Unmanned Aircraft Systems (UAS)

Broad Agency Announcement (BAA)

Call# 005

Final Report

Project Title:
Airborne Omni-Directional Surveillance

Company Name:
Sagetech Avionics

Contract Period of Performance:
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I.Executive Summary

The "Airborne Omni-Directional Surveillance" project was performed to evaluate ACAS Xr surveillance when using an omni-directional antenna. Legacy Collision Avoidance Systems are required to have at least one directional antenna. The size, weight and installation complexities associated with a directional antenna can be obstacles for system installation on certain crewed and uncrewed aircraft due to limited fuselage area for installation and interfering components in the area of installation. The evaluation consisted of three flight test events, each of which included a series of planned encounters and a surveillance flight near a busy airport. Each of the tests were successfully performed and a Flight Test Report for each flight test event was prepared which provides details of the testing and the ACAS Xr performance. Observations, issues, and anomalies are described in the test reports. An important objective of the project was to communicate the test results and associated recommendations to RTCA Special Committees SC-147 and SC-228. This has been accomplished through Project Kickoff, Midpoint and Final (pending) briefings at scheduled committee meetings. This report provides a description of equipment integration, performance evaluation, and recommendations.

II.Introduction

Detect and Avoid (DAA) capability is a key enabler to unlock the potential of unmanned aircraft systems (UAS) by enabling routine and safe Beyond Visual Line of Sight (BVLOS) flight. Effective DAA requires the accurate and efficient detection and tracking of both cooperative (Aircraft Dependent Surveillance Broadcast (ADS-B) and/or Mode C or S transponder equipped)

aircraft and noncooperative aircraft. Detection and tracking of cooperative aircraft require an airborne interrogator to validate unencrypted ADS-B information and for tracking non-ADS-B equipped aircraft with transponder Mode S or Mode C replies. Legacy Collision Avoidance Systems such as Traffic Alert, Collision Avoidance System II (TCAS II) and some Airborne Collision Avoidance System X (ACAS X) derivatives use directional interrogations/replies to provide acceptable detection and tracking while minimizing spectrum congestion on the primary 1030/1090 MHz frequencies. The use of directional antennas, however, presents multiple issues for implementation on Unmanned Aircraft Systems (UAS) and Advanced Air Mobility (AAM), electric Vertical Takeoff and Landing (eVTOL), Rotorcraft and other aircraft. The size, weight and aircraft mounting requirements of the directional antenna are often prohibitive, and even when installation is possible the performance may be severely degraded due to an inadequate ground plane and interfering components near the antenna. This project evaluated the use of an omni-directional antenna to provide the necessary interface to cooperative aircraft for surveillance using ADS-B, Mode S and Mode C messages provided by the aircraft transponder.

The key objectives of the project include:

- Objective 1: Identify, assess, and propose mitigations for potential safety risks with incorporating an omni-directional surveillance system that is part of a Detect and Avoid system.

- Objective 2: Collect test data to characterize the capabilities and limitations of the omni-directional surveillance system for use in Detect and Avoid operations in order to assess potential risks and inform design requirements for RTCA standards that mitigate those risks.

- Objective 3: Assess the degree to which the omni-directional surveillance system can validate that an ADS-B report is associated with a real aircraft and the degree to which the system can flag an ADS-B report that is associated with a false aircraft transmitted by a malicious actor.

- Objective 4: Determine the data elements that can be verified, quasi-verified, or not capable of being verified that are contained within or derived from ADS-B reports to include; reported position and positional accuracy (both 2D and 3D), altitude, and derived vector and derived vector accuracy (both 2D and 3D). Explain the validation methodology used for each data element, and propose validation protocols for current standards development, specifically RTCA SC-228 and SC-147 committees.

- Objective 5: Provide risk assessments, lessons learned, findings, outcomes, and recommended requirements to RTCA SC-228 and RTCA SC-147 committees.

III. Methodology

The project included three flight test events to evaluate omni-antenna surveillance and performance of the ACAS Xr system. Each fight test event included a series of planned encounters and a surveillance evaluation flight. Realtime observations were made during the testing, and data was recorded for post flight analysis of surveillance and threat resolution functionality. Detailed analysis was performed and documented in a flight test report associated with each of the three flight test events.

Encounter Tests

The test aircraft for the encounter flights was a TigerShark UAS provided by the NYUASTS. The aircraft was equipped with a prototype ACAS Xr system and installed with a single omni-directional antenna mounted on the bottom of the aircraft. Encounter tests were

Surveillance Flights

A Piper Dakota was the test aircraft for the surveillance flights and was also equipped with a prototype ACAS Xr system installed with a single omni-directional antenna mounted on the bottom of the aircraft. Surveillance flights were performed in Portland, Oregon (Flight Test Event 1), Seattle, Washington (Flight Test Event 2), and Los Angeles, California (Flight Test Event 3). Airspace near major airports in these cities provided high density concentrations of aircraft in order to assess surveillance performance according to requirements for track capability and operation in the midst of rf interference.

IV. Results and Discussion

The project consisted of three major activities including 1) integration of equipment, 2) flight testing, and 3) data analysis and reporting. Key aspects of each of these activities are provided in this section.

A. Integration

Integration and installation were accomplished on the TigerShark UAS and the Piper Dakota aircraft.

The ACAS Xr prototype system with associated cabling were physically mounted on the TigerShark. The low SWAP characteristics greatly simplified the installation with no payload or power issues. The omni-directional antenna was also easily accommodated and mounted on the bottom of the TigerShark. Own aircraft information was provided from the existing 'Piccolo

Autopilot' system through the ACAS Xr serial interface. The aircraft 'Sylvis' C2 datalink was used to uplink control data to the ACAS Xr prototype and for downlink of traffic, guidance and advisory data to the Mission Control GUI. A diagram of the installed system is provided in the following figure.
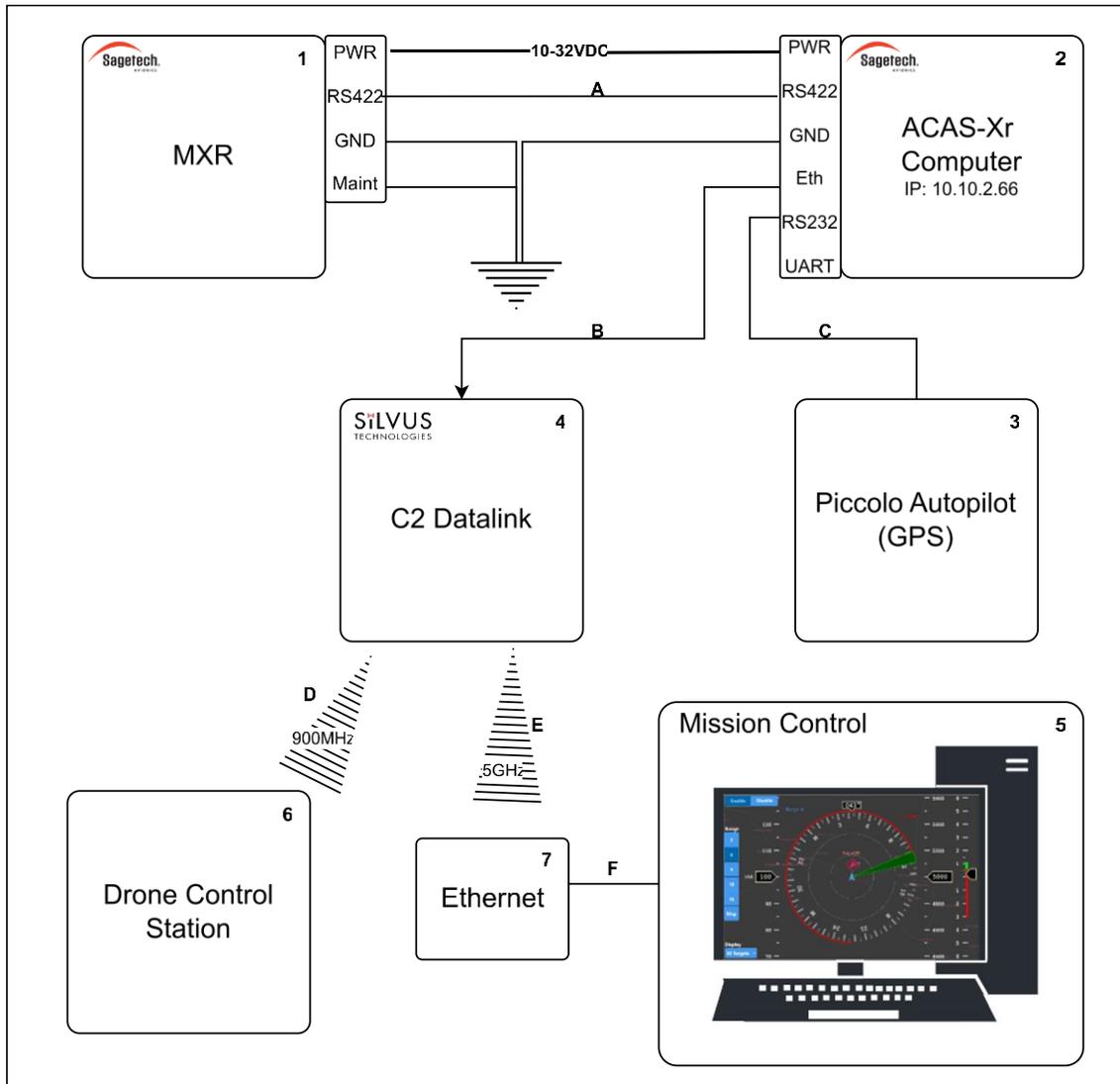
Integration of the ACAS Xr system into the Piper Dakota was accomplished using the ACAS Xr Flight Test Evaluation Kit (see Figure 1). The kit includes all ACAS Xr system components installed together as single portable unit. Ownship GPS data is provided from a Garmin GPS Puck

and ownship pressure altitude is obtained from a pressure altimeter contained within the Sagetech MXR. The kit was located within the cabin of the Piper Dakota and connected to an omni-directional antenna mounted on the underside of the aircraft.
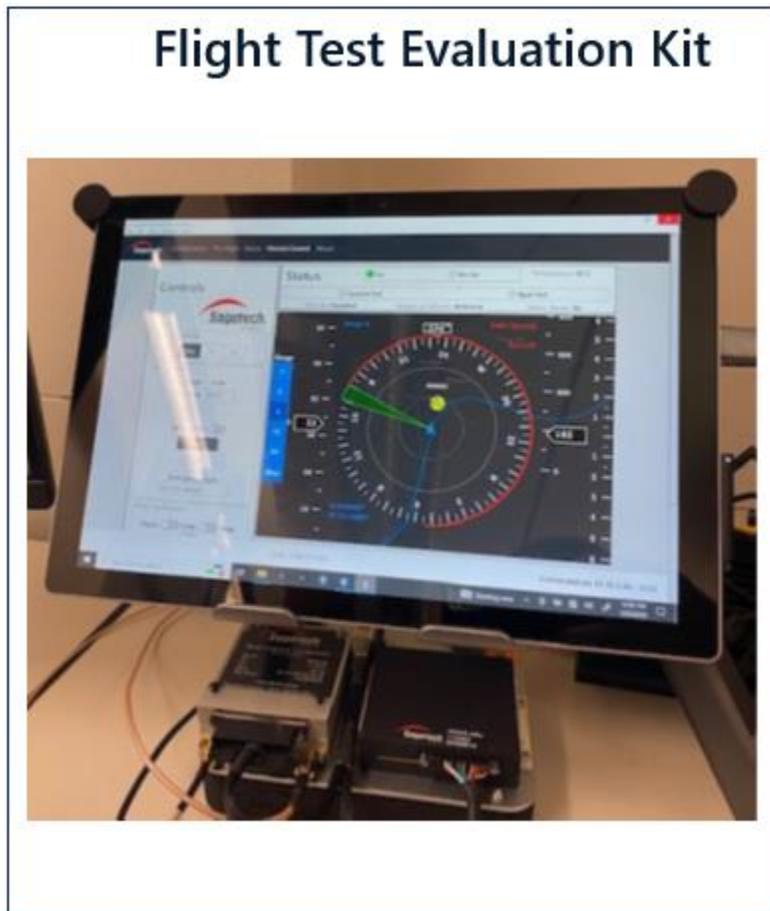

Figure 1 ACAS Xr Flight Test Evaluation Kit

B. Flight Test Events

1. Flight Test Event 1

Planned Encounter Flights

The UAS Encounter Flights were performed on Wednesday and Thursday, March 12 – 13, 2025. Flights were performed in the morning and afternoon of March 12th and in the morning of March 13th. The TigerShark UAS test aircraft departed from Griffiss International Airport in Rome, New York. The UAS test aircraft was met by the intruder

aircraft, a Cessna 172P Skyhawk to execute several runs of each of the test cards according to the flight test plan. Thirty-six total encounters were performed. The encounters were flown without any modifications (offsets, corruption, etc.) to the intruder cooperative surveillance data. The purpose of the testing was to evaluate system operation, including ADS-B validation under normal conditions.

Portland Surveillance Flight

The Portland Surveillance Flight was conducted on Friday, February 28, 2025, from approximately 2:15 – 7:00 PM (PDT). The flight departed from and arrived back at the Columbia Gorge Regional Airport near Dallesport, Washington. Surveillance data was recorded throughout the entire flight of approximately 3:45 minutes with approximately 3 hours of flight time in the Portland, Oregon area.

2. *Flight Test Event 2*

Planned Encounter Flight

The UAS Encounter Flights were performed on Wednesday and Thursday, May 13-14, 2025. The Skyshark UAS test aircraft departed from Griffiss International Airport in Rome, New York. The UAS test aircraft was met by the intruder aircraft, a Cessna 172P Skyhawk to execute several runs of each of the test cards according to the flight test plan. The testing included encounters with actual ADS-B data (latitude, longitude, altitude) received from the intruder aircraft as well as encounters where the ADS-B data was offset to determine the effect of erroneous or spoofed data on the ACAS Xr system. Thirty-six encounters were performed with the intruder aircraft. Four additional encounters were performed using a

simulated intruder. This was accomplished by flying the TigerShark over a ground-based transponder with simulated own position (latitude/longitude/altitude).

Seattle Surveillance Flight

The Seattle Surveillance Flight was conducted on Friday, May 9, 2025. The flight departed from and arrived back at the Columbia Gorge Regional Airport near Dallesport, Washington. Two landings and departures were performed at the Auburn Municipal Airport south of Seattle. Surveillance data was recorded throughout the entire flight time of approximately 5 hours and 20 minutes with approximately 3 hours of flight time in the Seattle, Washington area.

3. *Flight Test Event 3*

Planned Encounter Flights

The UAS Encounter Flights were performed on August 5 – 7, 2025. The TigerShark UAS test aircraft departed from Griffiss International Airport in Rome, New York. The UAS test aircraft was met by the intruder aircraft, a Cessna 172P Skyhawk to execute several runs of each of the test cards according to the flight test plan. Sixty-four total encounters were performed. The testing included encounters with actual ADS-B data (latitude, longitude, altitude) received from the intruder aircraft as well as encounters where the ADS-B data was offset to determine the effect of erroneous or spoofed data on the ACAS Xr system. Four additional encounters were performed using a simulated intruder. This was accomplished by flying the TigerShark over a ground-based transponder with simulated own position (latitude/longitude/altitude).

Los Angeles Surveillance Flight

The Los Angeles Surveillance Flight was conducted on Sunday, August 24, 2025, from approximately 9:30 AM – 12:40 PM (PDT). The flight departed from and arrived back at the Torrance Municipal Airport in Torrance, California. Surveillance data was recorded throughout the entire flight of more than 3 hours in the Los Angeles Basin. Ownship altitude was between three and five thousand feet and portions of the flight were over water. During the flight three approaches to minimums were also performed at the Torrance Municipal Airport.

4. *Planned Encounter Analysis*

Each of the encounters was evaluated with respect to tracking, hybrid surveillance , ADS-B validation, and ACAS Xr guidance and advisories. The evaluation consisted of various graphs (See Figure 2) and analysis that are detailed in the Flight Test Report associated with each Flight Test Event.
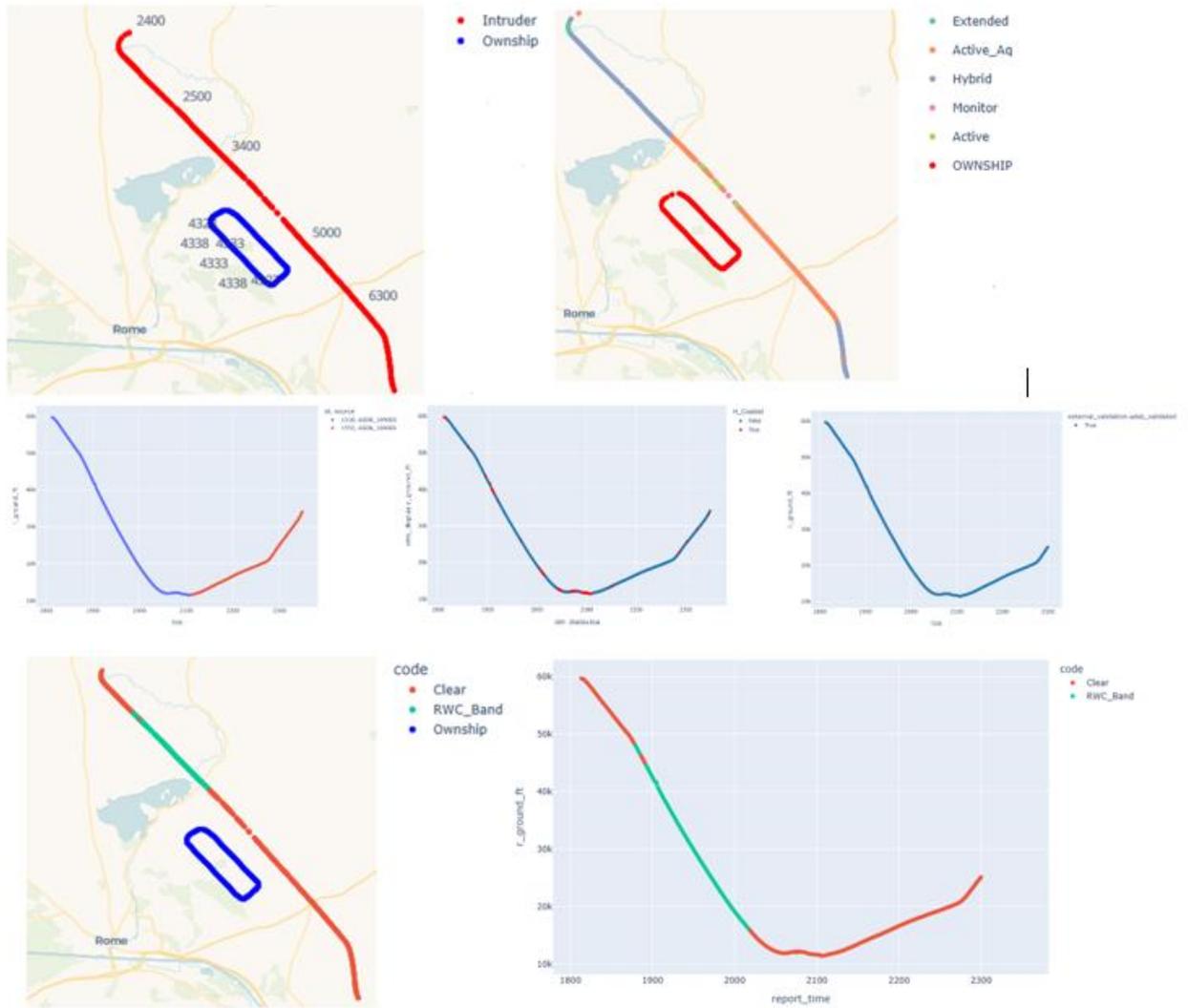
Figure 2 Encounter Description Graphs

The detailed analysis includes evaluation of track probability, hybrid surveillance transitions, success/failure of ADS-B validation, and efficient usage of active interrogations for Mode C active surveillance and Mode S active surveillance and ADS-B validation. A variety of graphs (see Figure 3) and metrics are presented in the flight test report associated with each flight test event.
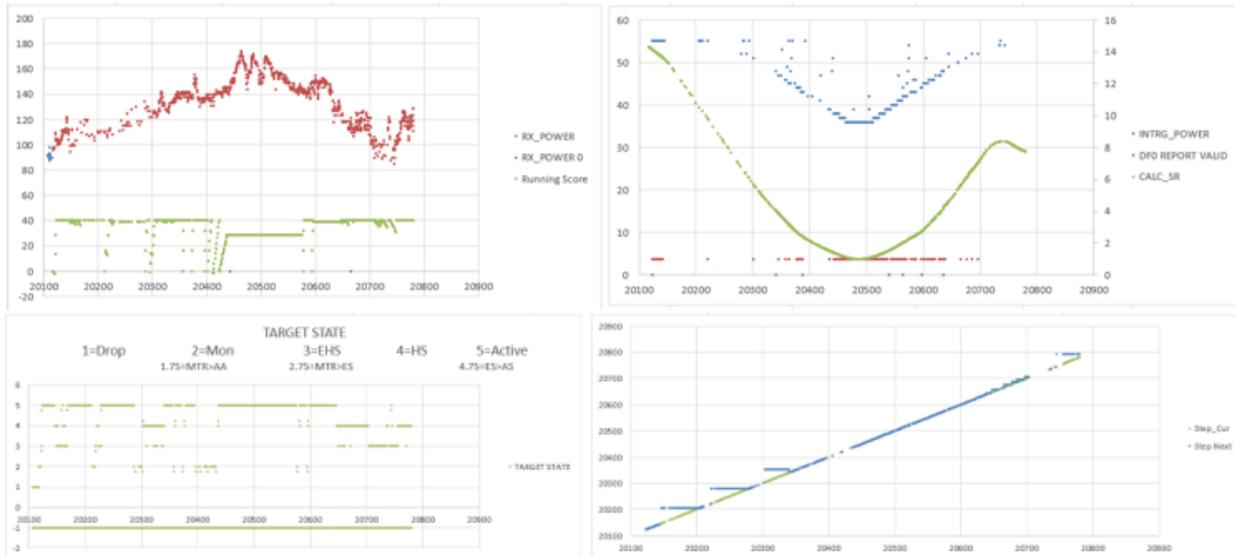
Figure 3 Hybrid Surveillance Analysis Graphs

5. *Surveillance Flight Analysis*

Mode C and Mode S track analysis were performed for each of the surveillance flights. This analysis included analysis of track probability, false tracks and overall capability of the system to accurately identify and track nearby aircraft when subjected to the rf interference and data processing complexities when operating in a high-density aircraft environment.

Graphical depictions of the reply and track data were utilized to visually analyze the system performance. Tabulated data was also utilized to determine track probability and reply probability and frequency.

The following graphs provide an example of surveillance data presented in the Flight Test Reports. These include Mode C replies overlaid with associated Mode C track data (Figure 4), Mode S replies overlaid with Mode S and ADS-B track data (Figure 5) and Mode S replies overlaid with range and altitude track data for an individual track that shows the track source (ADS-B or Mode S) and whether it is considered a target of interest for track probability evaluation (Figure 6).
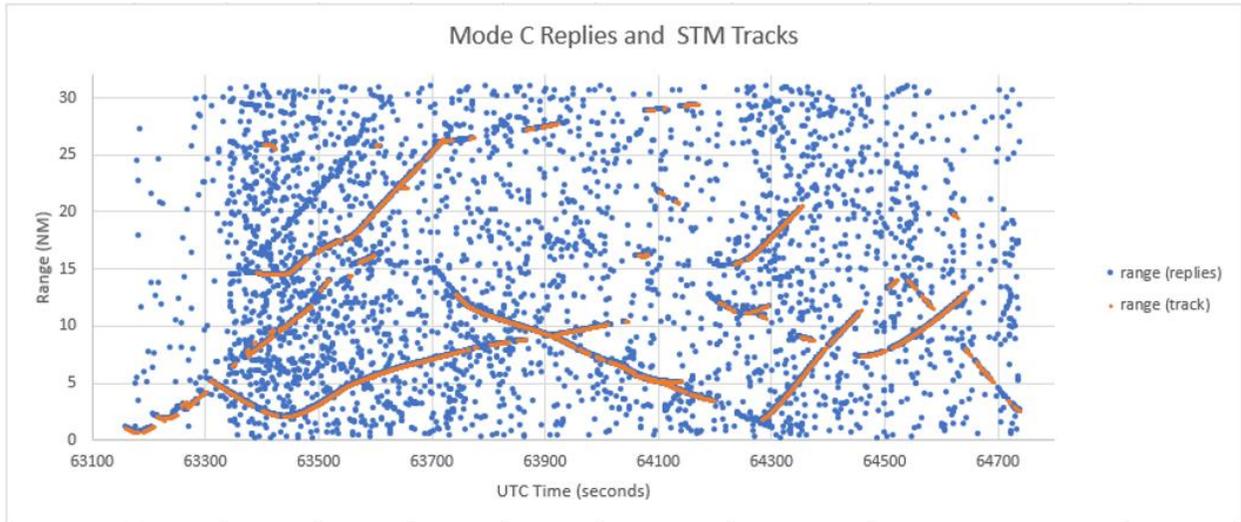
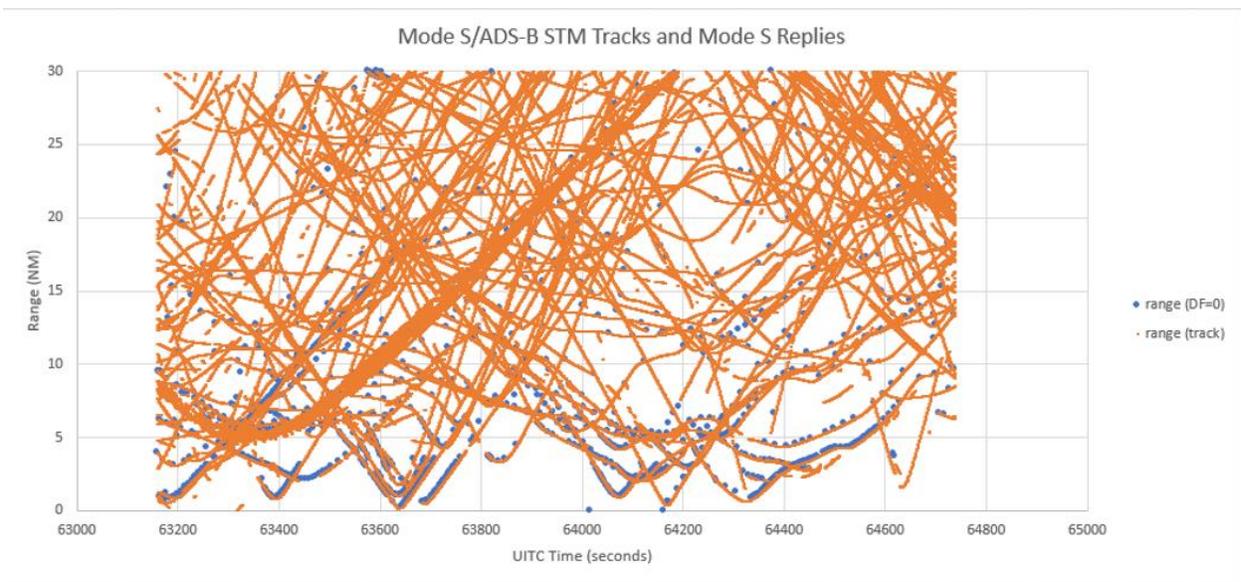**Figure 4 All Mode C Replies and Associated STM Tracks**

Figure 5 All Mode S Replies and Associated STM Tracks

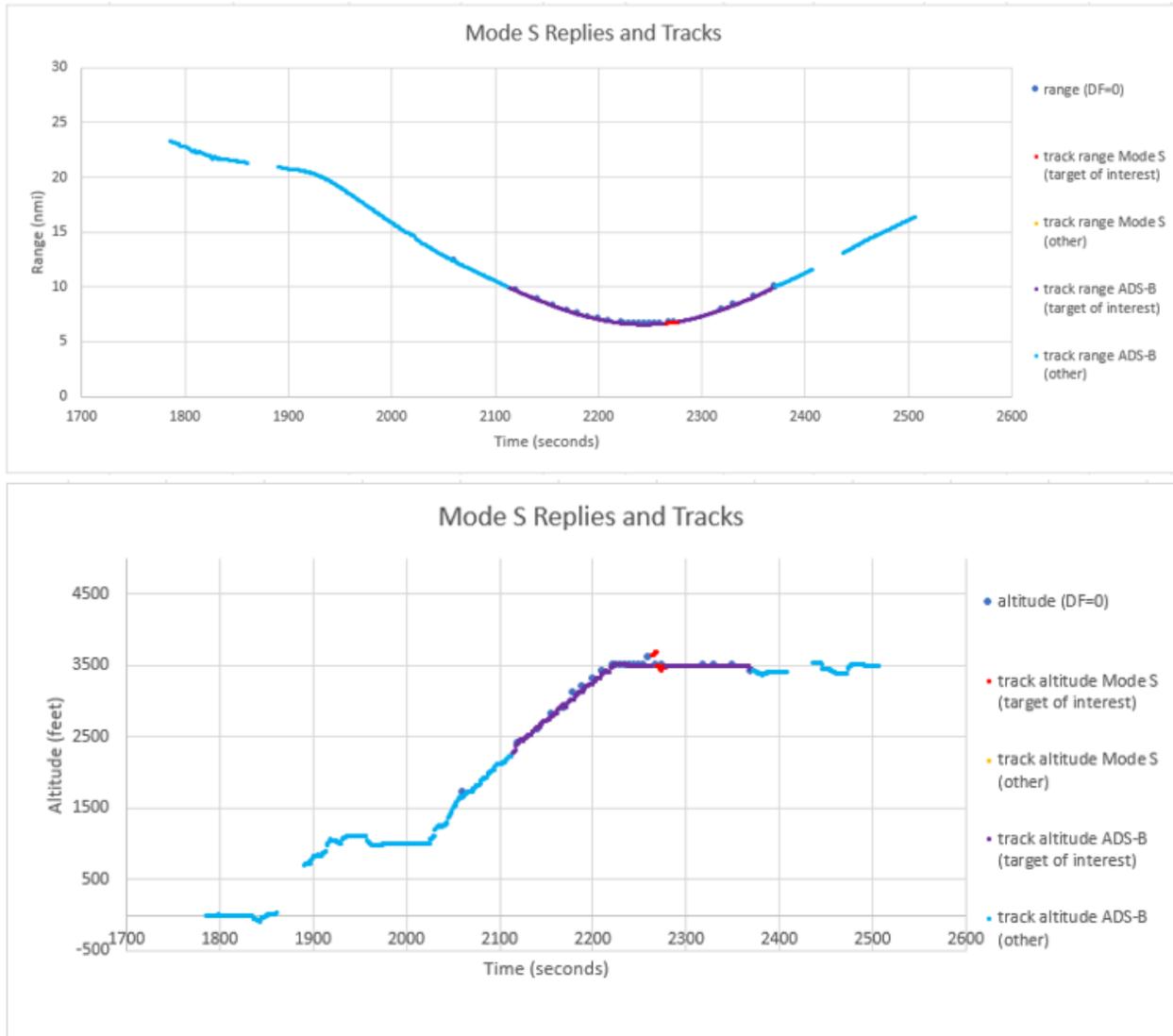**Figure 6 Individual Track (Range and Altitude) and Associated Mode S Replies**

C. Surveillance Performance

The surveillance performance was assessed from data obtained from both the encounter flights and the surveillance flights.

1. Mode C

Mode C surveillance was performed using a 23-step whisper-shout interrogation sequence transmitted from the bottom omni-directional antenna. The sequence was the same as defined for

TCAS II/ACAS X systems but eliminated the highest power interrogation to stay within the allowed power limits.

The Mode C surveillance received and processed Mode C replies appropriately, and the overall surveillance looked good. There were, however, some isolated instances of received replies that should have been correlated and tracked but were not. There were also gaps in the Mode C surveillance tracks which are common for Mode C equipped aircraft. The ADS-R data, when available filled in some of the gaps. There were no anomalies or issues observed that could be attributed to utilization of an omni-directional antenna.

The following graph provides an example of the Mode C track performance from the Los Angeles surveillance flight. The graph shows Mode S replies overlaid with track data for aircraft that are considered targets of interest in red (< 5 NM and with in 2700 ft altitude), and other tracked aircraft in yellow.
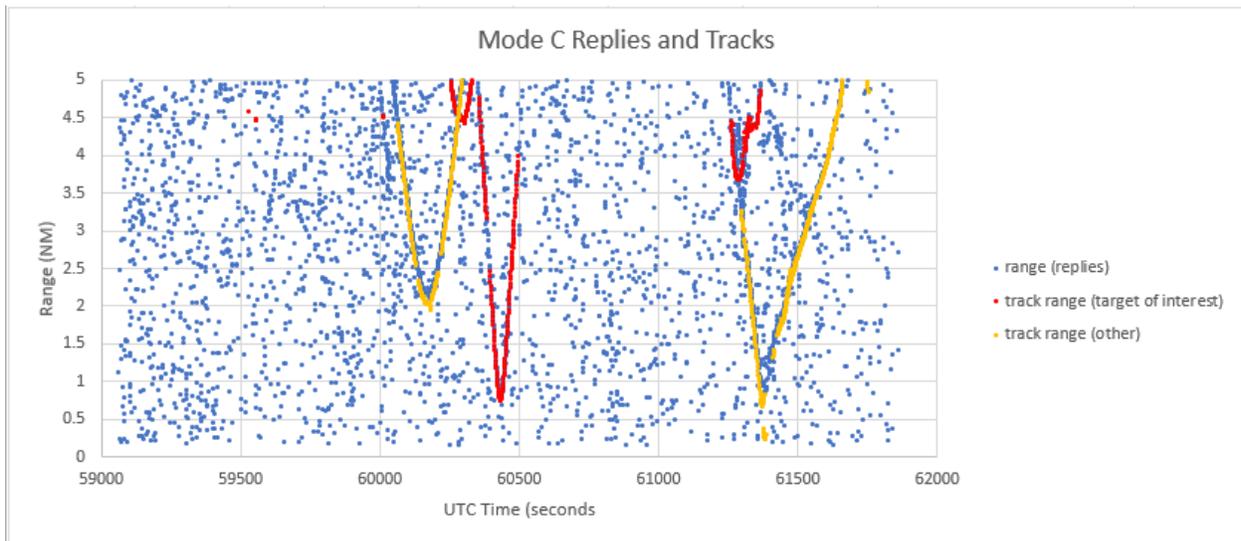

Figure 7 Mode C Replies and Tracks from Los Angeles Surveillance Flight

During this segment of approximately 2,800 seconds there were 322 track seconds for aircraft considered targets of interest. A reliable analysis of Mode C track probability and false track rate is impacted by this limited number of Mode C equipped aircraft. MOPS flight test requirements call for evaluation of 'at least 5,000 seconds of target track reports on targets-of-interest and a minimum duration of three hours.' MOPS flight test requirements should be revisited to ensure the track second requirement is reasonable.

2. *Mode S/ADS-B*

Mode S/ADS-B surveillance was implemented according to requirements for hybrid surveillance. In today's environment most aircraft are equipped with ADS-B Out which means most aircraft should be tracked passively using ADS-B position data. Mode S active replies are used to validate the ADS-B data and to track actively when ADS-B data is unavailable or does not validate.

The acquisition of Mode S replies through interrogations using the omni-directional antenna were reliable and were effectively utilized to either validate ADS-B data or actively track aircraft. The following graph shows Mode S replies overlaid with Mode S/ADS-B tracked range. The graph shows the increased interrogation/reply rate required for ADS-B validation at closer ranges and the more sporadic rate used for ADS-B validation at more distant ranges. Notice the track with continuous replies from T=60,000 (6 NM) through T=60,800 (11 NM). This is a Mode S track (no ADS-B) that is reporting 0 feet altitude (onground).
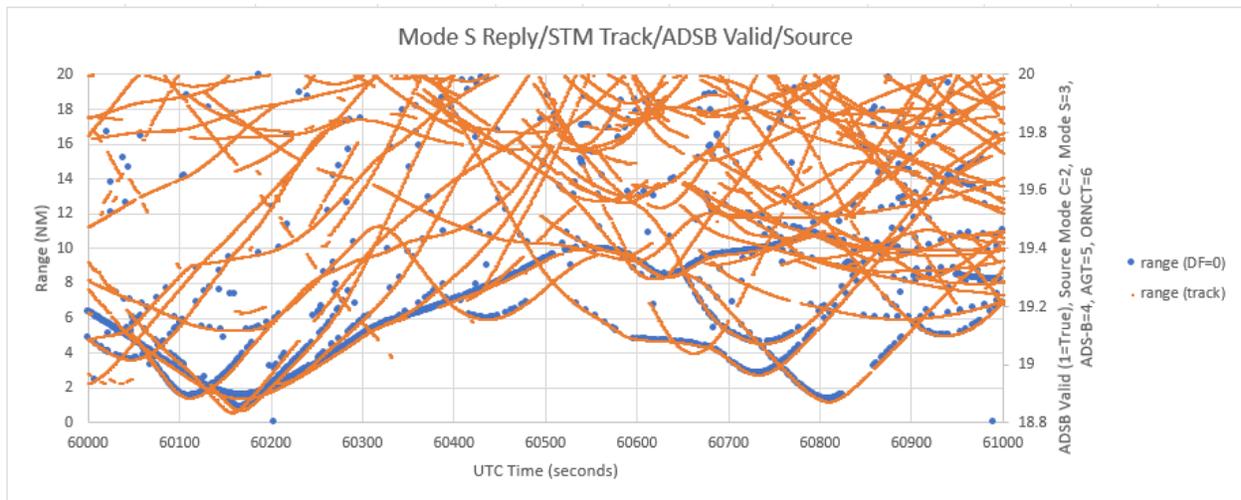
Figure 8 Mode S Reply Data Overlaid with STM Track Data from Los Angeles Surveillance Flight

There were issues with the front-end surveillance that impacted the systems transfer of ADS-B position messages to the ACAS Xr processor. This resulted in a range limitation of ADS-B tracks and allowed the ACAS Xr to detect and track, using active Mode S interrogations/replies, aircraft that were beyond the ADS-B track range of the system. Several enhancements were made to resolve this issue but with each surveillance flight test in increasing aircraft density the problem was still manifested. In the Los Angeles surveillance test the issue was primarily due to an erroneous threshold setting for active (DF=11) detection. The following graph depicts the presence of the Mode S active tracks beyond the ADS-B track range. Ideally, these active tracks would either be ADS-B passive or not even be tracked as they are well beyond the required range requirement for ACAS Xr. This issue has no impact on the surveillance analysis of aircraft within the required surveillance range required for ACAS Xr or similar systems.
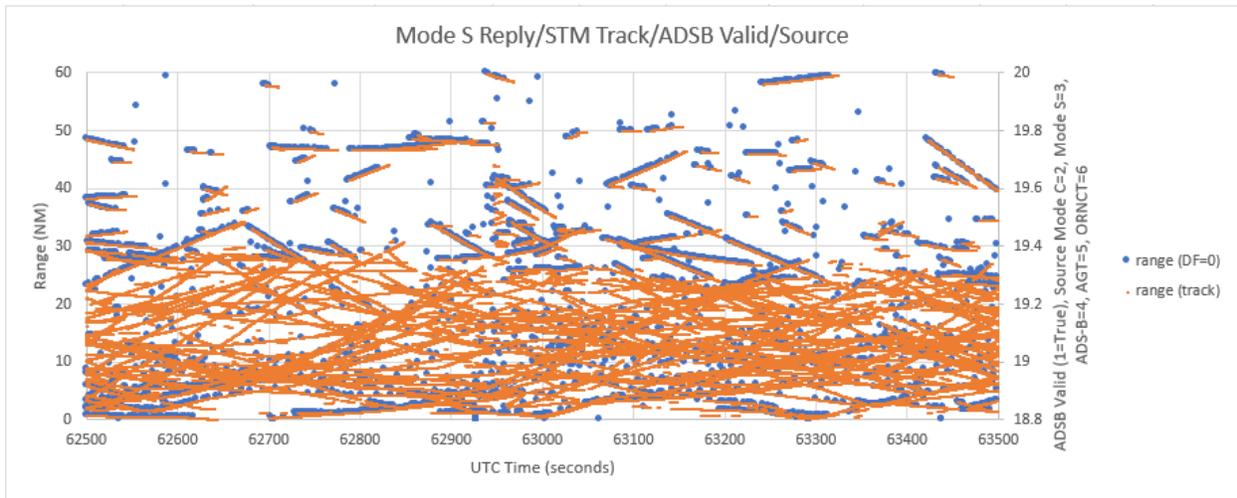
Figure 9 Example of Mode S Active Tracking at Distant Ranges (Los Angeles Surveillance Flight)

3. *ADS-B Validation*

ADS-B validation was accomplished reliably throughout the testing. Tests were performed for conditions when validation should pass and when validation should fail. The flight test reports provide detailed information regarding the validation success rate. The following graph from flight test event report 2 shows ADS-B valid while the applied ADS-B position error is -500 feet and then fails to validation when the applied ADS-B position error is 1,750 feet.

Range Validation

ACAS Xr range tracking associated with intruder.
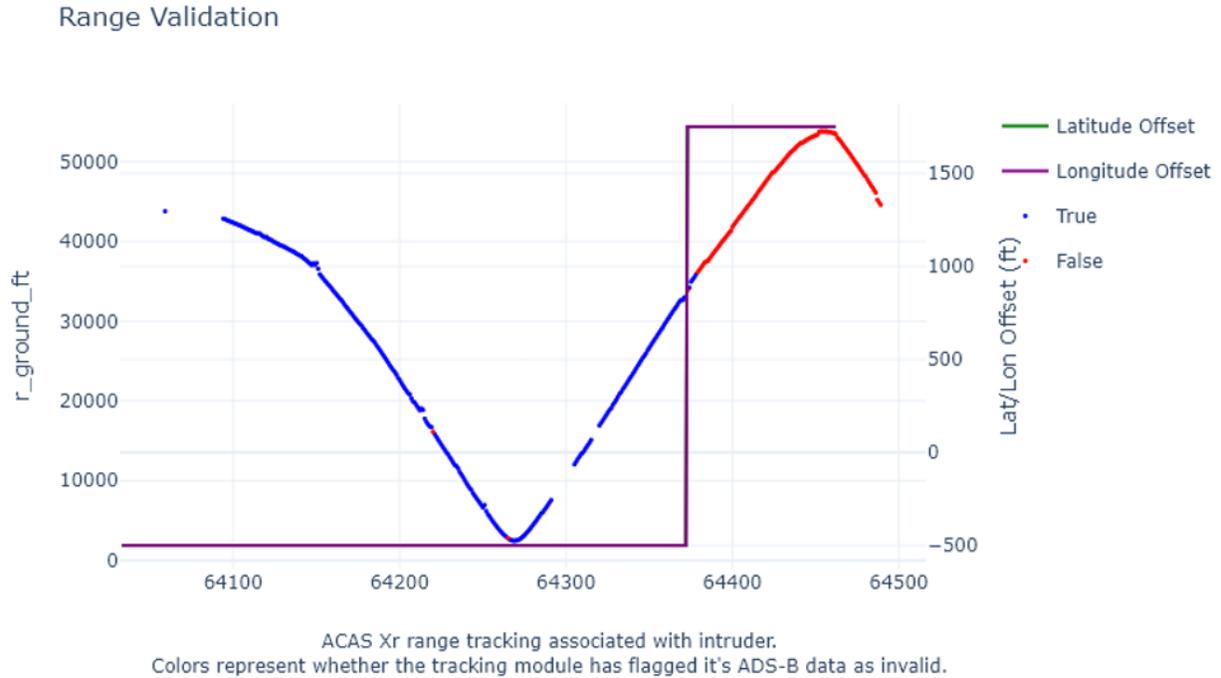Colors represent whether the tracking module has flagged it's ADS-B data as invalid.

Figure 10 Track Range With ADS-B Validation Status (Test Event 2 Encounter 14)

The test results were typically as expected with successful when validation criteria was met and failed validation when it was not met. There were some exceptions that have been summarized in section E.

D. Guidance and Advisories

The ACAS Xr records pertinent data to describe the guidance and advisories issued. In addition, a screen capture of the Mission Control GUI is saved to allow post flight evaluation of displayed traffic, RWC guidance, and Resolution Advisories. These data sources were used in preparation of the Flight Test Reports and are also archived for further analysis if needed. For each encounter the advisory 'code' was presented in graphical form (See Figure 11), showing the various levels of guidance and advisories as the intruder approached. A sequence of the displayed advisory is also provided as shown in

ACAS Xr intruder ground range shown alongside the intruders advisory code.

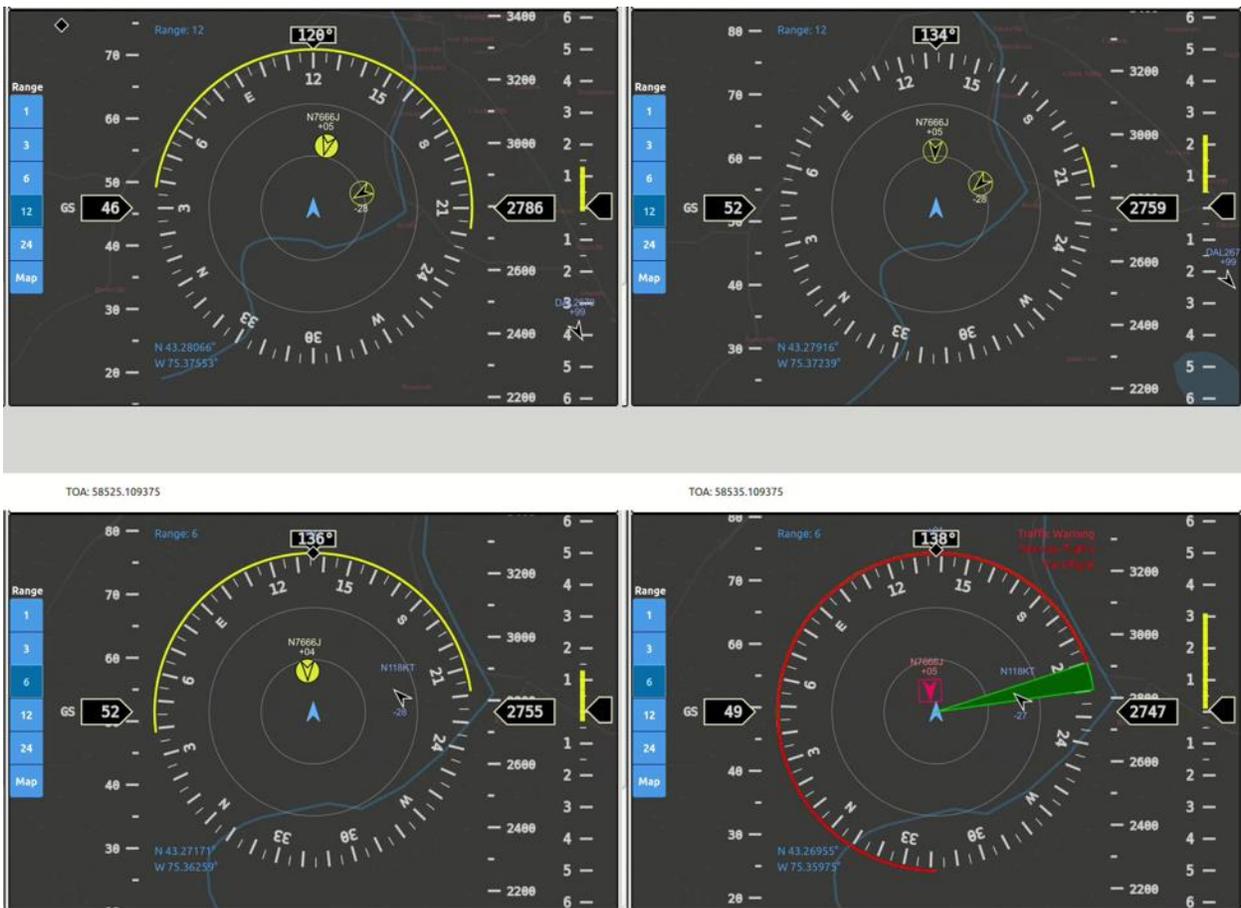**Figure 11 Example Graph of Advisory Code**

Figure 12 Mission Control GUI Display of Traffic and Advisories

Several potential issues were observed. These include:

- RWC guidance that intermittently is removed then returns after several seconds. This is apparent from the displayed guidance and confirmed in the ACAS Xr recorded display data.

- As an intruder approaches Closest Point of Approach (CPA) the horizontal RA will often reverse (Turn Left to Turn Right or vice versa). This is common among many of the test runs.

- As the intruder passes CPA the horizontal RA transitions to a Maintain Heading RA. Sometimes, this RA persists for many seconds beyond the CPA. This occurs for many of the test runs.

- There is a display issue associated with the Maintain Heading RA such that the appropriate green and red bands are not displayed on the Sagetech Mission Control GUI display.

E. Conclusion and Recommendations

Throughout the testing the ACAS Xr system demonstrated the capability to perform intended functions. There were, however, several anomalies and issues observed and further analysis of these is warranted. Additional analysis of the recorded flight data may also reveal areas of concern or with potential for improvement.

In general, it was determined that an omni-directional antenna can be utilized to provide surveillance for systems such as ACAS Xr. With exception of bearing measurements, the antenna provides similar reception capability as a directional antenna, and while bearing information is not available via direct measurement, intruder bearing can be calculated from ADS-B data which is

available for most aircraft. Issues that once required a directional antenna, such as synchronous garble of Mode C replies, have been largely overcome by the replacement of Mode C transponders with Mode S transponders on most aircraft. The availability of ADS-B data for passive tracking has also greatly reduced interference issues associated with active Mode S surveillance.

The following highlight observations from the flight testing.

Mode S Active Tracking – The system was able to accurately initiate, and track Mode S transponder equipped aircraft. The abundance of available ADS-B data reduces drastically the reliance on Mode S active tracking.

The reply to interrogation ratio appeared acceptable but could potentially be improved with an enhanced power programming algorithm, specifically with respect to retry interrogation rate and transmission power.

There were issues observed with respect to active Mode S tracking of aircraft beyond the ADS-B reception range of the system. This related to throughput issues and the Minimum Threshold Level (MTL) for reception of ADS-B and detection of Mode S equipped aircraft. This resulted in unnecessary interrogations and active tracking of aircraft at distant ranges.

Mode C Active Tracking – The system was able to accurately initiate, and track Mode C transponder equipped aircraft. There were no indications of excessive garble or interference issues. There were occurrences of multi-path reply reception and the STM appropriately recognized the multi-path and accurately tracked only the actual aircraft range.

The quantity of Mode C transponder equipped aircraft and Mode C FRUIT are drastically reduced from estimates that have been used in TCAS II and ACAS X MOPS. This presents opportunities to adapt existing interrogation sequences to accommodate the use of omni-directional antennas.

ADS-R data was sometimes received that corresponded to aircraft replying to ACAS Xr Mode C interrogations. The ACAS Xr was effective in correlating data from the two sources and displaying a single track. There were some isolated instances of received replies that should have been correlated and tracked but were not.

Hybrid Surveillance – The system accurately transitions between surveillance states, however there was considerable quick, back and forth switching between states. This should be evaluated to determine if additional hysteresis or other criteria would be beneficial.

ADS-B Data Validation (normal conditions) – According to imposed offsets of altitude, latitude and longitude the ADS-B validation was typically successful with offset within validation limits and typically failed when the offset was outside the limits (validation passes when ground range difference < 1,115 feet and altitude difference < 100 feet). There were instances, however, when validation failed even with no offset. Additional analysis is recommended to evaluate exact trigger points for both the external and internal validation criteria and determine the reason for failed validation within expected limits and assess whether requirements could accommodate improvement.

ADS-B Data Validation (offset applied) – Depending on the amount of offset applied the ADS-B data was typically validated when minimum (within validation criteria) offset was applied and was typically not validated when the offset forced the data beyond the validation criteria limits. There were, however, several instances of ADS-B data validating when the conditions for validation were not met. Additional evaluation is needed to determine if this is due to system performance issues or the result of the test data and if availability of bearing as a criterion for validation would improve results.

There is a possible mismatch between the external validation of ADS-B and the STM track indication of validated ADS-B. Validation of ADS-B data is performed by both the ACAS Xr algorithm and the front-end surveillance. The ACAS Xr considers the ADS-B data validated if either of the validation methods are successful. The data shows that often when the front-end validation fails, the data is still considered valid. This suggests that the internal validation passed even though the front-end validation failed. Further evaluation is recommended to determine how the two validation methods differ and whether the decision to accept ADS-B data when one of the methods has failed is the preferred method.

Source Selection when validation fails - There were multiple instances when ADS-B validation fails, and ADS-B is still selected as the track data source. While this may be appropriate if no other source is available, it may be appropriate to select Active Mode S as the source when active Mode S is available and ADS-B validation has failed. Additional analysis is recommended to ensure correct source selection and ensure availability of active Mode S data when ADS-B data has failed. This could also be an area for requirements enhancement to ensure active Mode S tracking is appropriately invoked when ADS-B validation has failed.

Alerting and Guidance – Throughout testing ACAS Xr guidance and alerting was observed and evaluated. Several potential issues were identified including 1)guidance that was unclear and perhaps unnecessary, 2) RWC horizontal bands that were split, and 3) alerts on intruders that had ample separation or were not moving toward own aircraft. These observations were shared with the FAA TCAS Program Office and improvements have been considered for future versions of the ACAS Xr software.

Recommendations1

The following list provides recommendations to ensure and enhance appropriate ACAS Xr system performance.

1) Ensure appropriate requirements and testing for active Mode S tracking at distant ranges. Requirements and testing should ensure surveillance is not allowed to actively track Mode S equipped aircraft at distant ranges, particularly in high density airspace. This can happen if ADS-B data is limited due to track capacity or threshold settings and may result in unnecessary transmission of Mode S interrogations.

2) Evaluate instances of received Mode C replies that possibly should have been correlated and tracked but were not.

3) Possible enhancement to Mode S power programming. Mode S power programming is intended to reduce 1030 MHz interference by reducing the power or interrogations to aircraft that are within 10 NM. Enhancement of the existing requirements may provide a more efficient method that reduces retry interrogations.

4) Review hybrid surveillance state transition requirements and ensure appropriate hysteresis is applied to limit excessive and unnecessary transitions between states.

5) ADS-B validation criteria including compatibility between STM (internal) and front-end surveillance (external) validation and whether incorrect validation could have benefited from availability of bearing. Recommend a review of the requirements and STM implementation to ensure validation using either method is similar and compatible. This should include a review of validation criteria and requirements for validation retries when only one method fails validation.

6) Evaluate ADS-B track drops. There were many instances of ADS-B data drops out unexpectedly throughout the testing. Some of this may be due to the geometry between the aircraft and placement of the antennas. Further evaluation is needed to determine root causes and propose corrections or enhancements as needed.

7) Reconsideration of Interrogation rate when in the active surveillance region. Mode S equipped aircraft are interrogated at a 1 Hz rate whenever they are within the active surveillance region (60 seconds to within 3 NM and 4500 ft vertical separation). Although these interrogations are at lower power due to Mode S power programming, they still represent a significant percentage of overall Mode S interrogations. Reducing the rate may be further limit interference without compromising system safety.

8) Reevaluate flight test requirements for cooperative surveillance evaluation, particularly with respect to the number of track seconds that need to be evaluated for both Mode C and Mode S surveillance.

9) Evaluate ACAS Xr guidance and advisories

   ACAS Xr guidance and advisories were sometimes confusing or seemed unnecessary or inappropriate. Some of these issues have already been addressed and fixes incorporated into ACAS Xr V5. It is recommended that V5 testing be performed to verify corrections and further ensure that advisories are correct and appropriate. Some issues include:

   - Seemingly unnecessary (nuisance) advisories
   - RA switching between intruders (Resolved in ACAS Xr Version 5)
   - Horizontal reversals at Closest Point of Approach
   - RWC guidance (blinking) that is displayed, goes away for several seconds, then returns.

- Maintain Heading RA that persists after intruder aircraft has passed by.

10) Flight test evaluation using ACAS Xr version 5. All testing was performed using ACAS Xr version 4. Now that version 5, which includes corrections and enhancements, is available, evaluation is needed to verify improvements and ensure continued compliance.

F. References

1) Flight Test Plan for Airborne Omni-Directional Surveillance Project, Document number PLN07177 Revision B

2) Data Analysis Plan for Airborne Omni-Directional Surveillance Project, Document number PLN07165 Revision -

3) Flight Test Event 1 Report for Airborne Omni-Directional Surveillance, Document number PLN07181 Revision -

4) Flight Test Event 2 Report for Airborne Omni-Directional Surveillance Project, Document number PLN07200 Revision A

5) Flight Test Event 3 Report for Airborne Omni-Directional Surveillance Project, Document number PLN07202 Revision -