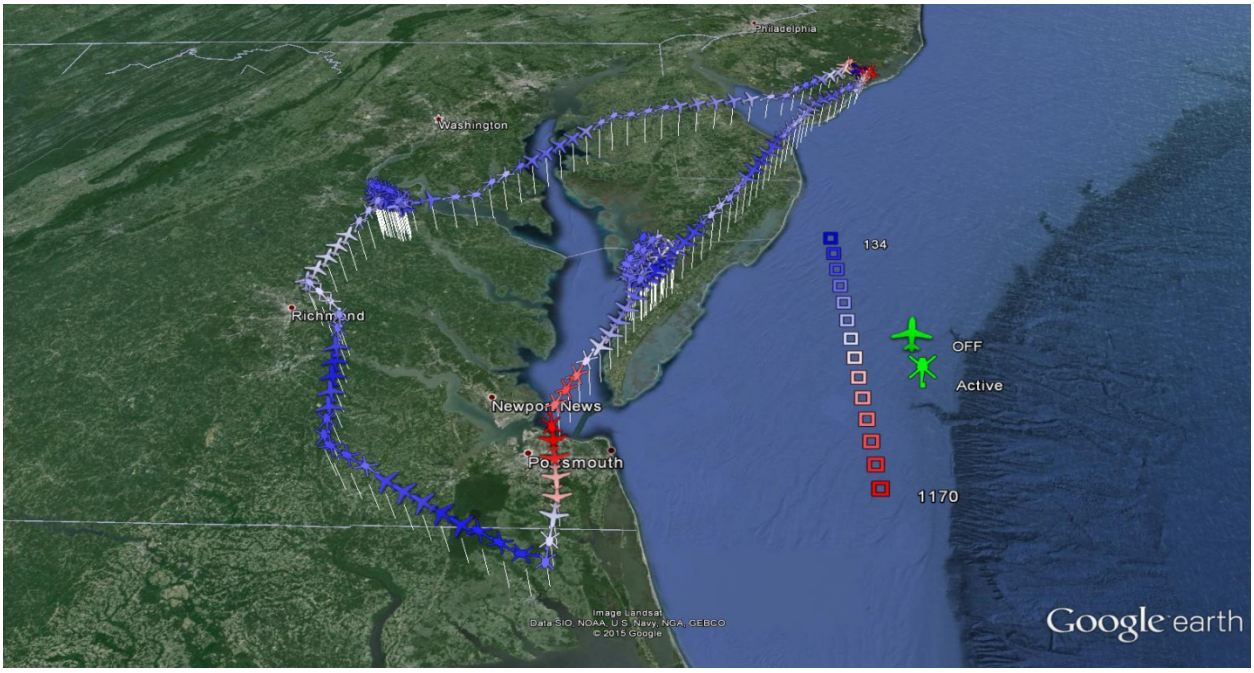


Figure 236. Geospatial Plot of Mode A/C/S Transponder ATCRBS Function Suppression Rate for Day 3 (60-sec Sliding Window Average)

Near Atlantic City and Richmond, the P1-P2 no P3 suppression type is prevalent. Investigation of this type of suppression showed that it came from a false target suppression technique called Improved Interrogator Sidelobe Suppression (IISLS) that is employed with older sliding window SSRs. In short, this technique ensures suppression of a transponder through the time when the transponder could receive an interrogation from a known reflector that creates a ghost aircraft reply. While it was known that Richmond had a sliding window BI-5 interrogator, FAA records showed the ACY was using a Mode S SSR. Upon further review with the FAA Mode-S/Digitizer/SBSM, AJW-145 team, it was found that ACY was actually using a BI-5 interrogator that employed IISLS. After changing ACY to a BI-5 and employing IISLS at ACY and Richmond Airport (RIC) in the Simulation, an increase in the Figure XXX simulated occupancy level for those areas was seen.

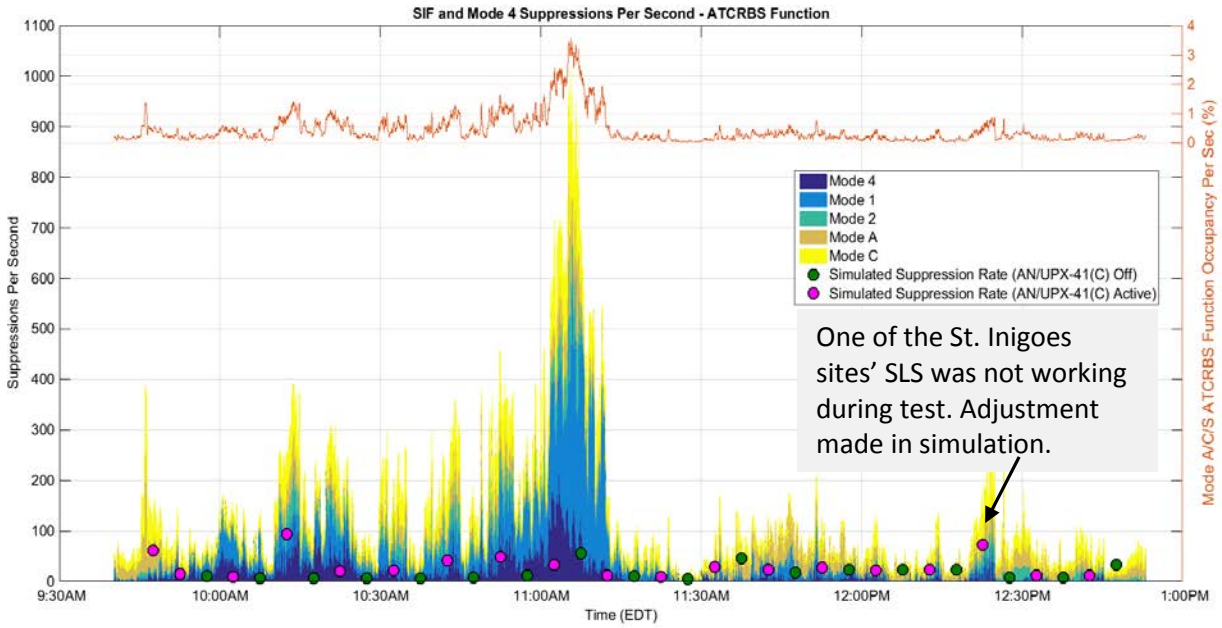


Figure 237. Mode A/C/S Transponder ATCRBS Function SIF and Mode 4 Suppression Rate and Occupancy for Day 3 – Breakdown by Event ((Stacked Bar Plot with 10-sec Sliding Window Average)

The other large discrepancy is in the Norfolk area which is evident in Figure 236 where the total rate increases nearly fourfold compared to most other areas of the flight circuit. Figure 235 shows that Modes 1, 2, A, C, and 4 contributed to the large suppression increase with Mode 1 being the most obvious culprit. From Figure 236 it is also clear that this general increase began as the WJHTC aircraft came out of the Eastern hold and flew toward Norfolk. Figure 237 further filters suppression rates from measurements and simulations to those only induced by SIF and Mode 4 interrogations. Again, the stark contrast between measurement and simulated suppression rates for the Norfolk area (10:45 a.m. – 11:15 a.m.) comes to light as it's seen that the suppression rate tracks fairly well in all other areas. This activity was not limited to one day as Figure 238, Figure 239, and Figure 240 show similar activity in the Norfolk area on Day 1, Day 2, and Day 4, respectively.

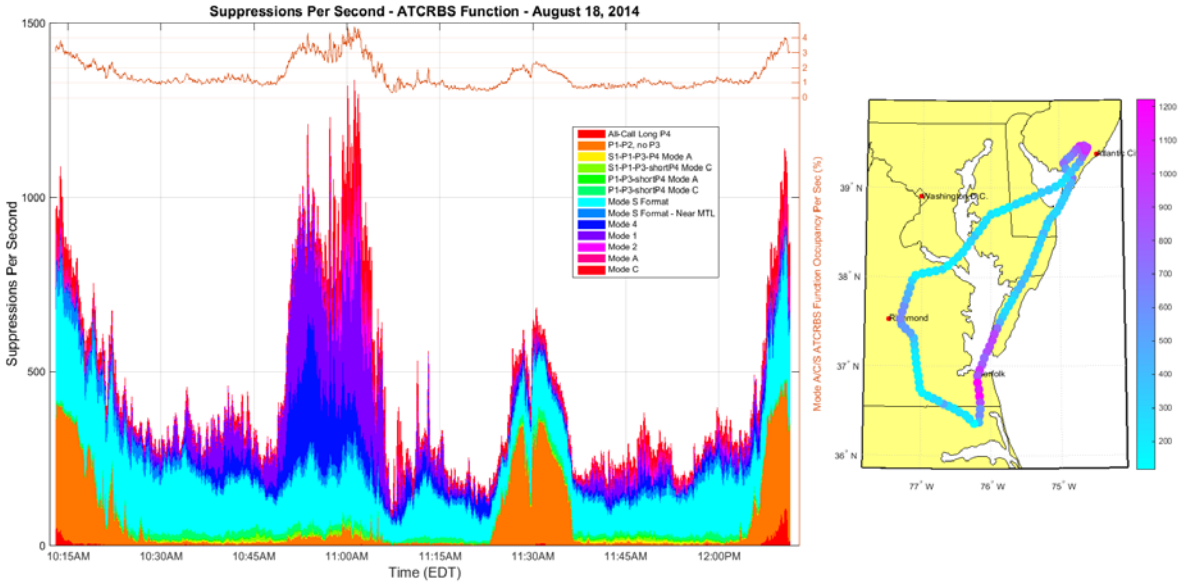


Figure 238. Mode A/C/S Transponder ATCRBS Function Suppression Rate and Occupancy for Day 1 – Breakdown by Event (Stacked Bar Plot with 10-sec Sliding Window Average)

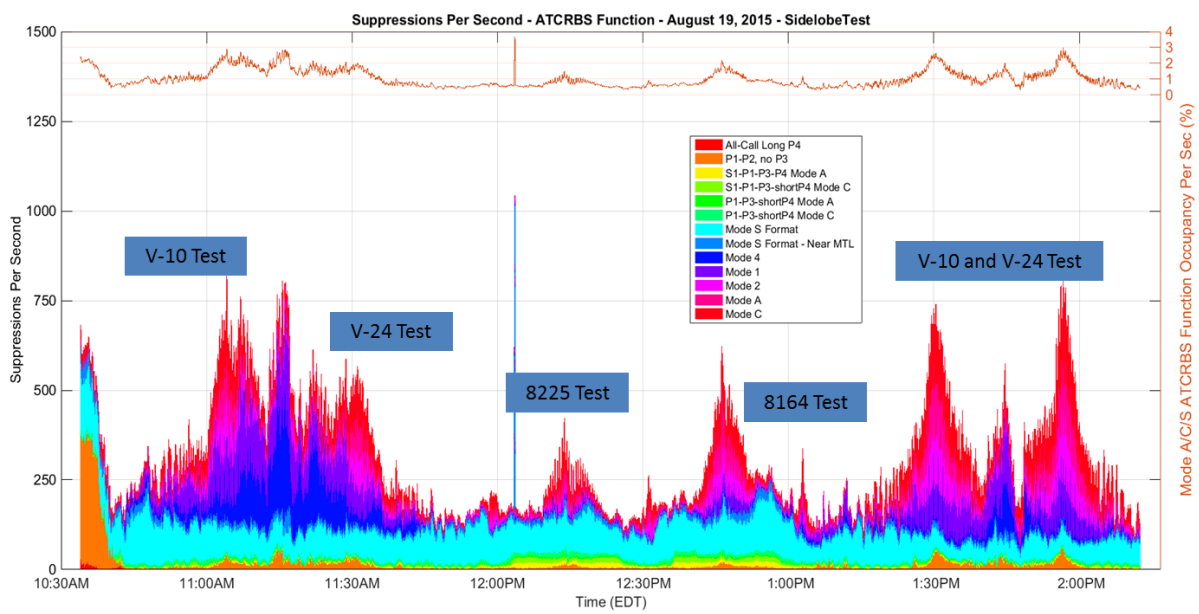


Figure 239. Mode A/C/S Transponder ATCRBS Function Suppression Rate and Occupancy for Day 2 – Breakdown by Event (Stacked Bar Plot with 10-sec Sliding Window Average)

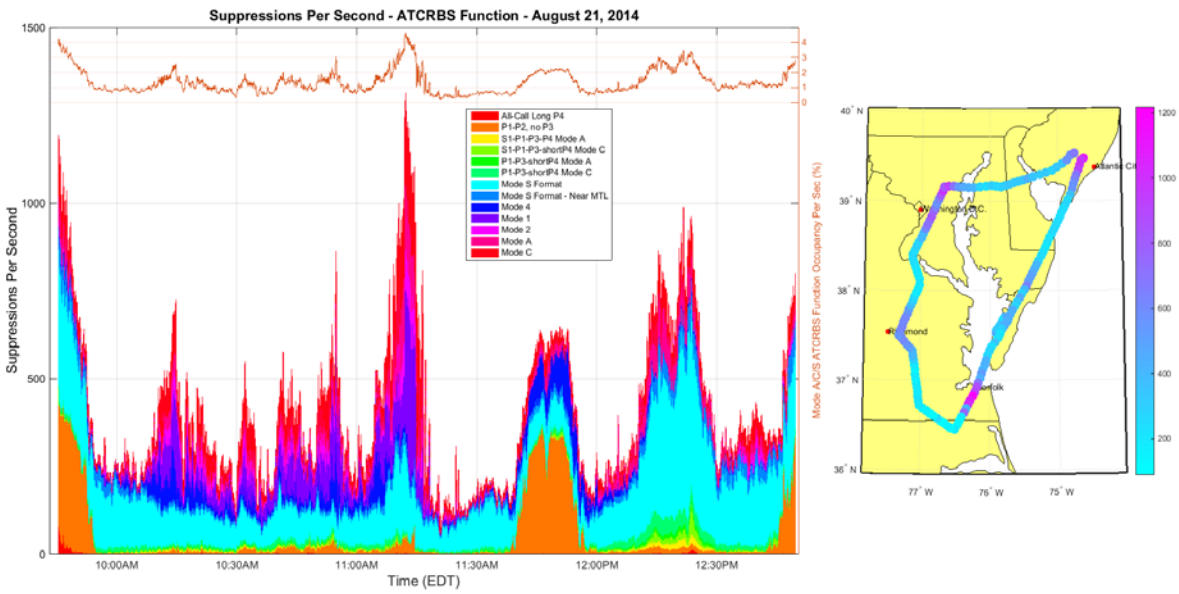


Figure 240. Mode A/C/S Transponder ATCRBS Function Suppression Rate and Occupancy for Day 4 – Breakdown by Event (Stacked Bar Plot with 10-sec Sliding Window Average)

To investigate this discrepancy, Volpe and the Navy did a comprehensive review of interrogators in the area. Volpe confirmed that the only FAA interrogators operating in the area were the Norfolk Airport (ORF) and Oceana long range (QVR) SSRs. The Navy, who, as described in the Test Plan in Ref. 4, instructed many military interrogators to remain off for the duration of the Test, confirmed that the military interrogators in Appendix E were indeed off. The set of military interrogators that could not be directly controlled were those aboard ships at sea. The captains of those ships were informed to remain Active from 5AM – 5 PM EDT if it was necessary for them to turn Active during any period of the Test. A review by the Navy of ships in the area found the movements shown in Figure 241. While this indicates that ships were in the area on Day 3, they were either not operating during the test period or were not close enough to shore to have the impact that is seen around Norfolk in Figure 235. The shape of the suppression rate points to the WJHTC aircraft having flown through the sidelobes of one or more high PRF interrogators and these ships do not fit that description. As of the publication of this report, the team has yet been able to discover the source of these interrogations and the Navy is recommending another flight test in that area to pin down from where these interrogations emanate.

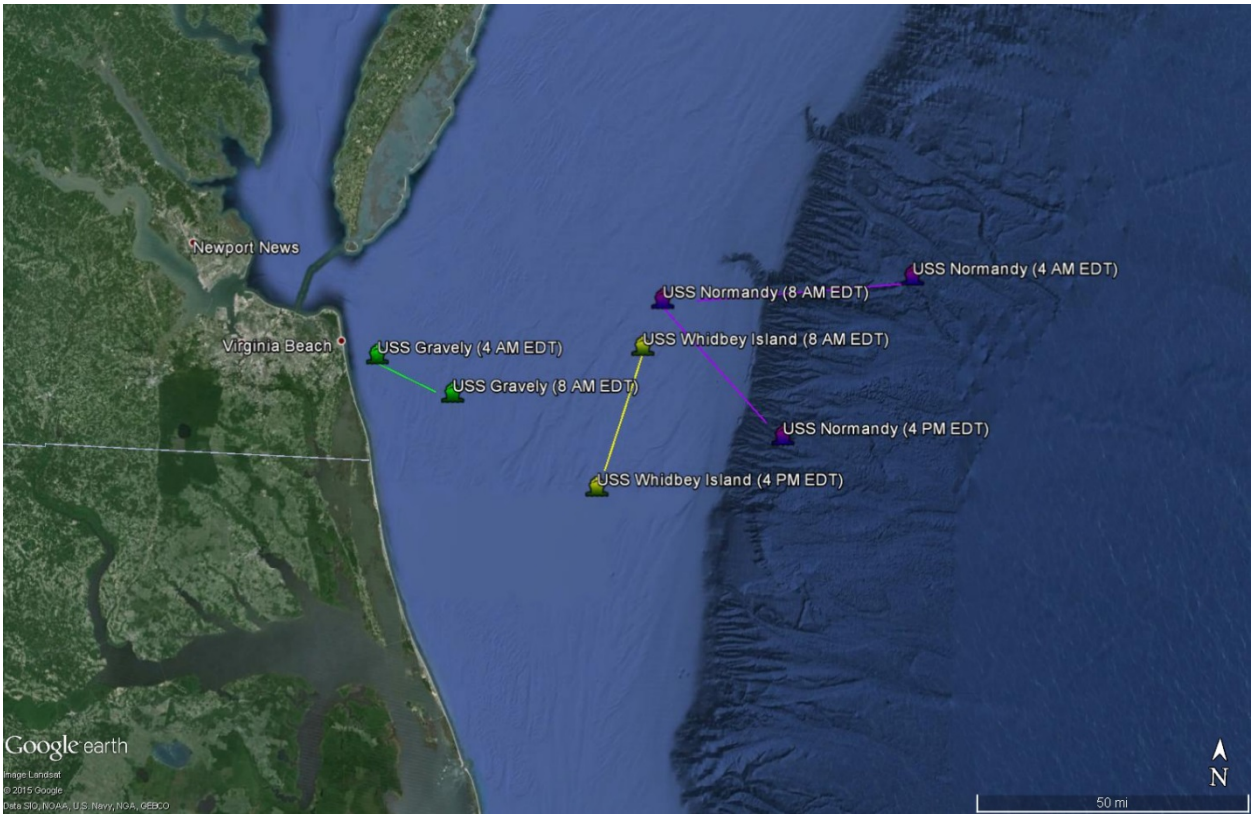


Figure 241. US Navy Ship Locations Near Norfolk – Day 3

Besides the trouble spots that have been described, there is, on average, a 0.3% occupancy difference for the areas where all activity is assumed to be known. The next sections discuss in more detail why these discrepancies arise.

F.4.3 Suppressions (Replies and Non-Replies) to Mode S Interrogations

The AN/UPX-41(C) system does not interrogate Mode S, but for purposes of validation of the simulation, Mode S parameters seen in the measurements were compared with flight test data. Presented in Figure 235 as the cyan color band, this section will investigate agreement between the suppression rates induced by Mode S interrogations in measurements and simulation. It should be noted that Mode S interrogations inducing suppression of the ATCRBS function of the Mode A/C/S transponder occur in two forms with respect to the Mode S function of the same transponder: 1) replies, and 2) non-replies. Replies are interrogations addressed for that transponder. Non-replies are interrogations either addressed to any other transponder or from an SSR commanding lockout which the transponder in question receives and decodes but does not generate a reply. Replies and non-replies to Mode S interrogations, where it is implicit that the ATCRBS function of the transponder is being suppressed, will be addressed separately to better understand the differences between the measurements and simulations.

Non-Replies to Mode S Interrogations

Figure 242 gives the breakdown of Mode S interrogation types that did not elicit replies from the Mode A/C/S transponder. The non-replies are dominated by TCAS Mode S interrogations (UF0) because the victim aircraft sees many more TCAS interrogators than ground-based Mode S interrogators. Comparison of measured and simulated non-reply rates show that the macro trends have developed well here for the simulation, but there are areas of concern such as around 10:45 a.m. and 11:20 a.m.. Similarly, Figure 243, which gives a comparison of measured and simulated UF0 non-reply interrogation rates, also shows that simulated UF0 rates match measurements well from the standpoint of the overall trend versus time, but the micro trends for periods of fifteen minutes or less have some large discrepancies.

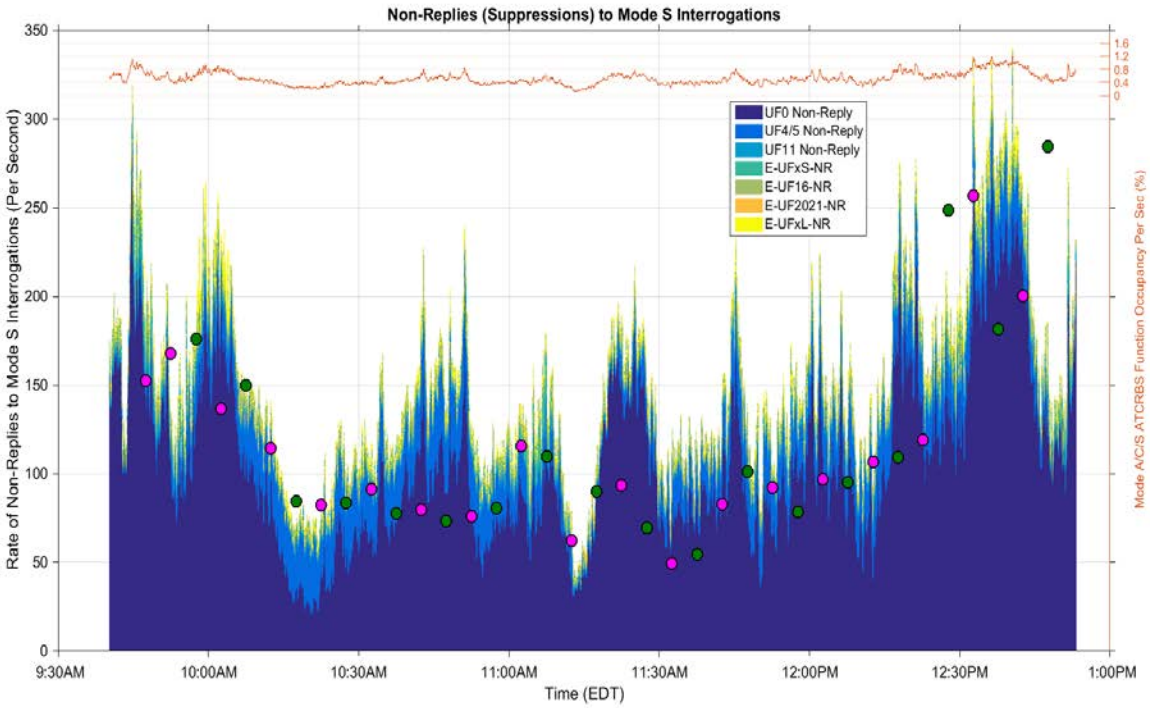


Figure 242. Mode A/C/S Transponder Non-Reply Rate to Mode S Interrogations and Transponder Occupancy for Day 3 – Breakdown by Event (Stacked Bar Plot with 10-sec Sliding Window Average)

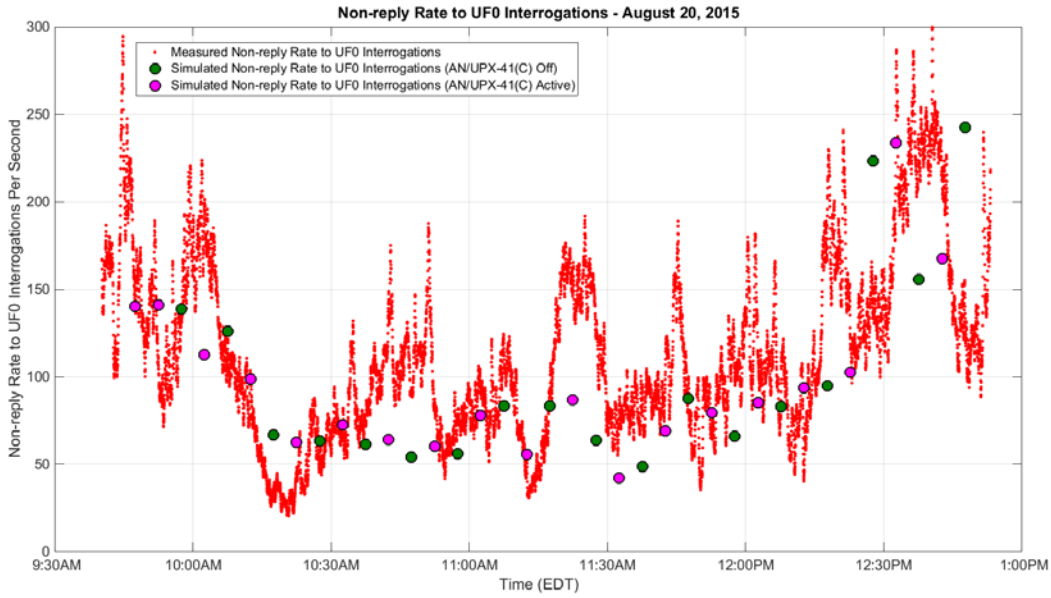


Figure 243. Mode A/C/S Transponder Non-Reply Rate to TCAS Mode S (UF0) Interrogations for Day 3 (10-sec Sliding Window Average)

Referring back to Section F.2 and the note about transponder equipage assumptions and the placement of the victim aircraft in an aircraft environment that does not directly mimic what the WJHTC aircraft was seeing at the time, matching measured and simulated TCAS interrogation rates is difficult considering the interdependencies of aircraft positions and equipages that contribute to an individual TCAS unit's derivation of interrogation rates and power levels from interference limiting algorithms. Anything but exact equipage of transponders that mimics what the WJHTC aircraft saw during the flight test leaves questions about whether the simulation is accurately representing the rate of TCAS UF0 interrogations. F.6 further examines the relationship between victim position and the aircraft around it with respect to the UF0 non-reply interrogations seen by the victim. As of the writing of this report, WJHTC has provided Volpe with a Number of TCAS Aircraft (NTA) count versus time for Day 3 and Day 4, as seen by the WJHTC aircraft during their circuits, and it should be possible to use this data to create a more accurate simulation setup of TCAS equipage.

UF4/5 and UF11 interrogations can also induce non-replies if the UF4/5 is not addressed to the transponder in question or the transponder is locked out from replying to UF11s through a selective interrogation that commands lockout to UF11 interrogations containing a specific II code. Note that, in the Simulator, lockout is predetermined by an aircraft's position relative to a Mode S interrogator. If the aircraft is within the interrogator's lockout range and altitude volume (user-specified parameters), the Simulator automatically commands the aircraft to not reply to UF11 interrogations. Figure 244 compares measured and simulated UF4/5 and UF11 interrogation rates. Unfortunately, the Simulator today does not have the ability to separate

UF4/5 and UF11 interrogations from the simulated victim uplink output for individual plotting. Still, observations can be made from this plot. There is a clear lack of UF4/5 and UF11 interrogations from 10:14 a.m. to 10:45 a.m. and 11:45 a.m. to 12:15 a.m..

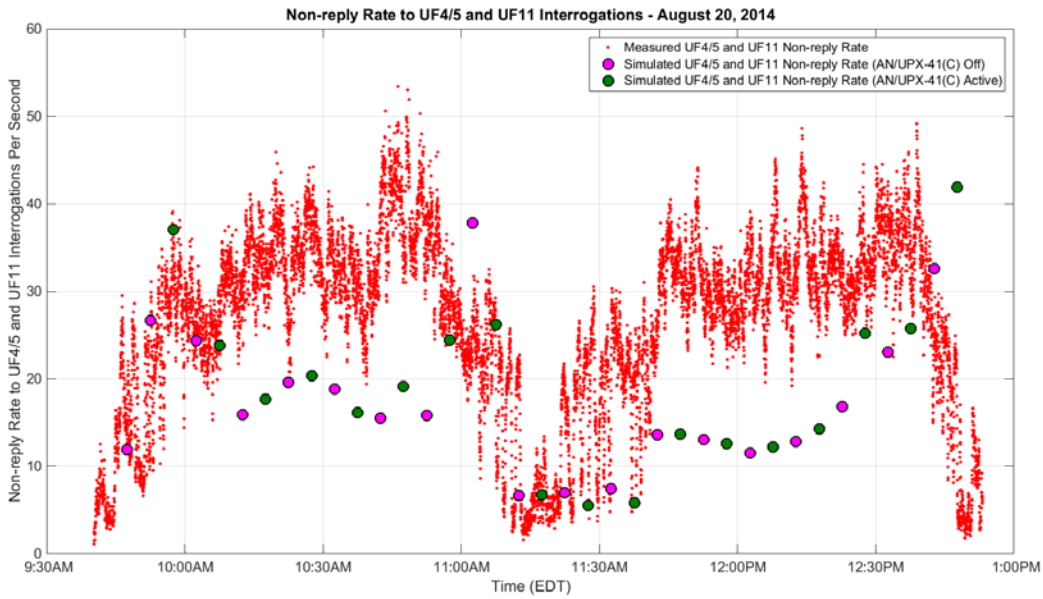


Figure 244. Mode A/C/S Transponder Rate of Non-Replies to Mode S Interrogator UF4/5 and UF11 Interrogations for Day 3 (10-sec Sliding Window Average)

Replies to Mode S Interrogations

While there are many more non-replies than replies to Mode S interrogations (approximately an order of magnitude with respect to position), it is still useful to examine the difference between measured and simulated Mode S interrogation reply rates. Figure 245 gives a comparison between the measured and simulated rates of Mode S interrogations that elicit replies. Note that there is a category of interrogations that are not Mode S format, namely Intermode A, Intermode C, Intermode A Mode 4, and Intermode C Mode 4. These are interrogations, either intended or unintended, that manifest with a P1-P2-P3-longP4 pulse train and thus command a Mode S (DF11) reply. Since the impact of these types of interrogations is so small, this section's title and the discussion of interrogations in this section lumps these under the umbrella of Mode S interrogations. Observations from Figure 245 are similar to the non-reply plots where the trend of simulated reply rates matches well with the trend of measured reply rates, but there is a distinct magnitude difference for all times. In this case, the simulated reply rates are consistently above the measured reply rates. While any drop to the simulated reply rates through refinement of the simulation would have a negligible effect on transponder occupancy, this is an issue worth diving deeper into since it brings up questions about the simulator interrogator setup.

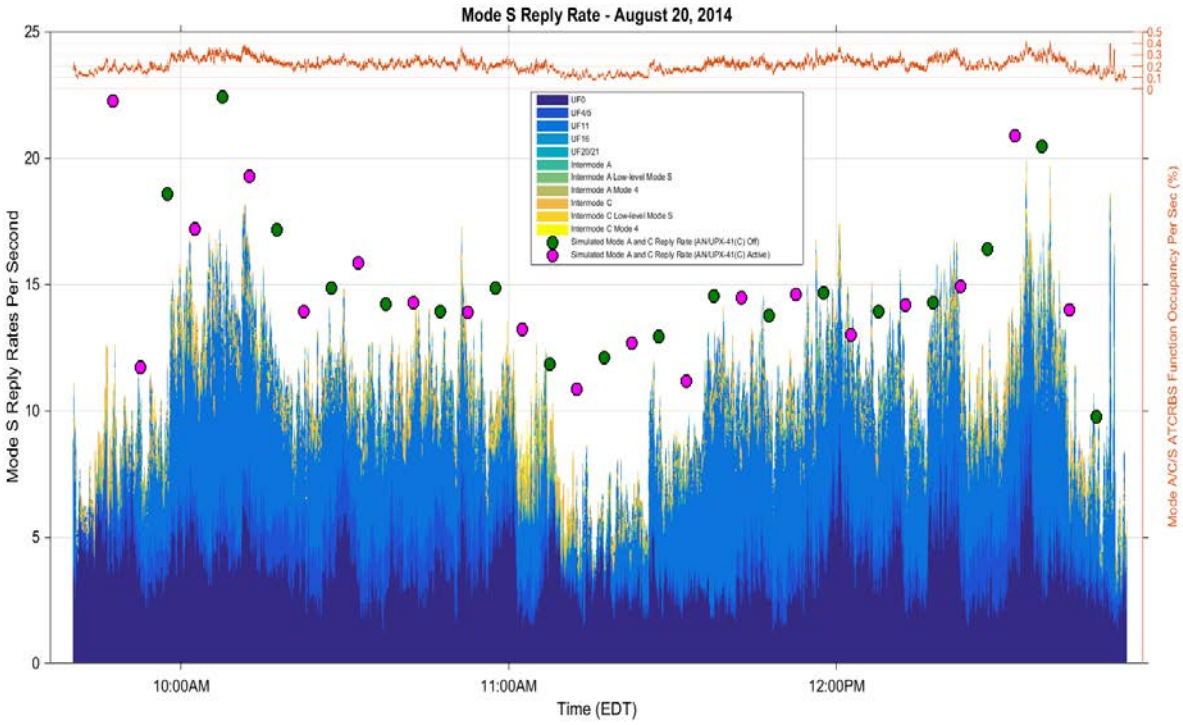


Figure 245. Mode A/C/S Transponder Rate of Replies to Mode S Interrogations and Transponder Occupancy for Day 3 – Breakdown by Event (Stacked Bar Plot with 10-sec Sliding Window Average)

Figure 246 compares the rate of replies to UF4/5 interrogations between measured and simulated data. Note that a reply to a UF4/5 interrogations means that the interrogation was discretely addressed for the victim and the victim is in the Roll-call range of the Mode S interrogator from which it's receiving the interrogation. Thus, the rate of UF4/5 replies changes as the aircraft moves into and out of Roll-call range of Mode S interrogators. The Roll-call range for Mode S terminal interrogators is nominally 60 nmi and 200-250 nmi for long range interrogators. While the simulation agrees well from the beginning of the circuit until 10:15 a.m. and 11:00 a.m. to 12:15 p.m., there are clear discrepancies from 10:15 a.m. to 11:00 a.m. and 12:15 p.m. to the end of the flight test.

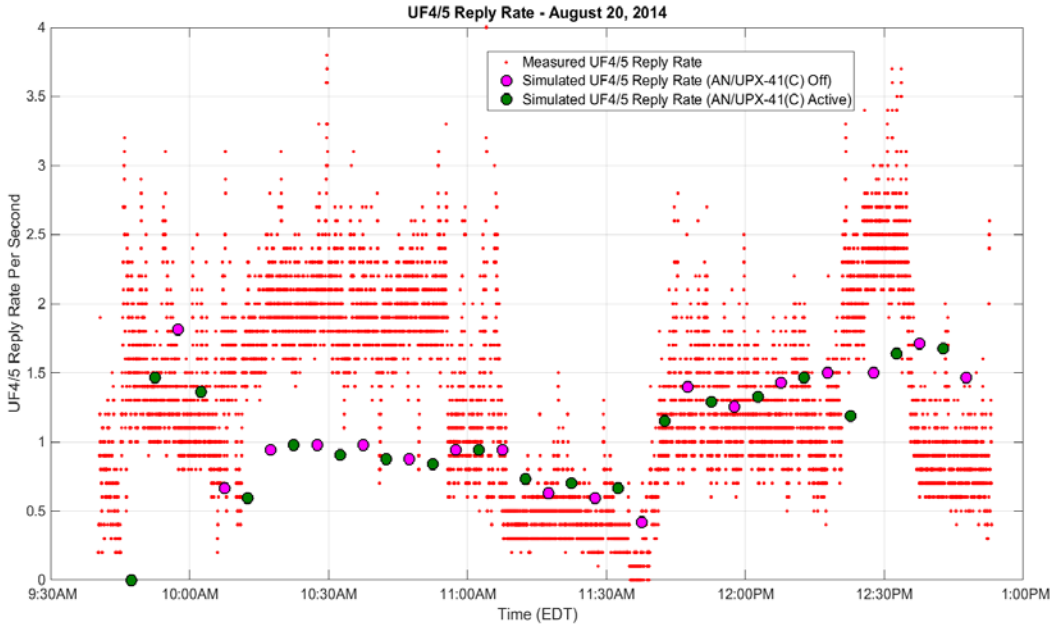


Figure 246. Mode A/C/S Transponder Rate of Replies to Mode S Interrogator UF4/5 Interrogations for Day 3 (10-sec Sliding Window Average)

Figure 247 compares the rate of replies to UF11 interrogations between measured and simulated data. Like Figure 245, the simulated points follow the trend of the measured data very well, but there is a clear difference in magnitude by about a factor of 2. The last set of replies to Mode S interrogations of significance are replies to UF0 interrogations, as shown in Figure 248. The comparison of measured and simulated data shows decent agreement but is again subject to the interdependencies of aircraft positions and equipages. It is expected that agreement in this plot will also improve when the NTA data can be implemented as discussed in the non-reply section.

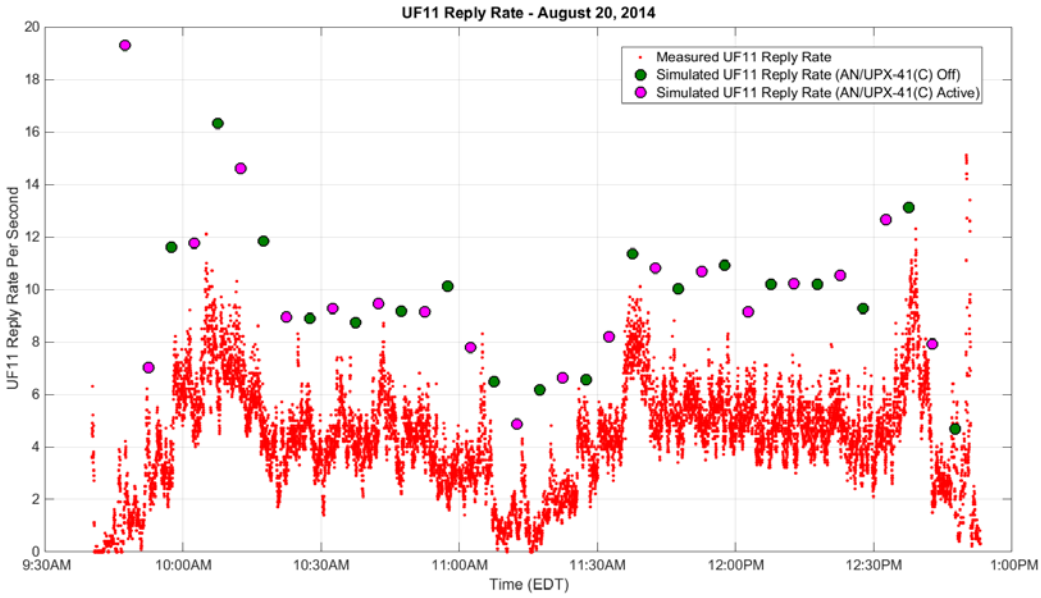


Figure 247. Mode A/C/S Transponder Rate of Replies to Mode S Interrogator UF11 Interrogations for Day 3 (10-sec Sliding Window Average)

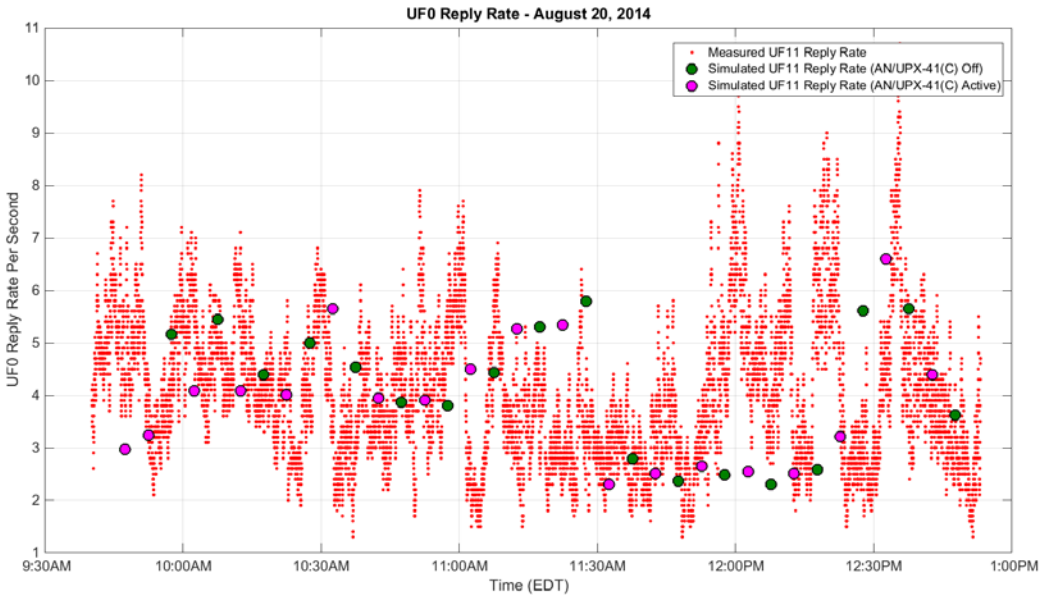


Figure 248. Mode A/C/S Transponder Rate of Replies to Mode S Interrogator UF0 Interrogations for Day 3 (10-sec Sliding Window Average)

UF0 rates aside, the discrepancies for UF4/5 and UF11 rates have implications on the setup of Mode S interrogators in the Simulator. As of the publication of this report, the team has

identified five areas to explore that could help reconcile the differences between measured and simulated UF4/5 and UF11 rates:

1) Interrogators believed to be Mode S that are actually transmitting ATCRBS-only or unknown interrogators that are transmitting Mode S. This would decrease the UF11 and UF4/5 rate.
2) Interrogators believed to be ATCRBS-only that are actually transmitting Mode S. This would increase the UF11 and UF4/5 rate.
3) The known Mode S interrogators are transmitting more UF4/5 interrogations than the Simulator models. If an interrogator did more than one to two UF4/5 interrogations per beam dwell (one to two modeled in the simulator) during the Roll-call window for each aircraft on the acquired aircraft list, the UF4/5 rate would increase.
4) The Roll-call range of Mode S interrogators does not follow the nominal distances. If the Roll-call range of a terminal Mode S interrogator was extended, the UF11 reply rate would decrease for some areas because there would be a larger lockout zone.
5) Transponders misinterpret low-level Mode S UF11 interrogations at the fringes of coverage. This would decrease the number of replies to UF11 interrogations.

F.4.4 Replies to ATCRBS Interrogations

While Figure 234 showed that replies to ATCRBS interrogations had the second smallest effect on transponder occupancy of the four major event types, it is worth comparing measured and simulated reply rates to assess simulation assumptions about interrogators as well as the abnormal activity around the Norfolk area. Figure 249 compares measured and simulated ATCRBS reply rates for Day 3. As seen in F.4.2, the large increase in transponder occupancy around Norfolk also comes from a nearly threefold increase in ATCRBS replies over the nominal rates. This activity was not limited to Day 3 as shown in Figure 250, Figure 251, and Figure 252.

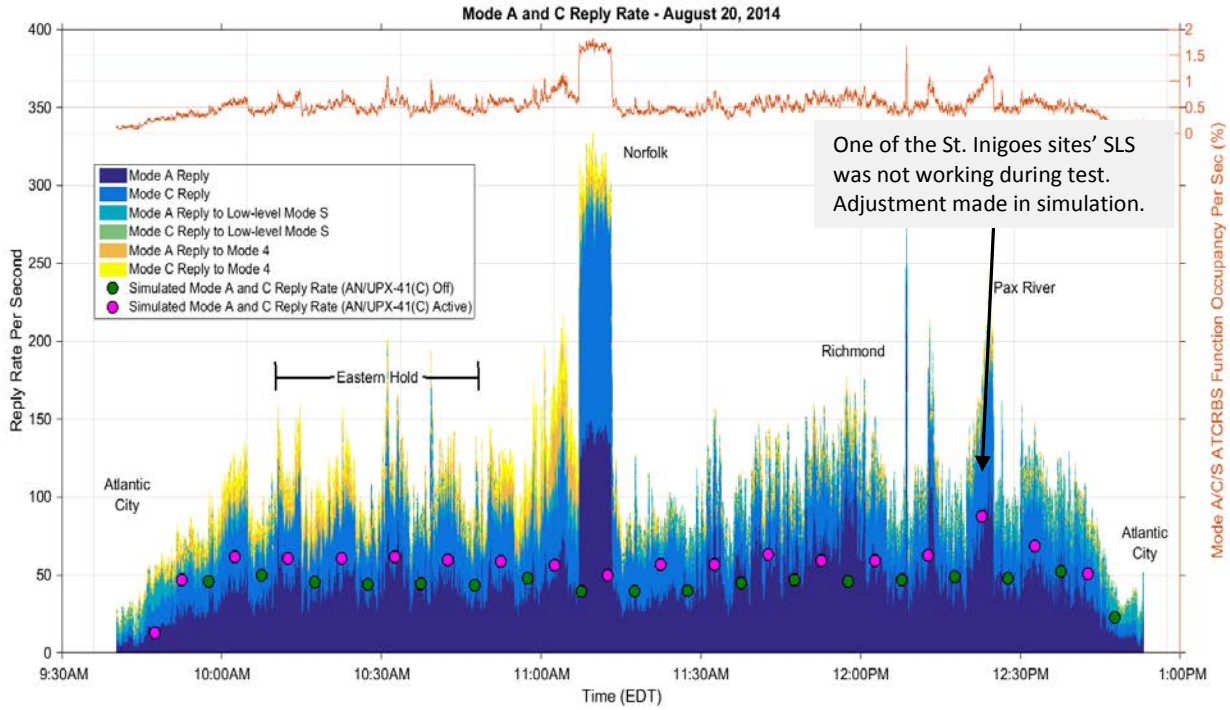


Figure 249. Mode A/C/S Transponder ATCRBS Reply Rate and Transponder Occupancy for Day 3 – Breakdown by Event (Stacked Bar Plot with 10-sec Sliding Window Average)

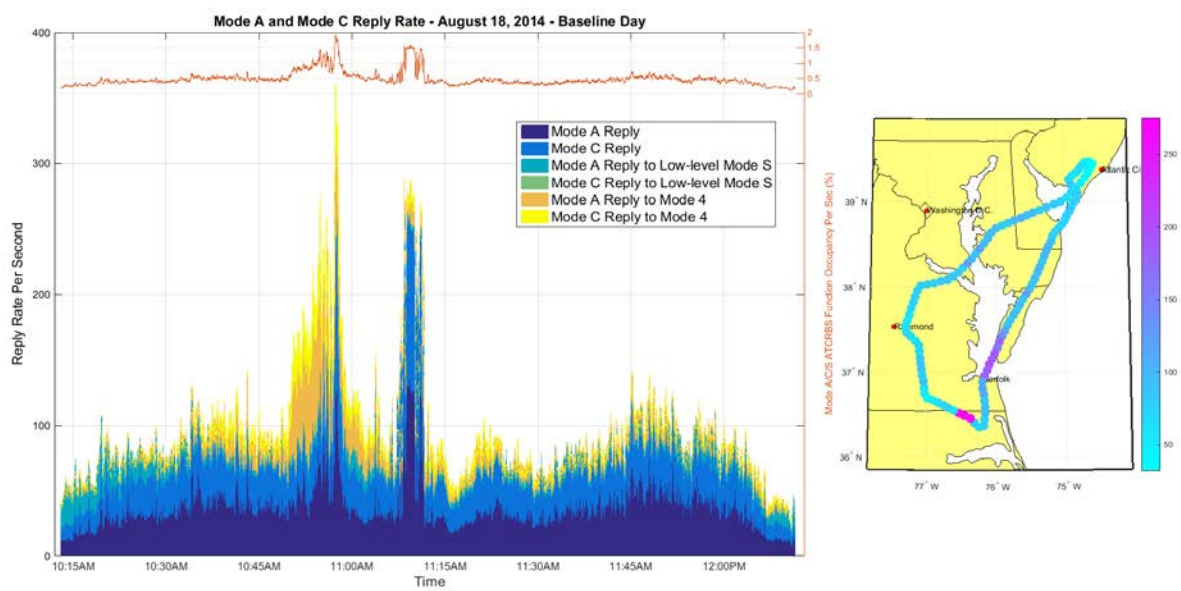


Figure 250. Mode A/C/S Transponder ATCRBS Reply Rate and Transponder Occupancy for Day 1 – Breakdown by Event (Stacked Bar Plot with 10-sec Sliding Window Average)

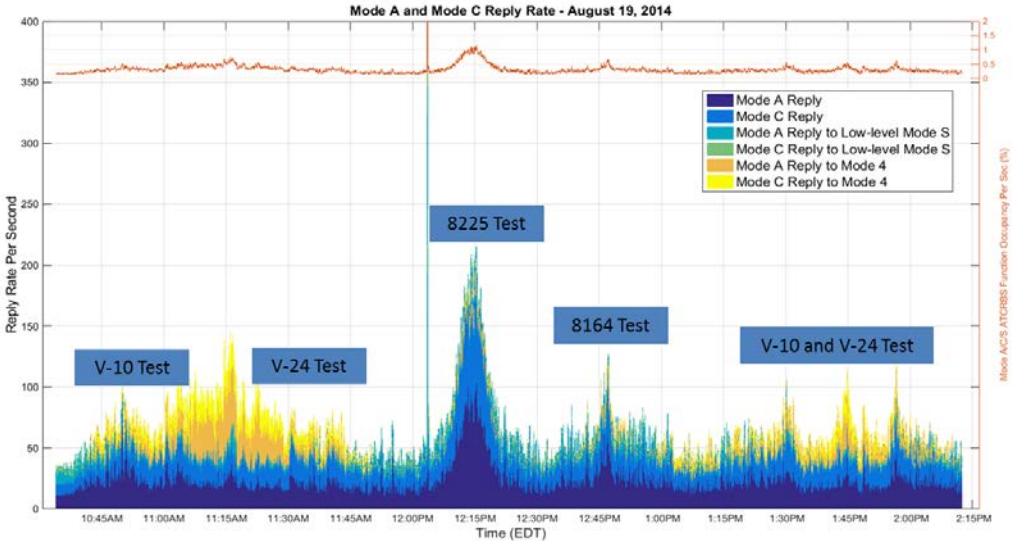


Figure 251. Mode A/C/S Transponder ATCRBS Reply Rate and Transponder Occupancy for Day 2 – Breakdown by Event (Stacked Bar Plot with 10-sec Sliding Window Average)

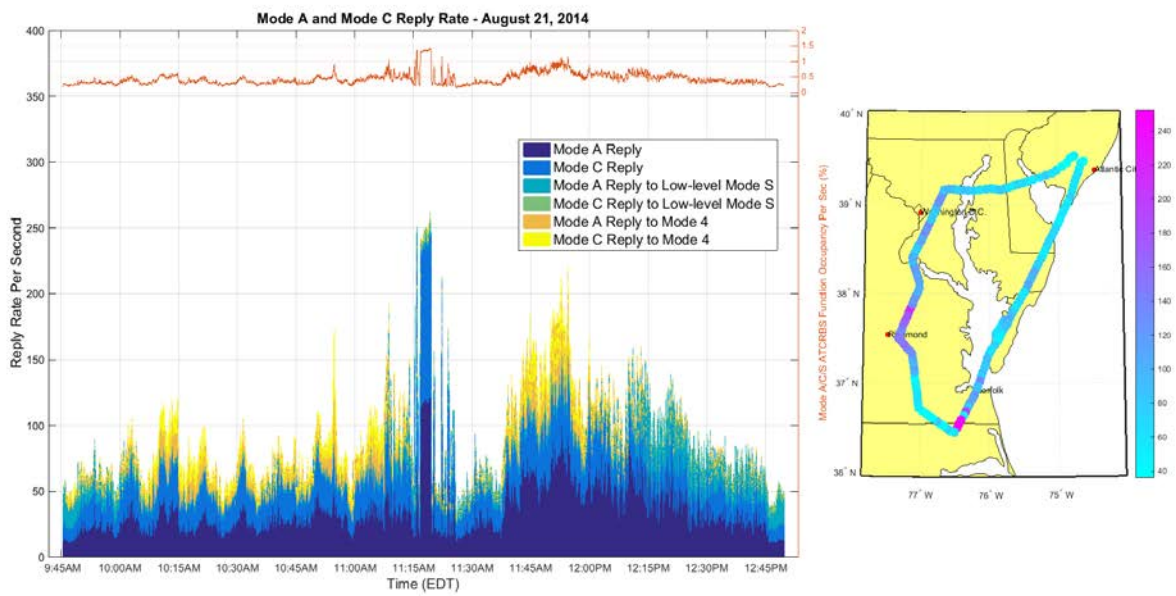


Figure 252. Mode A/C/S Transponder ATCRBS Reply Rate and Transponder Occupancy for Day 4 – Breakdown by Event (Stacked Bar Plot with 10-sec Sliding Window Average)

Figure 253 shows the Mode A reply rate on its own. The simulated rate agrees well with measurements for replies that come from actual Mode A interrogations when the LBTS were Off except in the areas south of Norfolk (see Figure 254) and around Richmond. When the LBTS were Active, there is some discrepancy in the Mode A reply rate and this has been attributed to building reflections as posited by the Navy. With respect to Mode A replies elicited by low-level

Mode S interrogations, the Simulator does not model receiver decoding of pulses so any of those types of replies in measurements can never be captured in the simulation. Misinterpretation of Mode 4 interrogations that trigger Mode A replies is modeled in the Simulator, but only through a probabilistic model that assigns a 10% probability of Mode A reply to any Mode 4 interrogation[9]. It is unclear what interrogator is generating the unexpectedly high number of Mode A replies to Mode 4 interrogations on the Eastern leg of the circuit (see Figure 255 for geospatial plot). During periods when the LBTS were Off, the only known interrogators within line-of-sight of the victim were three joint use DoD/FAA long range radars and no more than 3.5 Mode A replies to Mode 4 interrogations would be expected from them.

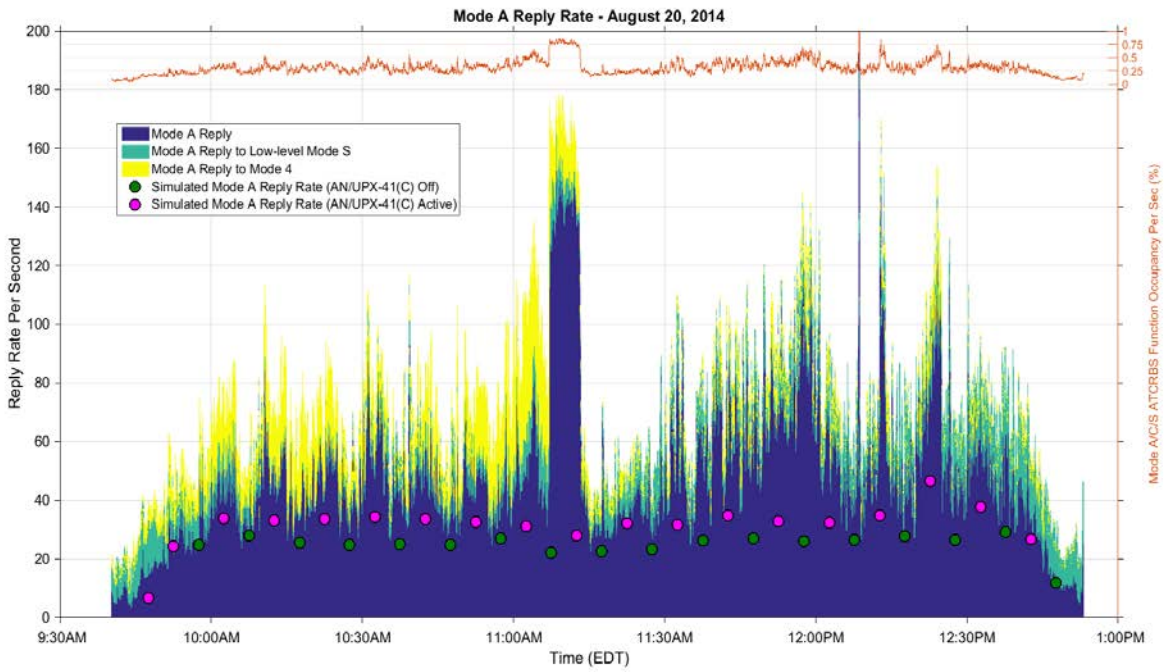


Figure 253. Mode A/C/S Transponder Mode A Reply Rate and Transponder Occupancy for Day 3 – Breakdown by Event (Stacked Bar Plot with 10-sec Sliding Window Average)

[9] Clarke, Robert, Angelo Libertino, Jr., Jefferson Walker, and David Blades. *A Summary of Transponder Measurements Performed by Germany, the United Kingdom, and the United States*. Field Test. Annapolis: US Department of Defense, Joint Spectrum Center. 1999.

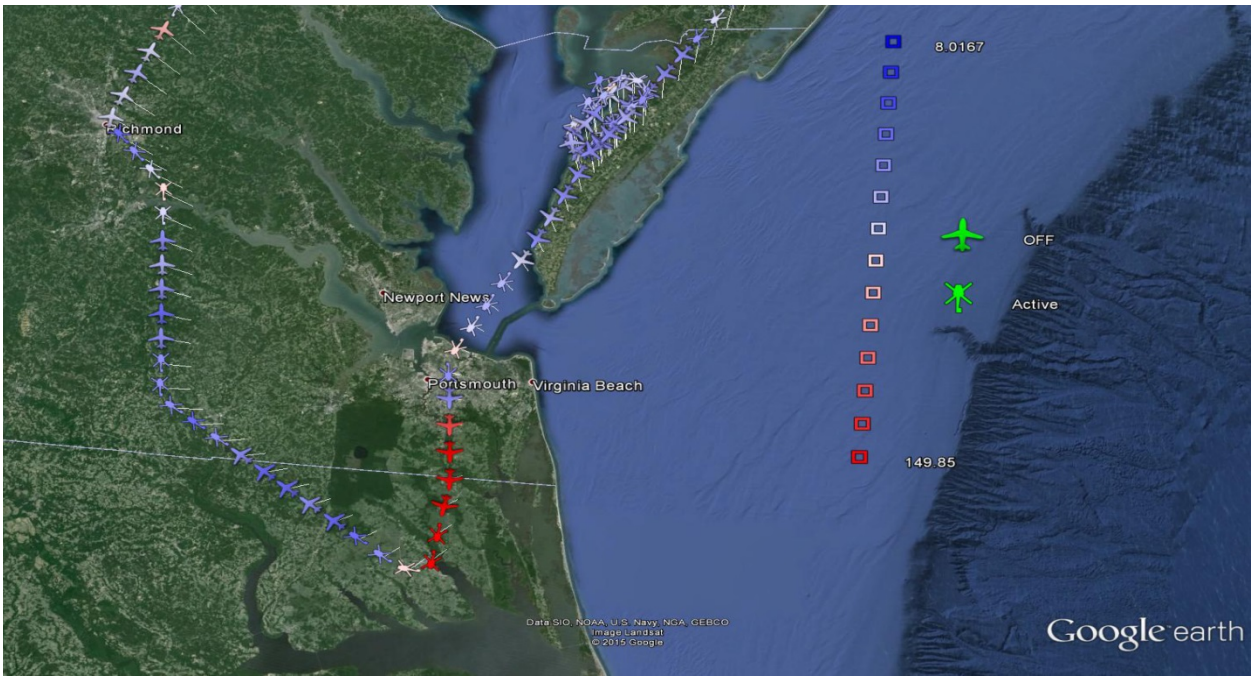


Figure 254. Geospatial plot of Mode A/C/S Transponder Mode A Reply Rate for Day 3 (60-sec Sliding Window Average)

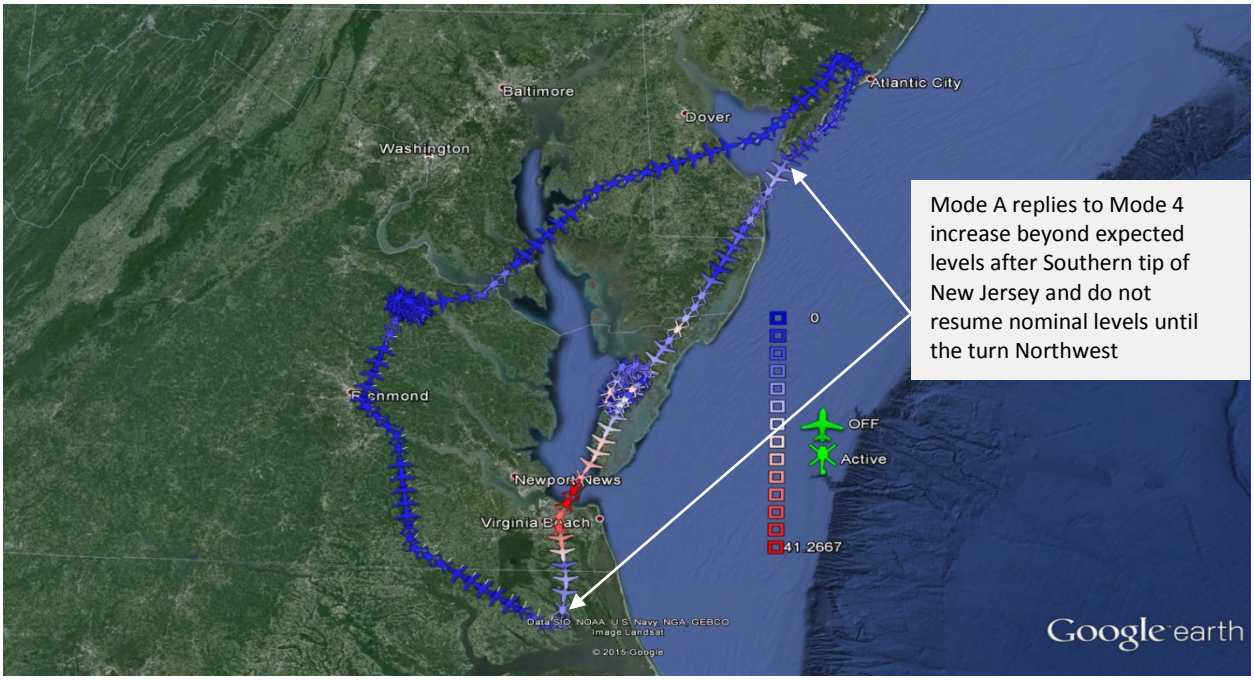


Figure 255. Geospatial plot of Mode A/C/S Transponder Mode A Reply Rate to Mode 4 Interrogations for Day 3 (60-sec Sliding Window Average)

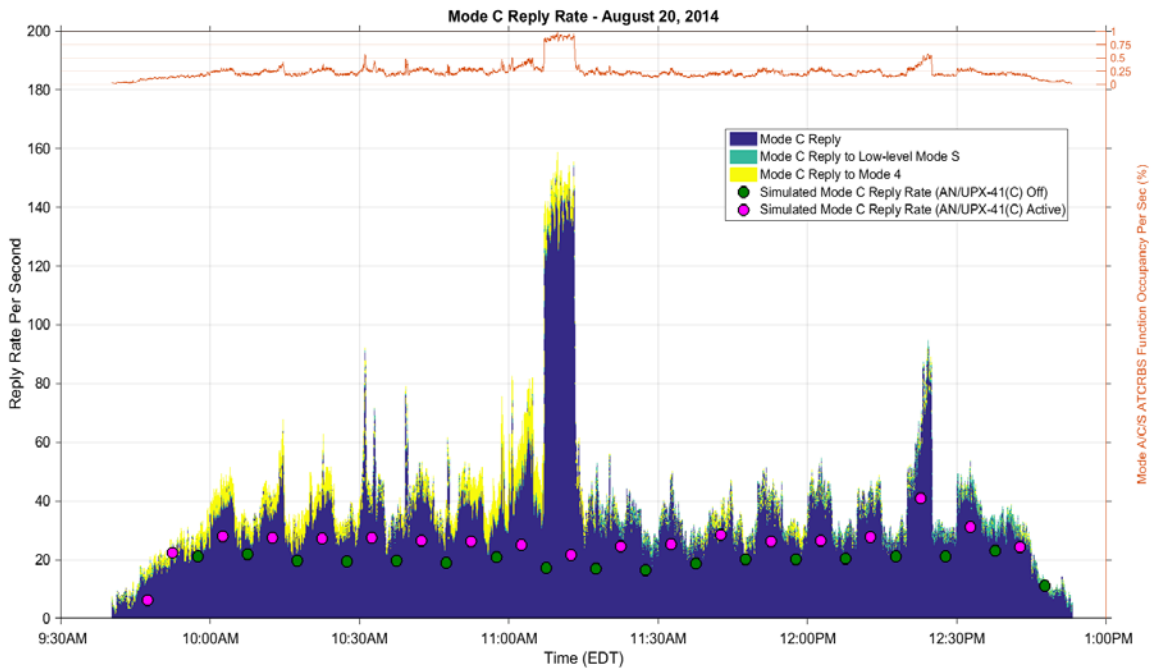


Figure 256. Mode A/C/S Transponder Mode C Reply Rate and Transponder Occupancy for Day 3 – Breakdown by Event (Stacked Bar Plot with 10-sec Sliding Window Average)

Similar to the Mode A reply rate, except in the area south of Norfolk, the simulated and measured Mode C reply rates match well for periods when the LBTS were Off, as shown in Figure 256. When the LBTS were Active, the simulated and measured Mode C reply rates have a discrepancy that is likely due to building reflections. For reflectors to elicit multiple replies, they must be located within close distance to the interrogator. This is especially true for the two LBTS at Wallops Island which are collocated with large reflective buildings in close proximity. Note that there are many fewer Mode C replies than Mode A replies to Mode 4 interrogations, but they still occur. As of today, the Simulator does not have a model for eliciting Mode C replies from misinterpretation of Mode 4 interrogations.

F.4.5 Suppression Bus Rate (Ownship TCAS Interrogations)

Surprisingly, the measurement data shows that denial of use of the transponder by the suppression bus was at least the second if not top culprit for transponder occupancy. This was due both to the rate at which these events happened as well as the duration of the occupancy times as specified by the MOPS. TCAS MOPS DO-185B Volume I Section 2.2.3.1.2 specifies that the suppression bus shall be active for 70 µs when using the TCAS antenna on the top of an aircraft and 90 µs when using the TCAS antenna on the bottom of the aircraft. Figure 257 shows the per second rate for number of interrogations coming from the top antenna versus the bottom

antenna. There are consistently almost 140 interrogations per second with most of them coming from ATCRBS whisper-shout interrogations as shown in Figure 258.

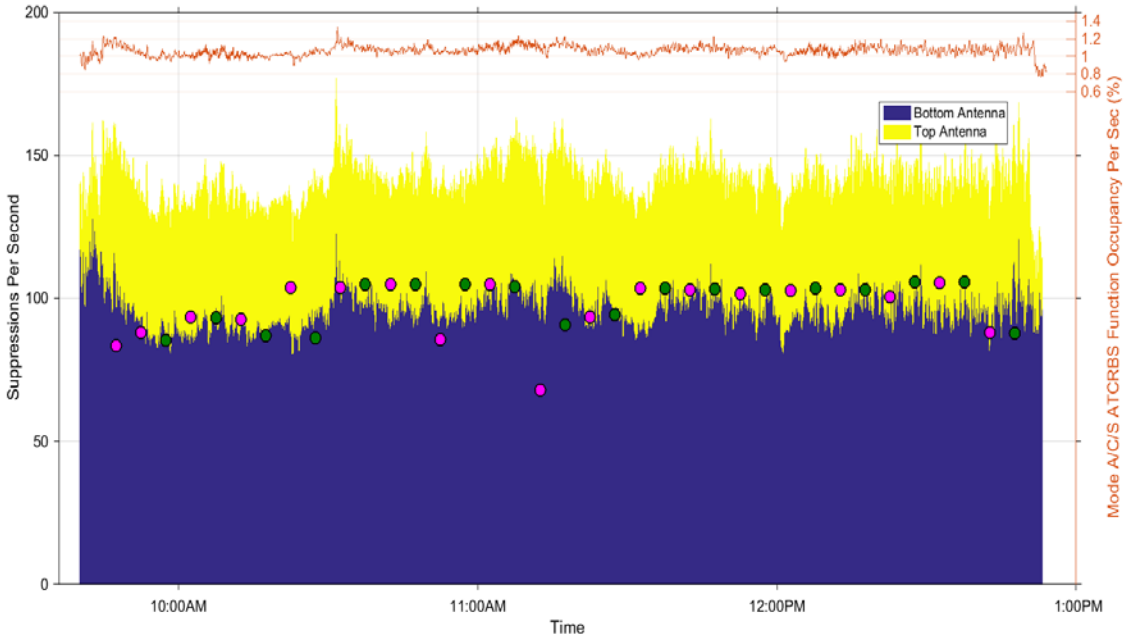


Figure 257. Mode A/C/S Transponder Suppression Bus Antenna Use Rate for Day 3 (10-sec Sliding Window Average)

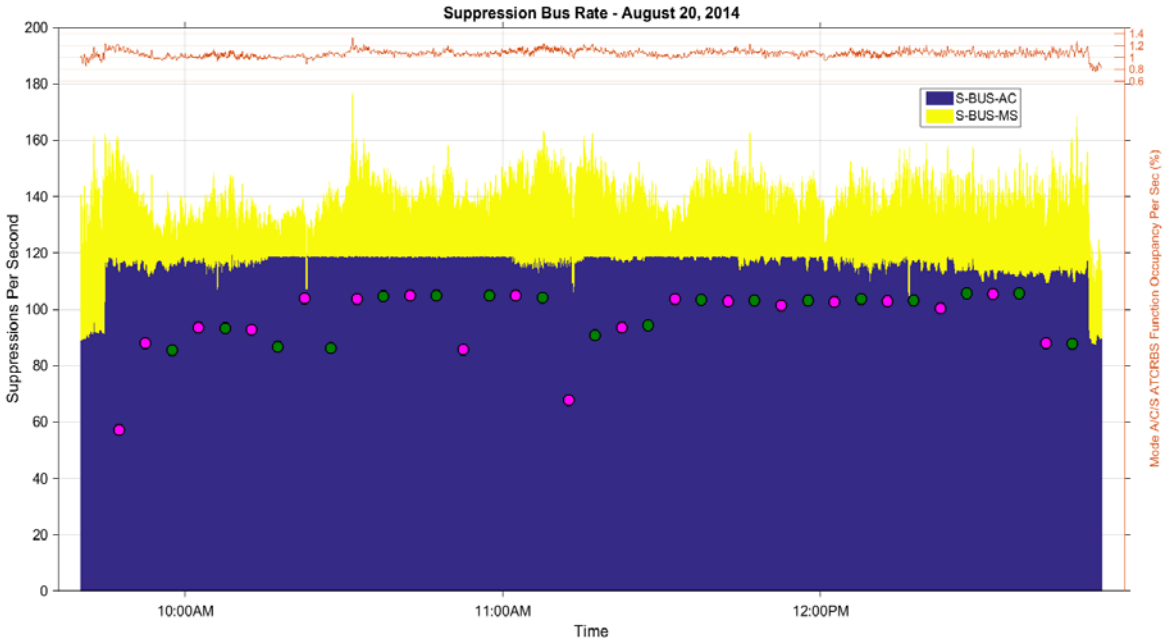


Figure 258. Mode A/C/S Transponder Suppression Bus Event Rates for Day 3 (10-sec Sliding Window Average)

The simulated suppression bus rates are only about two thirds of the measured rates. Figure 259 and Figure 260 breakdown TCAS transmissions by Mode S and Mode C, respectively. Simulated and measured TCAS Mode S transmissions match fairly well except for 9:45 a.m. to 10:30 a.m. which is likely due to the assumed distribution of TCAS equipped aircraft. Still, this is of less consequence to the suppression bus rate and transponder occupancy as measured TCAS Mode C interrogation rates average four times more than the TCAS Mode S interrogation rates. TCAS Mode C transmission rates again show that simulated rates are two thirds of the measurements and this warrants further investigation.

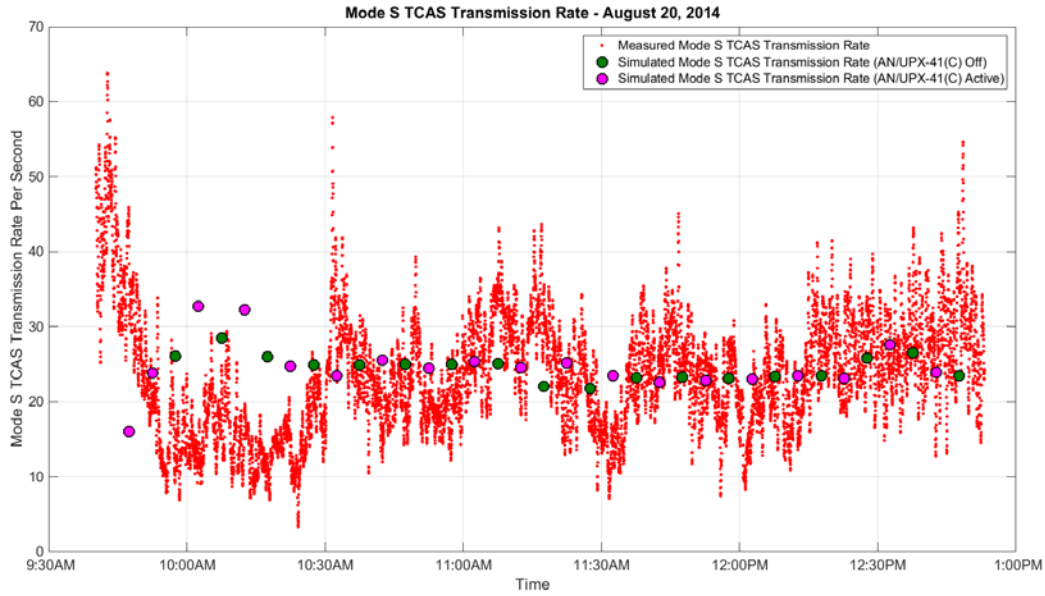


Figure 259. Measured TCAS Mode S Transmission Rate for Day 3 (10-sec Sliding Window Average)

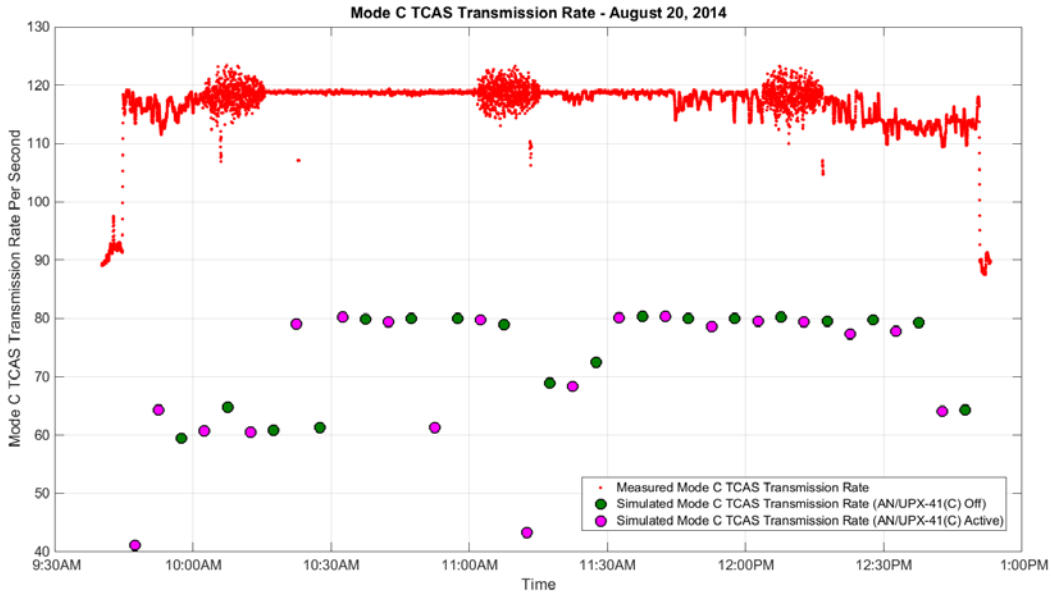


Figure 260. Measured TCAS Mode C Transmission Rate for Day 3 (10-sec Sliding Window Average)

The WJHTC determined from TCAS experts that their TCAS unit's maximum Mode C interrogation rate was about 119/sec. Looking through the Simulator development documents, it was found that the maximum rate for TCAS Mode C interrogations was set to 83/sec. This at least confirmed that the discrepancy was present, but the question of why those rates are different still remains. Additional investigation is required.

F.4.6 Discrepancy Adjustment

By removing the discrepancies from the previous sections that were known to not be simulated[10] or at least not simulated to the extent shown in the measurements, the simulated Mode A/C/S transponder ATCRBS function Typical transponder occupancy changes to what is shown in Figure 262. There is clearly much better agreement between measurements and simulation and the average percent difference is 15%, reducing to 10% if Norfolk and Atlantic City are removed.

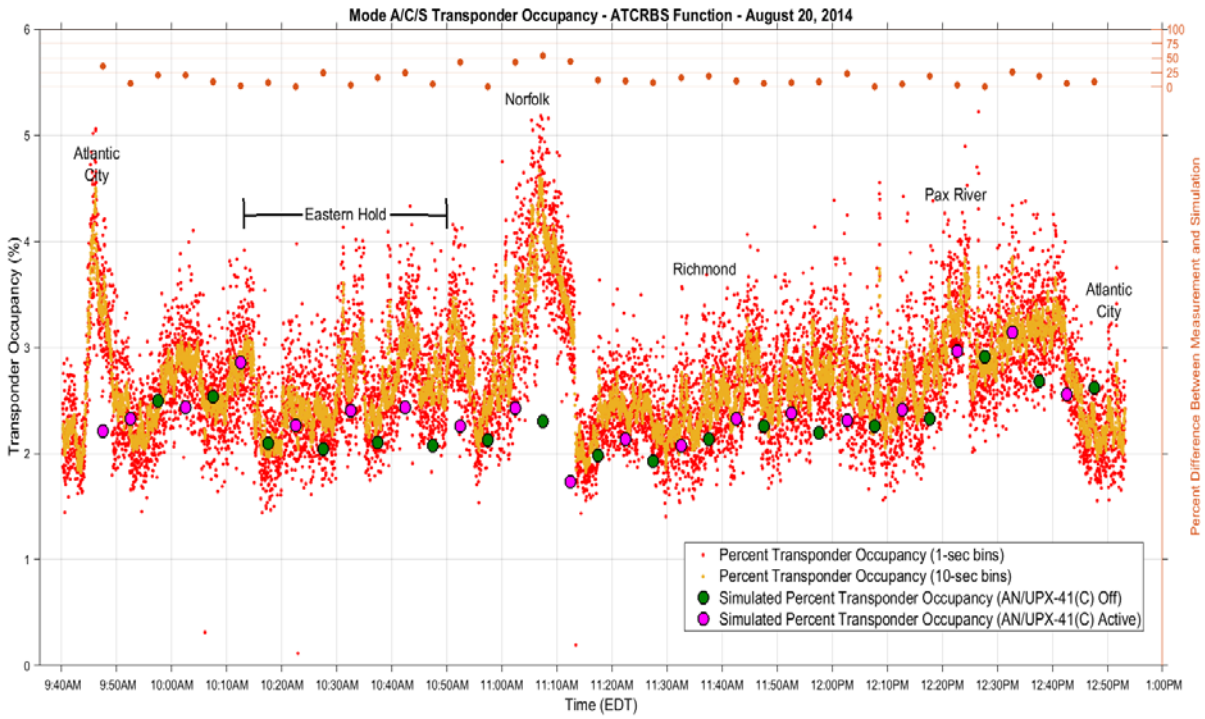


Figure 261. Mode A/C/S Transponder Occupancy for the ATCRBS Function using Typical Transponder Occupancy Times for Day 3 with Discrepancies Removed

This is a better assessment of how well the Simulator replicated what was known to be operating. It would be expected that the transponder occupancy levels from the simulation would better match the levels in Figure 229 if all interrogators and transponder response mechanisms were accurately modeled. The simulator acts as a sanity check against real world measurements to show which areas of the country have 1030/1090 MHz activity that was not previously expected. To the extent that the Simulator replicates how the NAS should operate, it is an effective tool in

[10] Mode 1 and Mode 4 suppressions, P1-P2-P3-longP4 suppressions, P1-P2-noP3 suppressions, low-level Mode S-induced Mode A and C replies, Mode 4 ATCRBS replies, TCAS ownship interrogation occupancy rate difference

pointing out the anomalies in how it actually operates. Still, there is much work to be done to improve this simulation model based on the results of this test.

F.5 1090 MHz – FRUIT Rates

The victim aircraft was moved around the simulation circuit in five minute intervals to record 1090 MHz signals for comparison with measured data. The term FRUIT traditionally refers to replies received by SSRs that were elicited by a different SSR, but, at a flight test aircraft receiver, it is generally accepted to mean all received 1090 MHz signals. Thus, the term FRUIT will be used herein to refer to all 1090 MHz signals. These include replies to SSRs, MLAT, TCAS interrogators, short and long squitter, and ADS-B ground-radio broadcast signals.

In the simulation, the victim's 1090 MHz receiver was modeled as an omni-directional antenna with 0 dB gain and MTL at the receiver of -90 dBm. Section 2 plotted ATCRBS FRUIT measured down to -79 dBm and Mode S FRUIT down to -84 dBm; the respective simulated FRUIT is also pared down to these power levels. Note that the measured FRUIT rates shown in the next sections are for top- and bottom-mounted antennas which the simulation does not employ.

F.5.1 ATCRBS FRUIT

Figure 262 and Figure 263 compare Day 3 measured and simulated ATCRBS FRUIT per second that is greater than or equal to -79 dBm for the WJHTC aircraft top antenna and bottom antenna, respectively. Figure 264 plots the ATCRBS FRUIT measured at the bottom antenna with respect to aircraft flight path. Since the WJHTC aircraft was flying at FL200 on Day 3, the majority of aircraft are below the WJHTC aircraft so more FRUIT was seen at the bottom antenna versus the top antenna. Like the 1030 MHz data, the simulated ATCRBS FRUIT trend matches well with the measured ATCRBS FRUIT except for the areas around Norfolk, but there are distinct differences in magnitude. Overall, the measured ATCRBS FRUIT is greater than the simulated FRUIT by a factor of two or less. Compared to previous validation efforts (Ref. 6), this is an improvement as the discrepancy had been shown to be greater than a factor of 2.5 near New York City in 2007.

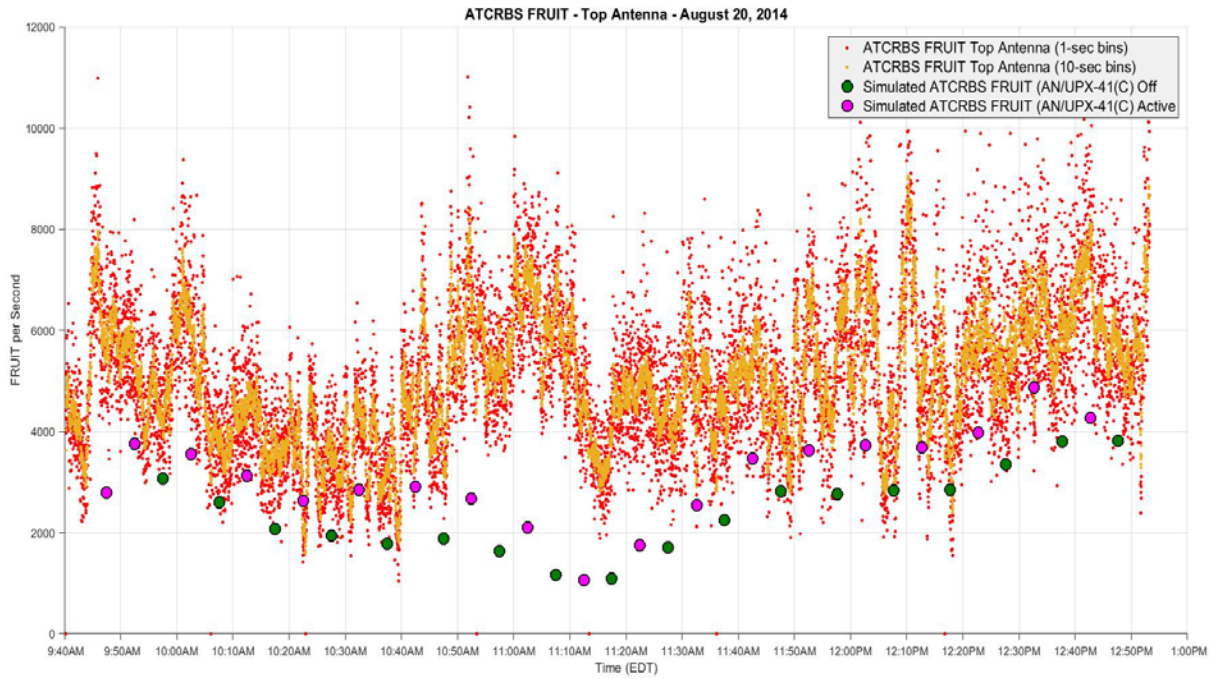


Figure 262. Measured (Top Antenna) and Simulated ATCRBS FRUIT ≥ -79 dBm for Day 3

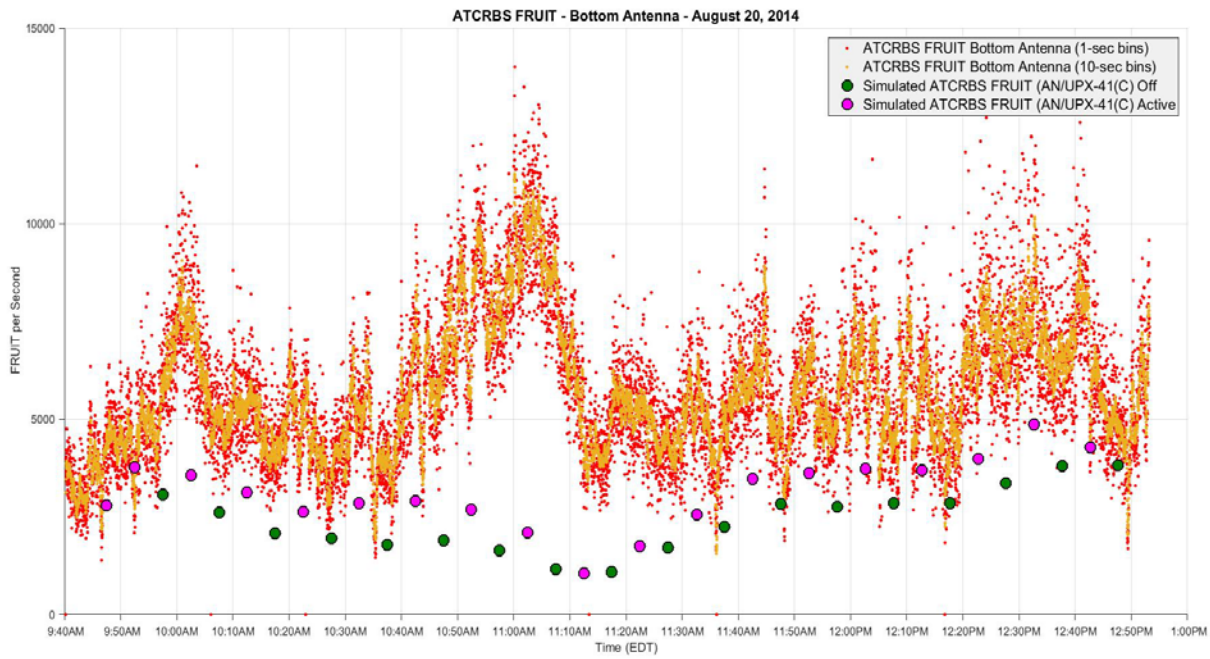


Figure 263. Measured (Bottom Antenna) and Simulated ATCRBS FRUIT ≥ -79 dBm for Day 3

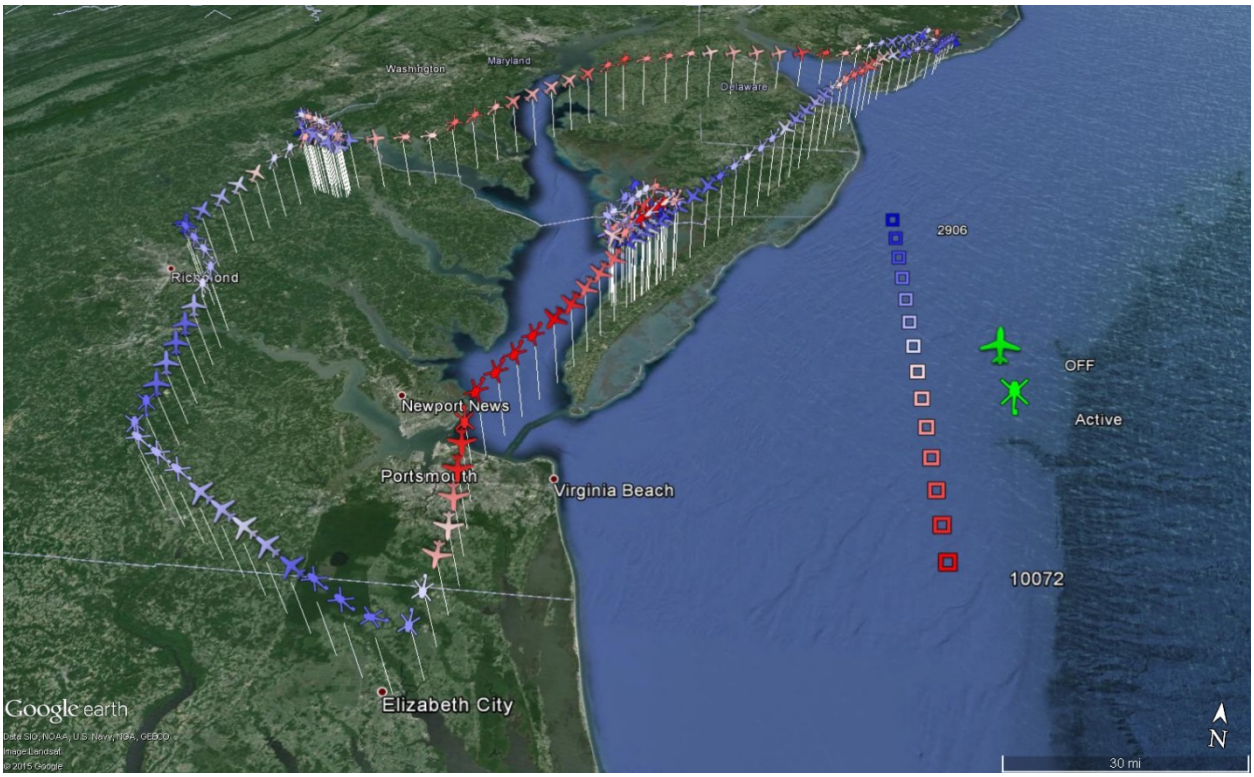


Figure 264. Geospatial Plot of Measured (Bottom Antenna) ATCRBS FRUIT ≥ -79 dBm for Day 3

While the discrepancies do occur and more work is required to correct them, it is clear where they originate. As shown in Figure 265, the measured ATCRBS reply rate is always greater than the simulated ATCRBS reply rate. Because ATCRBS replies become ATCRBS FRUIT, the discrepancy in the ATCRBS reply rates is the genesis of the discrepancy in ATCRBS FRUIT. Increasing ATCRBS reply rates in the simulation will increase ATCRBS FRUIT rates.

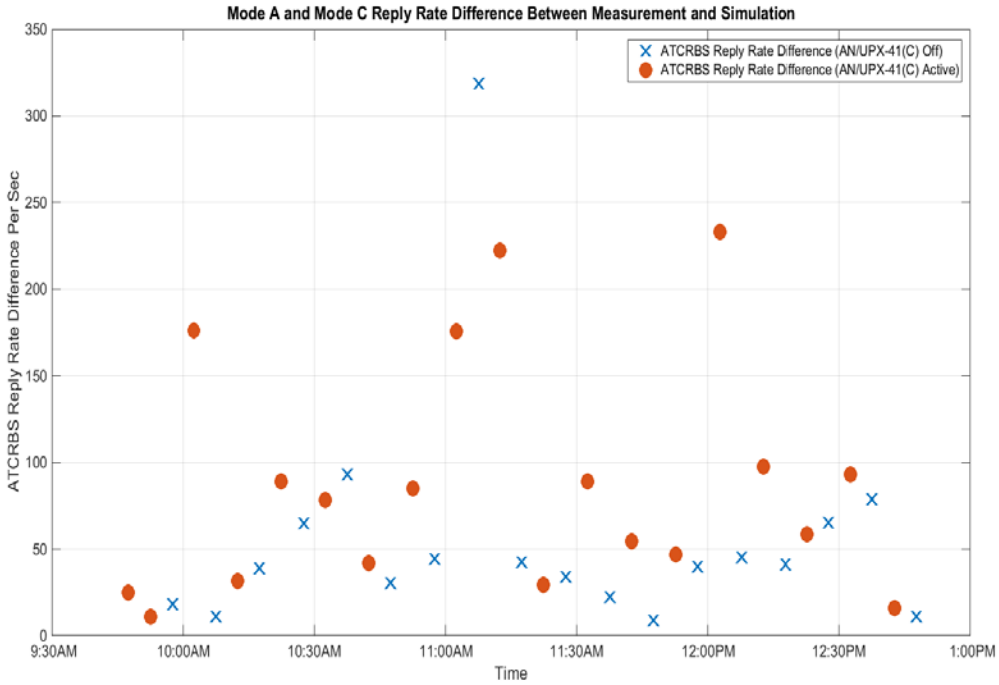


Figure 265. Mode A and Mode C Reply Rate Difference between Measurement and Simulation

There are many theories as to why the measured and simulated ATCRBS reply and FRUIT rates are different. The most likely theory, and one that has been partially proven, is that the difference is due to transponders, both Mode S and ATCRBS only, incorrectly decoding low-level Mode S interrogations. While the Mode S transponder MOPS DO-181E Section 2.2.2.4g [11] prescribe that the spurious ATCRBS reply ratio resulting from low-level Mode S interrogations[12] shall be no more than an average of 1% and maximum of 3% for signals ranging from -81 dBm to MTL, it has been documented that these percentages can be much higher for certain transponders. The Simulator does not currently have a probabilistic model to handle this possibility and as such, likely lacks ATCRBS replies and FRUIT that would normally be elicited by sub- or near-MTL Mode S interrogations.

Another theory, which also revolves around the modeling of transponders, is that the idealized transponder used in the Simulator may be under-replying to clear ATCRBS interrogations

[11] RTCA. *Minimum Operational Performance Standards (MOPS) for Air Traffic Control Radar Beacon System / Mode Select (ATCRBS/Mode S) Airborne Equipment*. DO-181E. Washington, D.C. March 17, 2011.

[12] This occurs when the Mode S interrogation preamble is not properly detected, which does not lockout the ATCRBS function when it should, and the transponder interprets the Mode S data block chips as an ATCRBS interrogation

(replies to intentional ATCRBS interrogations). The Mode S transponder MOPS DO-181E Section 2.2.2.4d and f state that the reply ratio shall not be more than 10 percent for interrogations at signal levels below -81 dBm and that the reply ratio shall be at least 90 percent for ATCRBS interrogations between MTL +3 dB and -21 dBm, respectively. The simulated transponder employs only a hard cutoff at MTL for determining if an interrogation warrants a reply. Upon further investigation, it is expected that simulated transponders can produce up to 40% more ATCRBS replies per second depending on the lowest power level that can be differentiated from noise.

Unknown, undocumented, or misbehaving interrogators, along with noise from emitters or the environment could also contribute to the difference in ATCRBS FRUIT/sec. As noted in Section F.4.4, measured replies to ATCRBS interrogations, especially North of and into the Norfolk area, were much greater than simulations. Considering the number of ATCRBS replies to Mode 4 interrogations for the same period, it is likely that the unknown interrogators were military units since the reply rate measured was much greater than any Mode 4-enabled interrogator in the FAA inventory could produce.

As noted previously, the Simulator does not employ top and bottom antennas for 1090 MHz signal reception. The omni-directional 0 dB antenna does not model the peaks, nulls, and fading associated with antennas mounted on a fuselage. In MATLAB, a probabilistic antenna, similar to the antenna used to receive 1030 MHz interrogations, for use during post processing of 1090 MHz signals was created. The results show that there is a 25% increase in the ATCRBS FRUIT rate when a probabilistic antenna is utilized to receive 1090 MHz signals.

F.5.2 Mode S FRUIT

Figure 266 and Figure 267 compare Day 3 measured and simulated Mode S FRUIT per second that is greater than or equal to -84 dBm for the WJHTC aircraft top antenna and bottom antenna, respectively. Figure 268 plots the Mode S FRUIT measured at the bottom antenna with respect to aircraft flight path. Like the ATCRBS FRUIT, the trend of the measured and simulated Mode S FRUIT match well, yet there is a difference in magnitude outside of the area around Norfolk. Unlike the ATCRBS FRUIT, the simulated Mode S FRUIT is greater than what was measured by a factor of about 1.5 to 2.

According to the ATCBI-6 second level engineering SMEs, some of the ATCBI-6 systems that were modeled as Mode S in the simulation may not have been operating with Mode S during the Test. Unfortunately, the SMEs said it was not possible to know exactly which systems were operating in this manner and when that occurred. To determine the sensitivity of Mode S FRUIT levels to ATCBI-6 operation with Mode S, the simulation was run with ATCBI-6 systems within LOS of the victim in ATCRBS-only mode. The drop in Mode S FRUIT was small and it was realized that long range radars that interrogate Mode S inherently produce small amounts of

Mode S FRUIT relative to terminal radars. This is because the majority of Mode S FRUIT produced by SSRs comes from replies to All-calls from aircraft outside the Roll-call range. Since long range radars have Roll-call ranges of 200 to 250 nmi and the curvature of the Earth limits LOS to about 267 nmi at and below 42,000 ft, there is only a small zone where aircraft would constantly reply to All-calls from a long range radar. Hence, almost all ATCBI-6 SSRs would have needed to be changed to ATCRBS-only to produce results comparable to the measured Mode S FRUIT environment. Therefore, this alone could not rectify the differences in measured and simulated FRUIT rates.

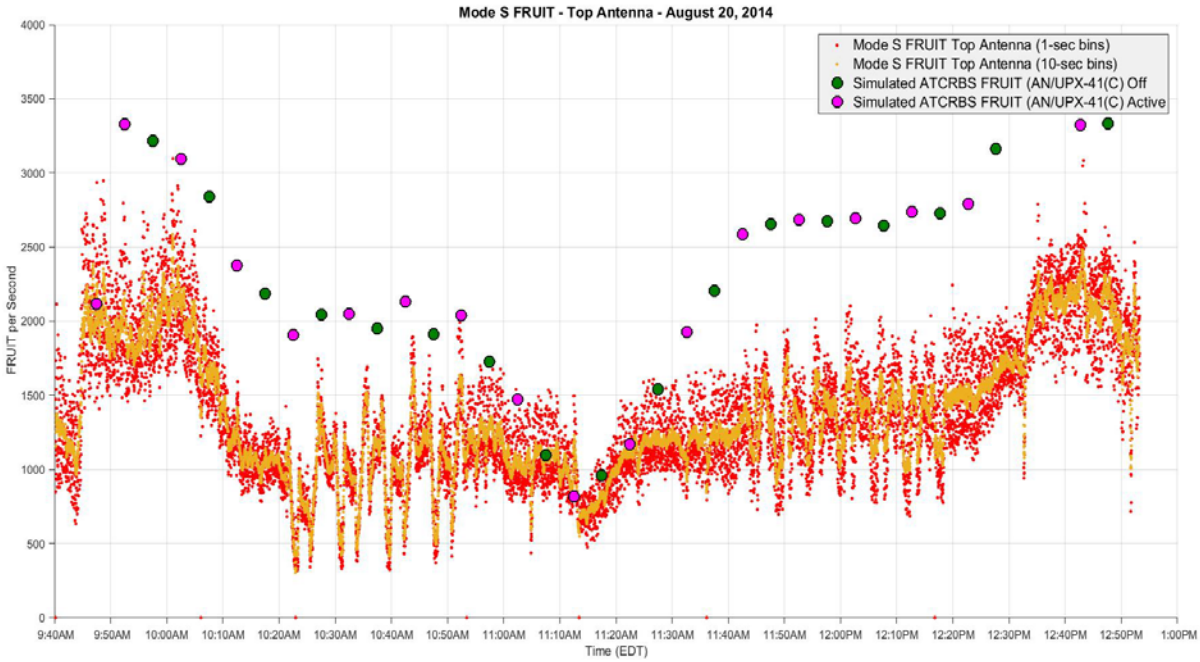


Figure 266. Measured (Top Antenna) and Simulated Mode S FRUIT ≥ -84 dBm for Day 3

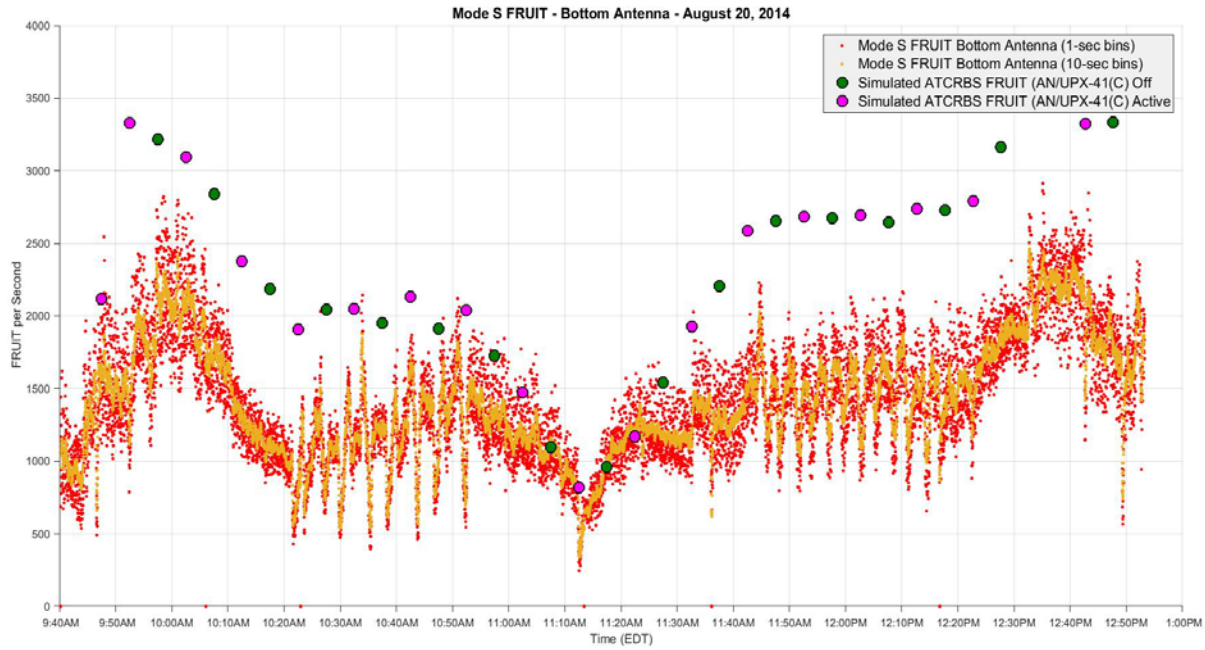


Figure 267. Measured (Bottom Antenna) and Simulated Mode S FRUIT ≥ -84 dBm for Day 3

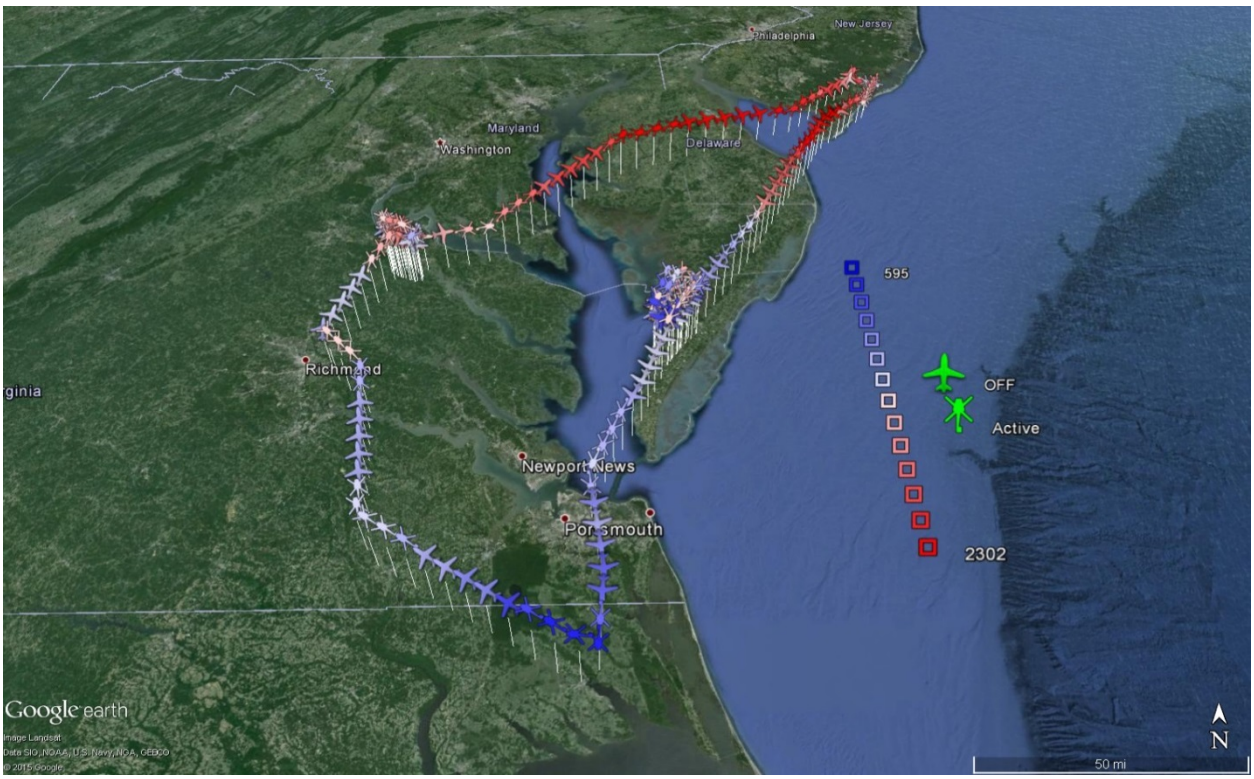


Figure 268. Geospatial Plot of Measured (Bottom Antenna) ATCRBS FRUIT ≥ -84 dBm for Day 3

Figure 269 and Figure 270 depict breakdowns of Mode S FRUIT for DF0, DF11, ID squitter, and DF4 and DF5 for flight test and Simulation, respectively. It is important to note that Figure 269 only includes messages that are determined to have good parity before or after error correction and, therefore, is only a subset of the total measured FRUIT rate. Also, Figure 269 and Figure 270 are not inclusive of all types of DF seen in the FRUIT data (e.g. DF17 squitter).

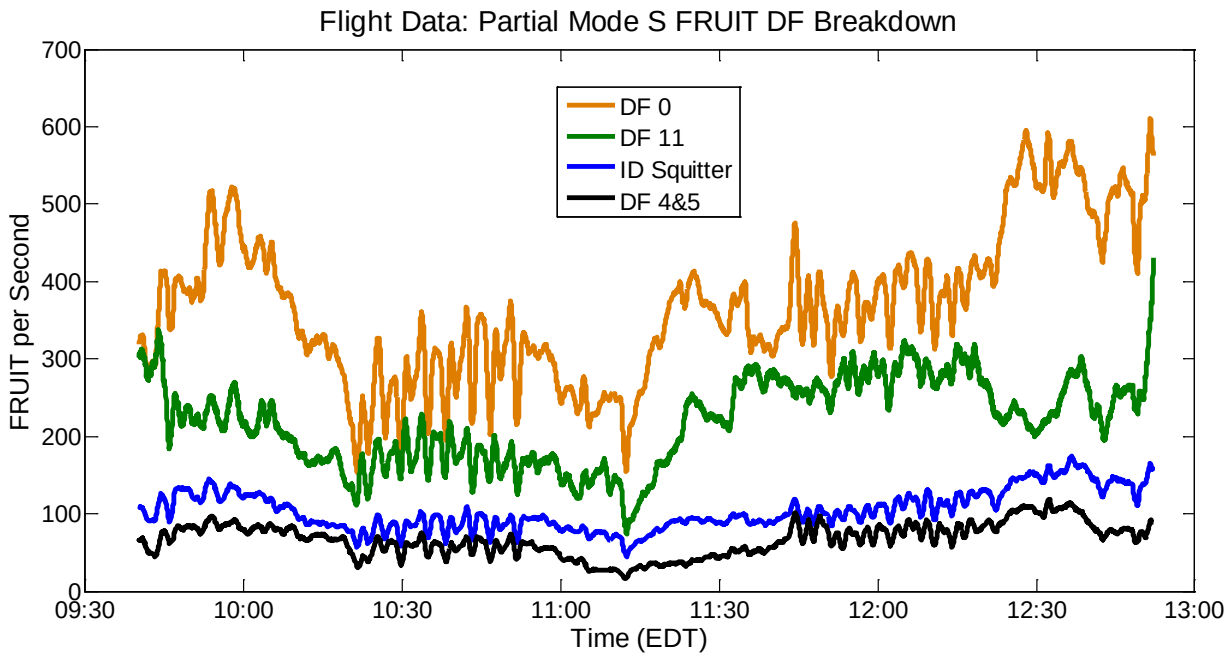


Figure 269. Day 3 - Partial Mode S FRUIT DF Breakdown from Flight Test

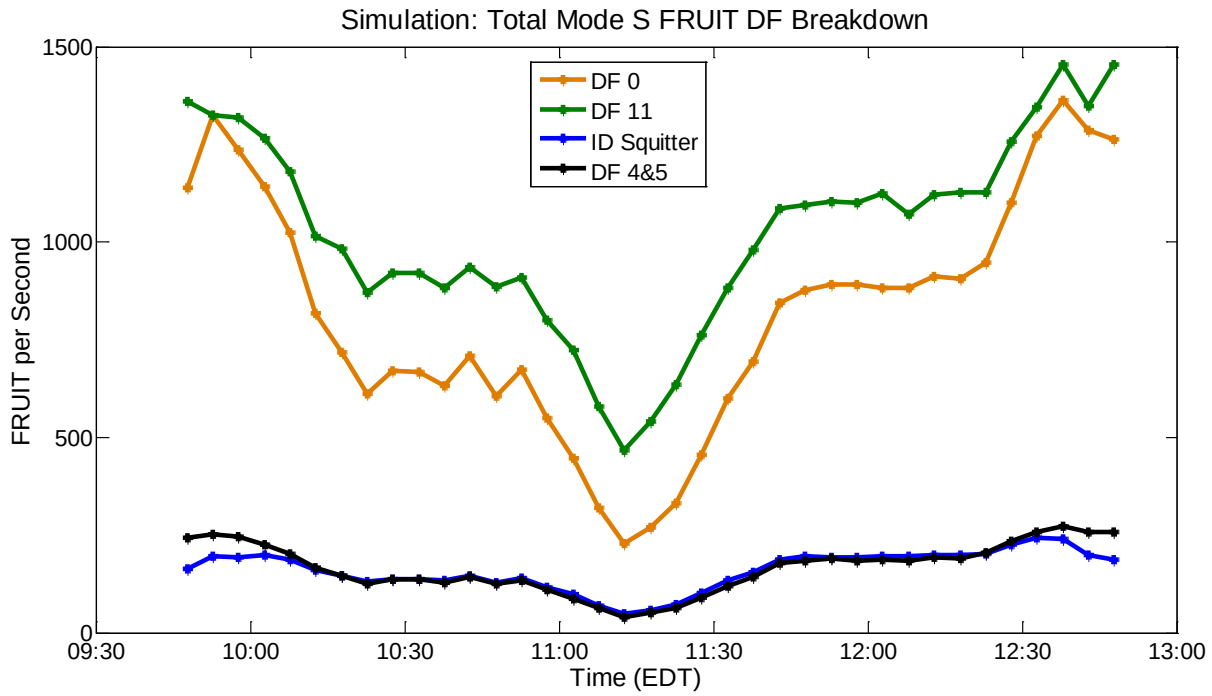


Figure 270. Day 3 - Total Mode S FRUIT DF Breakdown from Simulation

Measurements show that DF0 FRUIT is the top contributor to Mode S FRUIT, but simulation results predict DF11 FRUIT as the top contributor. While initially it would seem that simulated DF0 FRUIT needs to increase to match the measurements, this would increase total simulated Mode S FRUIT even further beyond measurements when a decrease is actually needed.

The only known simulation change that would decrease Mode S FRUIT is the replacement of the ACY Mode S SSR as a BI-5. However, this change alone does not reconcile the differences in simulated and measured FRUIT rates. Theories as to what causes discrepancies in simulated versus measured Mode S FRUIT rates, specifically, DF0 and DF11 rates, have been entertained. These include generating scenarios that are specific to the position N39 is at a given time, increasing Roll-call ranges, removing aircraft on the ground, and removing certain short range radars. One scenario, which has not yet been tested, is that low-level Mode S interrogations may not be correctly decoded by a transponder and generate no reply at all. Further study is required to determine the magnitude of this effect.

Generating scenarios specific to a given time did not cause a significant change in the simulated FRUIT rate. Increasing Roll-call ranges by thirty nautical miles through removal of DF11 FRUIT produced results that were comparable with measured data; however, measured UF11 reply rates in conjunction with UF4 and UF5 reply rates showed that Roll-call ranges of 60 nmi for terminal radars and 200-250 nmi for long range radars were indeed correct. Removing aircraft on the ground lowered DF0 FRUIT, but this did not address DF11 rates being higher than DF0. Finally, we removed different combinations of terminal and en route Mode S SSRs to

assess their DF11 contributions. Similar to changing Mode S ATCBI-6 radars to ATCRBS-only radars, removing terminal radars did not drop DF11 FRUIT enough to match measured data.

There are additional factors that could produce differences in measured and simulated Mode S FRUIT rates. A more comprehensive process of determining Mode S and TCAS equipage on aircraft could help narrow the gap in Mode S FRUIT rates. Also, modeling top and bottom antennas with a probabilistic gain model for 1090 MHz signal reception, as well as investigation into lack of replies generated near aircraft transponder MTL could help narrow the Mode S FRUIT rate gap further.

F.6 TCAS UF0 Non-Reply Detailed Examination

Figure 271 shows Day 4 Mode A/C/S transponder ATCRBS function occupancy. Circled under the Eastern Hold, there is a notable timespan of transponder occupancy that seems higher than it should be when compared to transponder occupancy for Day 3 for the same location. At an average of 2.5%, the transponder occupancy is 25% higher than Day 3. The Day 4 flight test altitude was lower than Day 3 so a transponder occupancy less than or equal to Day 3 was expected.

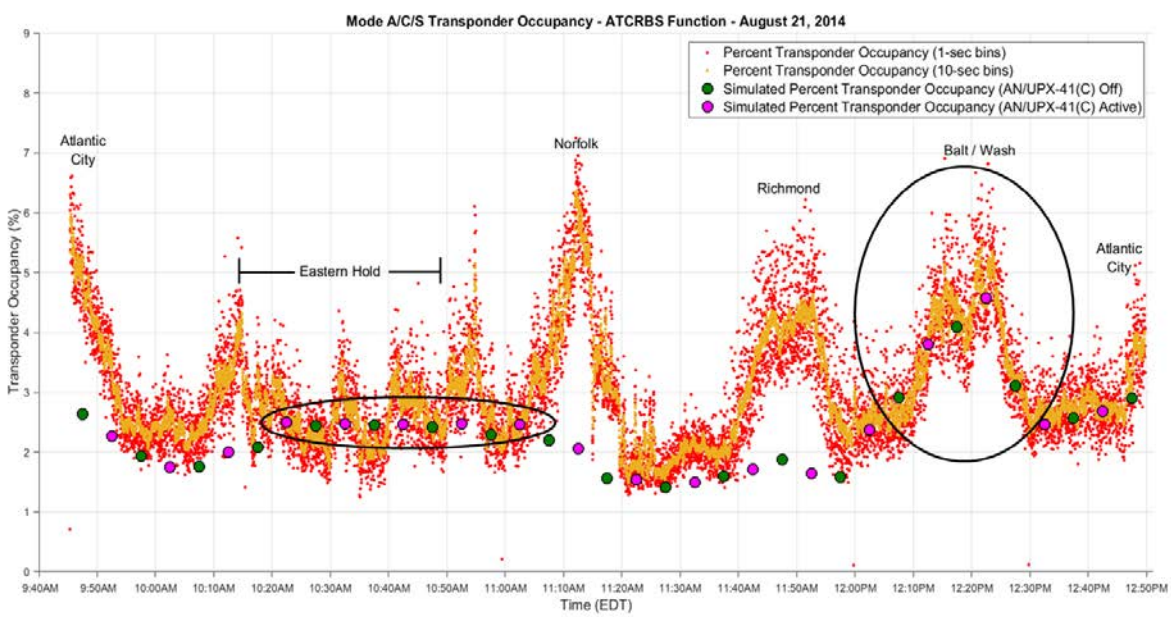


Figure 271. Day 4 – Mode A/C/S Transponder Occupancy (ATCRBS Function – Typical Times)

By examining a breakdown of transponder events for Day 4, like the plots shown in F.4, it was determined that there was a large discrepancy in the non-reply rate to Mode S interrogations. Figure 272 shows the breakdown of the rate of non-replies to Mode S interrogations per second by type that occurred on Day 4 for measurements and simulations. The green and magenta points, denoting simulations with Off and Active LBTS, respectively, begin to ramp beyond

measurements around 10:15 a.m., plateau around 300/sec and drop back to comparable measurement levels at 11:15 a.m. Breaking down the non-reply types, it was found that the spike in non-replies was due to non-replies to UF0 interrogations, as shown in Figure 273. In the simulation, N39 was seeing more TCAS unit Mode S interrogations meant for other aircraft than in the measurements.

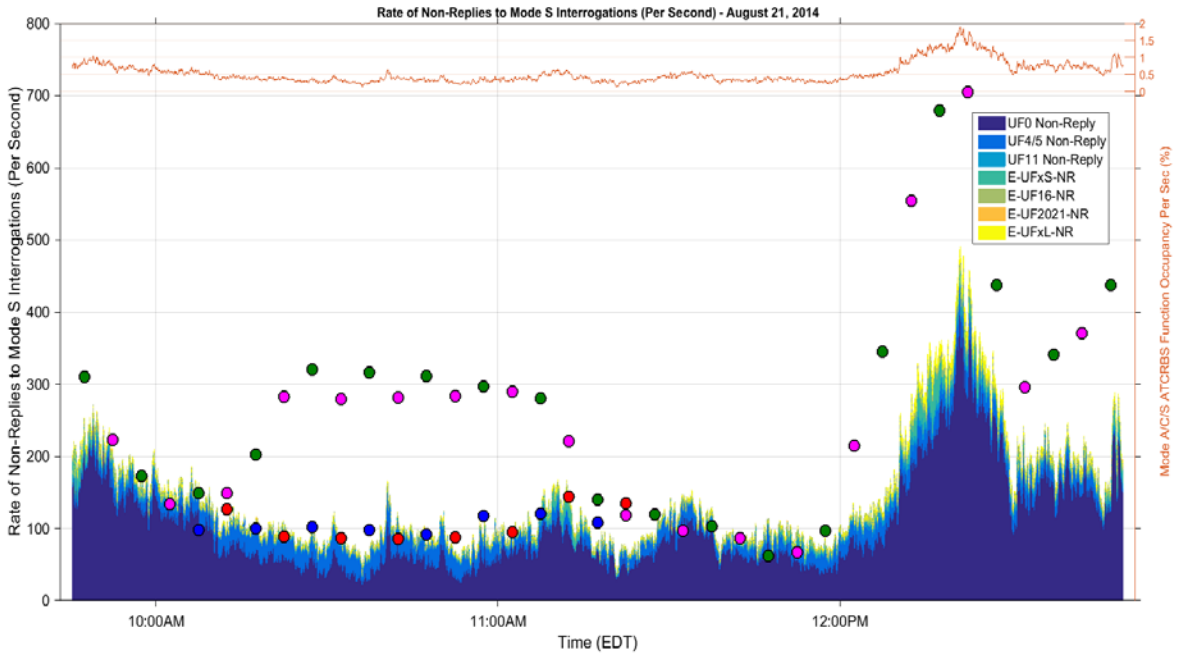


Figure 272. Mode A/C/S Transponder Non-Reply Rate to Mode S Interrogations and Transponder Occupancy for Day 4 – Breakdown by Event (Stacked Bar Plot with 10-sec Sliding Window Average)

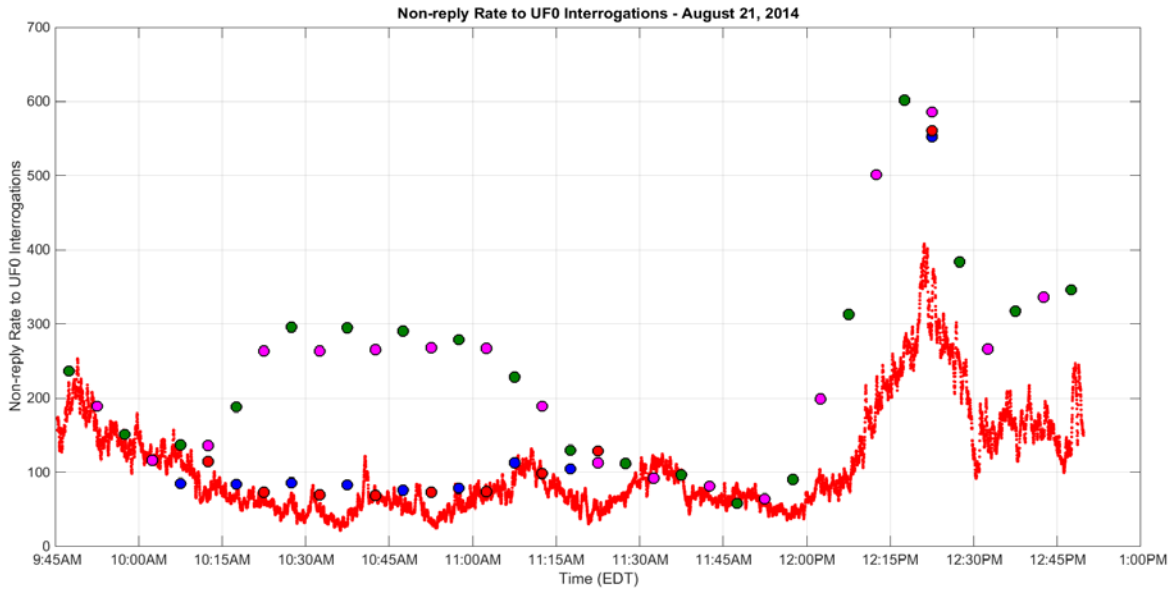


Figure 273. Mode A/C/S Transponder Non-Reply Rate to TCAS Mode S (UF0) Interrogations for Day 4 (10-sec Sliding Window Average)

It was theorized that the scenario setup, having used the same aircraft snapshot from 10:15 a.m. to simulate all five minute intervals, as noted in F.2, was to blame. The WJHTC aircraft, as the victim in the simulation, was seeing UF0 activity from 10:15 a.m. while placed in a spot corresponding to 10:27 a.m. At 10:15 a.m., the WJHTC aircraft was actually 35 nmi Northeast of the 10.27 a.m. spot. To the test theory, a new simulation setup was made for 10:27 a.m. and non-replies to UF0 events at N39 were compared for the 10:15 a.m. and 10:27 a.m. setups, as shown in Figure 274. Each shaded dot represents an aircraft with a TCAS unit that was creating UF0 interrogations. At 10:15 a.m. (left plot), there were clearly many TCAS units in the area contributing UF0 interrogations at rates over 10/sec while at 10:27 a.m. (right plot) there were fewer TCAS units interrogating at rates below 10/sec.

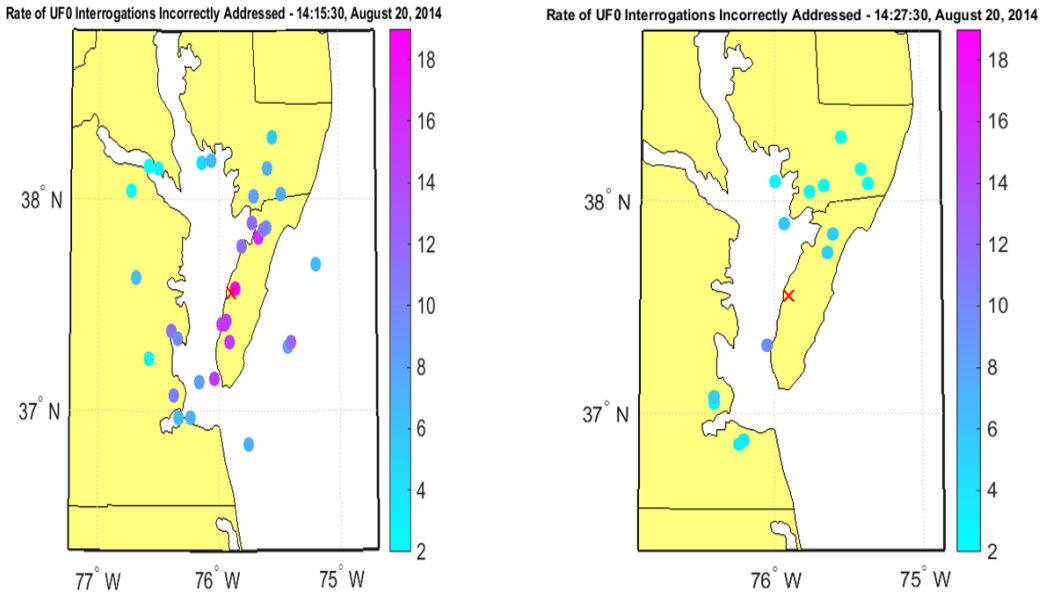


Figure 274. Mode A/C/S Transponder Non-Reply Rate to UF0 for 10:15 a.m. Scenario (left) and 10:27 a.c. Scenario (right) with Victim (red x) at 10:27 a.m. Position

Flowing back up to the non-reply UF0 plot (Figure 273) and the non-reply Mode S plot (Figure 272), the blue and red simulated points show the Off and Active, respectively, non-reply levels for the 10:27 a.m. scenario. Now, the simulated rates match measured rates much better than with the 10:15 a.m. scenario. This demonstrates the influence of scenario setup on simulated rates of TCAS activity, but proves that when the correct scenario is used, the Simulator can closely match measured TCAS Mode S interrogation rates.

Figure 272 demonstrates a similar situation in the Baltimore/Washington area. Reconfiguring the scenario setup from 10:15 a.m. to about 12:22 p.m. dropped UF0 non-reply rates only slightly (red and blue points in Figure 275); a surprise compared to the previous example. Further examination found that many of the TCAS UF0 interrogations were meant for aircraft on the ground at BWI, DCA, and IAD. Removing aircraft on the airport surfaces, the simulation produced the rates at the cyan and brown points for the Off and Active periods, respectively, in Figure 275. As an aside, aircraft simulated on the airport surfaces were worst case scenarios leftover from ASDE-X capacity studies with over 100 aircraft at these three airports. Still, the range of UF0 interrogations with or without aircraft on the airport surfaces is greater than or equal to the measured rates and there should be an expectation that there will be at least some aircraft on the ground at these three airports at any given time. Further investigation is needed to determine if aircraft TCAS unit equipage was appropriate as well as ensuring that TCAS interrogation rates for aircraft on ground (weight-on-wheels flag on) were appropriate.

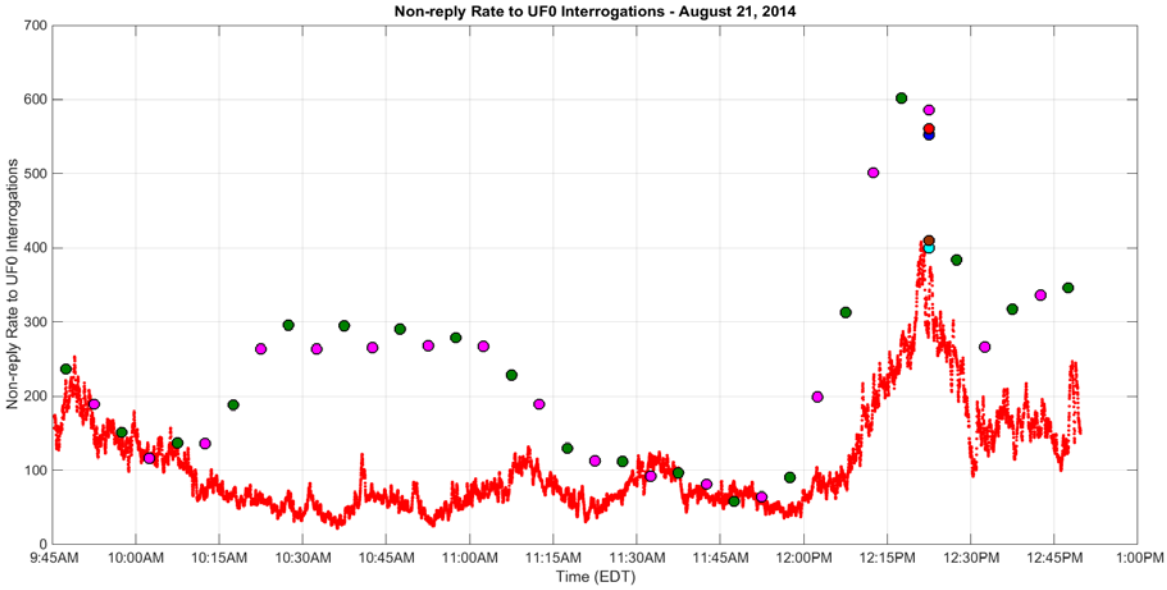


Figure 275. Day 4 – Mode A/C/S Transponder UF0 Non-Replies (Mode S Function)