Unmanned Aircraft Systems (UAS)
Broad Agency Announcement (BAA)

Call #005

Final Report

Project Title:
Reliable Robotics Ground-Based Detect and Avoid (GBDAA)

Company Name:
Reliable Robotics

UAS Test Site:
Virgina Tech Mid-Atlantic Aviation Partnership (MAAP)

Contract Period of Performance:
September 2024 through September 2025

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Executive Summary

The Reliable Robotics Ground-Based Detect and Avoid (GBDAA) project is a FAA Broad Agency Announcement (BAA) project to assess a GBDAA system in the terminal environment, including the use of Airborne Collision Avoidance System Xr (ACAS Xr) for collision avoidance.

A comprehensive Detect and Avoid (DAA) solution capable of operations through all phases of flight remains a critical gap to the commercial operation of UAS in both controlled and uncontrolled airspace. Consensus technical standards for DAA have matured substantially and the version of DO-365 in development will provide the industry with a comprehensive DAA system. The DO-365C Class 6 architecture, which uplinks tracks from GBSS to an airborne DAA processor to ensure seamless transition from enroute to terminal area environments, has not been validated. Under the FAA BAA a Reliable Robotics Cessna 208B was operated to collect flight test data at and around Hollister Airport (KCVH) through both en-route and terminal airspace. Flight testing included several intruder aircraft to fully test the GBDAA system and the ACAS Xr avoidance logic.

The overarching goal of this project is to collect data on the performance of the DAA system and critical subsystems to inform the validation of consensus-based standards. This is broken into four main objectives:

1. Collect and analyze GBSS tracks to inform validation of RTCA DO-381A
2. Analyze performance of GBSS tracks uplinked to airborne DAA processor through a DO-362A-representative Control and Non-Payload Communication (CNPC) datalink to inform validation of RTCA DO-365C Class 6 equipment
3. Collect and analyze ACAS Xr alerting and guidance to inform development of RTCA SC-147 MOPS for ACAS Xr and updates to DO-365 to include Class 4 equipment
4. Collect and analyze omnidirectional SSR tracks to inform development of RTCA SC-147 MOPS for cooperative surveillance

GBDAA System

The system under test comprised an optionally crewed Reliable Robotics Cessna C208B Caravan and a prototype GBDAA system. The GBDAA architecture integrated a Collins Skyler radar, Reliable Robotics' ground control systems, and airborne components including the Sagetech DAA processor running ACAS Xr v4. Cooperative and non-cooperative traffic data were fused from onboard and ground-based sources, with communications managed via the uAvionix C-Band CNPC radio. Testing involved both crewed and uncrewed intruder aircraft, a Cessna 182 and a DJI Inspire 2 sUAS, respectively.

Summary of Testing

Test planning centered on the development of realistic, repeatable encounter scenarios designed to challenge ACAS Xr's alerting logic across a range of geometries and operational contexts. Encounters were categorized as En-Route, Boundary, or Terminal based on their location relative to the DAA Terminal Area (DTA), and were executed using scripted test cards to ensure safe separation while provoking well clear violations. A total of 56 encounters were flown over eight test days at Hollister Municipal Airport, with 52 deemed successful at achieving the desired closest point of approach. Crewed and sUAS intruder encounters were flown live. The sUAS encounters required the radar track altitudes to be manipulated to simulate conflicts due to regulatory separation constraints. Data was collected from all system components, including GBSS, airborne and ground segments, and participating aircraft, and was supplemented by pilot surveys.

Data Analysis

Analysis was performed on all data collected, and a number of artifacts were generated. These artifacts are included in the data package included with this report. Each artifact type is detailed below by folder name.

- Flight Test Encounter Reports provide metrics and overviews of each encounter and behavior of ACAS Xr Alerting and Guidance. One report is provided per encounter.
- uAvionix Link Reports provide metrics and overviews of performance of the uAvionix C-Band CNPC uplink of GBSS tracks. One report is provided per day of testing.
- Remote Pilot Surveys provide direct feedback of ACAS Xr alerting and guidance from the remote pilot for each encounter.
- Sagetech Mode C analysis provides logs from the ACAS device and charts for comparison of different track sources
- ACAS Xr Ground Truth Error Calculations provide quantitative metrics and plots for performance of ACAS provided tracks compared against ground truth logs.
- Skyler Analysis provides quantitative metrics and plots for performance of GBSS tracks against recorded ADS-B data.

Conclusions and Recommendations

Objective 1: GBSS Performance

Test results showed that both Skyler Radars meet Collins provided accuracy requirements for performance of range and azimuth error metrics. Elevation requirements were not generally met. Unknown causes of lost tracks decrease confidence in the system as a whole. Some tracks provided over a testing day have shown that the radars reliably track the target aircraft over the course of its flight path within its boundaries, but other tracks, even those well within the same boundaries of farther targets, are lost and dropped from recorded tracking with no clear reason for their absence. Suggestions are made to limit tracks to within a conforming installation's declaration volume, and to consider requirements or suggested methods for the required feature of time synchronization between GBSS systems and airborne systems.

Objective 2: C-Band CNPC Datalink Performance

The C-Band CNPC link performed well throughout the campaign. The system functioned with low uplink latency well within the 1000ms latency requirement of DO-377. The average link continuity performance did not meet Reliable's internally derived requirement for link continuity, but came close, especially when exercised on flight paths without identified link dropout regions. It is suggested that C-Band CNPC link installations should include comprehensive link characterization testing as a part of installation.

Objective 3: ACAS-Xr Alerting and Guidance

The ACAS Xr system provided an appropriate course of action to maintain safe separation in only 67.7% of considered encounters. Across encounters determined to require intervention, guidance was determined to be provided too late in 25.8% of cases. It is hypothesized that the degraded performance in some encounters is a result of the poor performance of the Mode C Omnidirectional SSR tracks. In regards to the DAA display, suggestions are made to consider traffic display elements for bearingless tracks, and to consider options to mitigate issues resulting from the conversion between bearing/range relative positions and absolute positions.

Objective 4: Omnidirectional SSR

Review of encounter reports shows range error in thousands of feet and altitude error in hundreds of feet across the majority of encounters. Many encounters either do not have any track which can be associated with the intruder aircraft, or only a small segment of the encounter where a track was provided. Further development work is suggested to improve performance of SSR Mode C tracks.

Future Testing

Reliable expects that many of the recommendations provided will require further HITL or flight testing as a part of solution space exploration, investigation and/or resolution verification. There are also a number of upcoming opportunities for HITL and flight testing for ACAS X DAA integrations and updates. With the capability set developed over the course of this contract, Reliable Robotics intends to continue working with its partners to pursue testing efforts.

Version History

Version #	Revision	Date
1.0	Draft Release	09/05/2025
2.0	Final Release	09/22/2025

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1.0 Introduction

1.1 Purpose

The Reliable Robotics Ground-Based Detect and Avoid (GBDAA) project is a FAA Broad Agency Announcement (BAA) project to assess a GBDAA system in the terminal environment, including the use of Airborne Collision Avoidance System Xr (ACAS Xr) for DAA Well Clear (DWC) and Collision Avoidance (CA) functions. This report is the final report of the project and presents the overall project and the results gathered during flight testing.

1.2 Background

A comprehensive Detect and Avoid (DAA) solution capable of operations through all phases of flight remains a critical gap to the commercial operation of UAS in both controlled and uncontrolled airspace. Reliable Robotics has demonstrated the remotely piloted operation of a Cessna C208B Caravan without any people onboard (i.e., operated as a UAS), but has not applied for a certification project, in part, because several key technologies have not been validated. Consensus technical standards for DAA have matured substantially and the version of DO-365 in development will provide the industry with a comprehensive DAA system, specifically: Class 4 (ACAS Xr-based) (or 3 ACAS Xu-based) and 6 (GBSS) with a Class 5 (Terminal Area alerting and guidance) capability. The DO-365C Class 6 architecture, which uplinks tracks from GBSS to an airborne DAA processor to ensure seamless transition from enroute to terminal area environments, has not been validated.

Under the FAA BAA a Reliable Robotics Cessna 208B was operated to collect flight test data at and around Hollister Airport (KCVH) through both en-route and terminal airspace. To achieve this, flights were conducted in transition into the DAA Terminal Area for KCVH. Existing and notional Instrument Approach Procedures (IAPs) were flown for the two runways at KCVH through appropriate missed approach points with an intruder aircraft placed at various locations to test nominal alerting behavior and transitions through the DTA.

This report will also outline the inclusion of a Cessna-182 along with a sUAS to further test DAA functionality on different targets of opportunity. Test cards were designed to collect data with varying angles and distances of separation. Test cards consisted of a mixture of overtaking, crossing, head on, and converging intruder / ownship geometries, along with varying altitudes on different glide slopes for the encounters. The sUAS used in this test was flown within the bounds of Part 107, in adherence to local and federal laws. The sUAS utilized a radar reflector to increase likelihood of a radar track at the further altitude offset of the Cessna 208B along with the smaller target of opportunity.

Flight testing was performed over a four week period beginning Aug 4th 2025 and concluding Aug 28th 2025. Flight tests occurred on August 6, 8, 11, 13, 14, 18, 25 and 28th.

1.3 Project Objectives

The overarching goal of this project is to collect data on the performance of the DAA system and critical subsystems to inform the validation of consensus-based standards. This is broken into four main objectives:

1. Collect and analyze GBSS tracks to inform validation of RTCA DO-381A
2. Analyze performance of GBSS tracks uplinked to airborne DAA processor through a DO-362A-representative Control and Non-Payload Communication (CNPC) datalink to inform validation of RTCA DO-365C Class 6 equipment
3. Collect and analyze ACAS Xr alerting and guidance to inform development of RTCA SC-147 MOPS for ACAS Xr and updates to DO-365 to include Class 4 equipment
4. Collect and analyze omnidirectional SSR tracks to inform development of RTCA SC-147 MOPS for cooperative surveillance

In addition to the above objectives, several key topic areas have been identified for investigation by the RTCA SC-228 and SC-147 working groups:

- SC-228 (DO-362, DO-365, DO-381):
  - Transition from Airborne Surveillance to/from Ground-based Surveillance
  - Transition into DAA Terminal Area
  - Validate Test Procedures for Class 4/6 System
    - Inform which of the test procedures are best suited for live flight
  - End-to-End Latency and performance (e.g., continuity) from GBSS Sensor to Airborne DAA Processor through CNPC
    - How does the Reliable Robotics integrated system compare to requirements?
- SC-147 (ACAS Xr):
  - Collect flight data on ACAS Xr version 4
  - Collect omnidirectional secondary surveillance radar (SSR)

2.0 Methodology

2.1 System Overview

2.1.1 Test Aircraft

2.1.1.1 Ownship

The ownship aircraft was the optionally crewed aircraft that was equipped with the DAA system. For all testing the ownship was the Reliable Robotics Cessna C208B Caravan, shown in Figure 1.

Figure 1. Reliable Robotics C208 in flight.

2.1.1.2 Intruders

During testing two different intruders were utilized. For most test points a crewed intruder was utilized. The crewed intruder was a contracted Cessna 182. Figure 2 shows an image of the intruder. The intruder aircraft was equipped with UAT ADS-B out and Mode C transponder equipment. This equipment set exercises the GBSS and Mode C SSR data collection objectives of the contract, as ACAS Xr considered Mode C replies to be higher integrity than unvalidated ADS-B replies. As such, when no GBSS Absolute Geodetic Track (AGT) data is available to associate to a track, ACAS Xr will provide the intruder track as a Mode C. When there is GBSS data to validate the track, the source will be provided as AGT.

Figure 2.Cessna 182 crewed intruder N71298
Image sourced from www.the111th.com

The sUAS intruder was provided and operated by the Virginia Tech (VT) Mid-Atlantic Aviation Partnership (MAAP). The sUAS aircraft was a DJI Inspire 2 that can be seen in Figure 3. The Inspire 2 was equipped with a 9sqm radar reflector underneath to increase its visibility to the GBSS radar. The sUAS was not equipped with an ADB-B out transponder.

Figure 3. DJI Inspire 2's base configuration

2.1.2 GBDAA System Overview

The system under test consisted of an optionally crewed aircraft (with safety pilot onboard), DAA system and supporting ground infrastructure. The overall system architecture is shown in Figure 4. The major subsystems of the system under test are the Collins Skyler Radar, Reliable Robotics ground infrastructure and the Reliable Robotics airborne system.

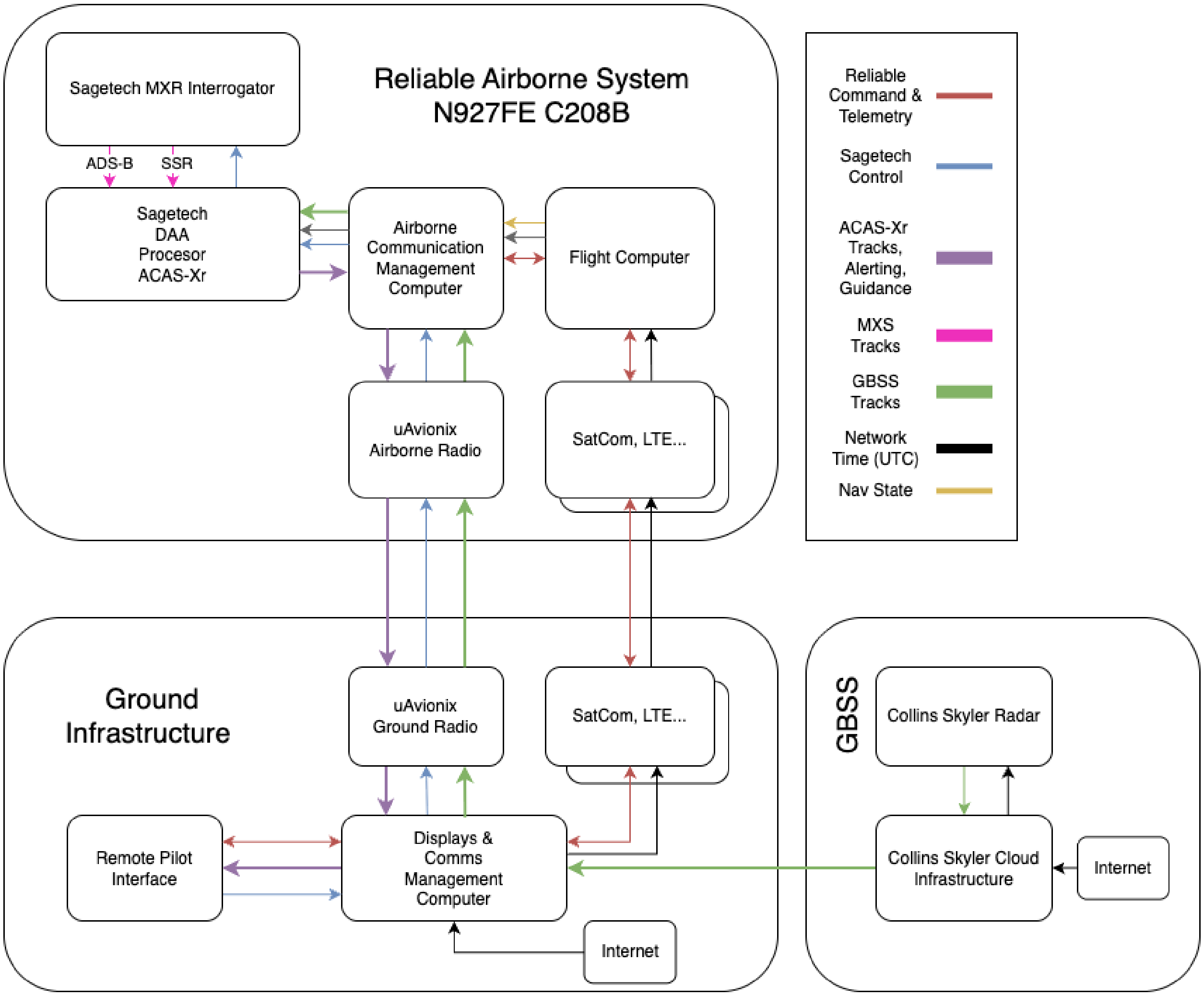

Figure 4. System diagram for the GBDAA system under test.

2.1.2.1 Collins Skyler Radar System (GBSS)

The Skyler Radar is a DO-381A representative Ground-Based Surveillance System (GBSS) radar. Skyler radars are installed in both San Martin and Gilroy, California, giving a coverage volume of Hollister airport and approaches for each runway. This system publishes tracks to the SkylerCloud system.

SkylerCloud is a cloud-based server giving centralized gRPC protocol subscription model access to any number of connected Skyler radar systems. Reliable subscribed to the San Martin and Gilroy installations on its Ground Displays & Communications Management Computer to receive tracks from each Skyler radar to uplink to the Airborne DAA Processor.

2.1.2.2 Reliable Robotics Ground Infrastructure

The Reliable Robotics Ground Infrastructure includes the ground computers and the associated communication links with the aircraft. The Ground Displays & Communications Management Computer handles communication links to the airborne system and aggregates data for display to the remote pilot. This system manages and utilizes the following communication links:

- uAvionix C-Band CNPC - This link is a DO-381A prototype CNPC link that is used exclusively for DAA command and telemetry during this campaign.
- Satcom (Iridum, Inmarsat) - Satcom links are used as the primary command and telemetry links for the Reliable Robotics system.
- LTE - LTE is used as an engineering data only link for the Reliable Robotics system.

GBSS tracks that are received from the SkylerCloud system are encoded into Absolute Geodetic Track (AGT) format. Each track is prioritized by the criteria in DO-365C, assigned a Universally Unique Identifier Designation (UUID), and the 10 highest priority tracks each second are passed to the uAvionix interface for uplink to the airborne system.

The ground infrastructure also includes the remote pilot interface.

Remote Pilot Display

The Remote Pilot Interface is a comprehensive graphical user interface that provides pertinent data to the remote pilot and functions as the command & control interface. The display is made up of three panels: System health & aircraft status, traffic map, and control.

ACAS-Xr alerting and guidance has been integrated into the traffic map as traffic icons and guidance bands. Alerting and guidance is downlinked from the airborne system over the uAvionix data link, then parsed and translated into display elements for the remote pilot. The traffic map is North-up, and requires use of ownship telemetry to convert between relative bearing and range information provided in intruder tracks to absolute position for display on the traffic map. Note that the traffic map on Reliable's Remote Pilot display has no provision for text based display. DO-365C requires a text readout for bearingless tracks, which as such is not currently implemented on the Remote Pilot display.

2.1.2.3 Reliable Robotics Airborne System

The Reliable Robotics C208B is nominally equipped with all required systems for full OPA operation, and has previously been flown without a pilot onboard. For this campaign, additional equipment was added to integrate the DAA system, detailed below. Note: Reliable's Airborne System has full redundancy across all existing systems (Airborne Communication Management Computer, Flight Computer). The DAA system was installed and operational on the primary system, and Reliable performed all operations for this campaign on the primary system. Note that the DAA system was not integrated with the flight control system, and had no authority over changes to airspeed, heading, altitude or otherwise.

Airborne Communication Management Computer

Similar to the Ground Displays & Communications Management Computer, the Airborne Communication Management Computer manages communication links and aggregates data. The system serves as a link between the flight computers and comms links and serves as a link between these systems and the DAA processor. The Airborne Communication Management Computer logged all messages received from all systems with a timestamp from its internal clock.

Sagetech DAA Processor

The Sagetech DAA Processor is a prototype of Sagetech's future Airborne DAA Processor product. This system was running ACAS-Xr v4. This system is provided cooperative tracks from the MXR interrogator and non-cooperative tracks from the uplinked GBSS AGT tracks.

Sagetech MXR Interrogator

The Sagetech MXR Interrogator provides Mode C/S and 1090 MHz ADS-B in, along with omnidirectional SSR. The MXR interrogator does not provide ADS-B OUT and does not reply to interrogation by other systems.

2.1.3 C2

Several data and command links were used during testing:

Flight Computer Data Link

For command and telemetry to Reliable's flight computers handling autonomy, two satellite links and a LTE link were used for communication. These exist as a part of Reliable's existing OPA configuration and are not used as a part of this campaign.

DAA System Data Link

The uAvionix C-Band data link was used for communication between the DAA system and the Reliable's ground systems. uAvionix installed permanent ground radios at San Martin airport and Hollister airports for this campaign. The Hollister airport ground station was used exclusively for this campaign. Reliable used uAvionix's Skyline interface for link management.

2.2 Overview of ACAS Xr

ACAS Xr is a member of the ACAS X family of algorithms developed in partnership between the FAA and MIT's Lincoln Laboratories. The system under test utilized ACAS Xr version 4, running on the Sagetech DAA Processor. The DAA Processor was fed cooperative traffic data from the onboard Sagetech MXR interrogator (Mode C/S and 1090 MHz ADS-B) as well as non-cooperative tracks from the Collins Skyler GBSS. The GBSS tracks were uplinked to the aircraft as Absolute Geodetic Tracks (AGT) over the C-Band CNPC datalink.

A key capability evaluated during this project was ACAS Xr terminal area function, which uses a modified set of DAA Well Clear (DWC) parameters to operate effectively in the denser, lower-speed airspace around an airport. Within the DAA Terminal Area, the DWC volume is defined with a smaller horizontal miss distance (HMD) of 1,500 ft (compared to 4,000 ft en-route) and a modified tau of 0 seconds (compared to 35 seconds en-route).

2.3 Hollister Airspace

2.4 Test Method

The primary testing was done via live flight encounters performed over a four week period beginning Aug 4th and concluding Aug 28th. During encounter testing the ownship flew the instrument approach procedures (IAPs) and the intruder flew a predetermined route to cause a conflict with the ownship.

Two different test setups were used based on the intruder being tested. For a crewed intruder (described in Section 2.6.1), the encounter was planned to either violate DAA Well Clear or cause a potential WC violation. The intention was to cause a resolution advisory (RA) to be sent to the ground operator. Shortly after each closest point of approach (CPA), the safety pilot onboard the ownship would take control of the vehicle and maneuver in coordination with the intruder pilot to deconflict. Given that the onboard safety pilot handled deconfliction maneuvering, the remote pilot was instructed to not maneuver based on the RA, and instead was asked to record what they would have done in remote pilot encounter surveys.

For a sUAS intruder (described in Section 2.6.2), safety and regulatory limitations required a larger separation between the two aircraft. To account for this, the radar tracks of the sUAS were modified by the system prior to sending them to the ownship. The tracks were modified to force a WC violation and subsequent RA. The sUAS testing was limited to one RNAV approach and encounter geometry due to limits on the sUAS flight and the need to ensure there is a consistent and reliable radar track of the sUAS.

2.4.1 Test Location and Personnel

All testing occurred at and around Hollister Municipal Airport (KCVH) in Hollister, California, shown in Figure 5. Two different ground radars were used during testing. One was set up in Gilroy, CA and one was set up in San Martin, CA.

Tests consisted of 7 personnel across 2 aircraft and the Reliable Robotics Remote Command Center (RCC) in Mountain View, CA.

- Ownship Reliable Autonomy System (RAS) & DAA equipped 208B Caravan 927FE Aircraft
    - Safety Pilot
    - Flight Test Engineer (FTE)
- Intruder 182 N71298 Aircraft
    - Pilot
    - Flight Test Engineer (FTE)
- Remote Command Center
    - Remote Pilot / Remote Test Director (RTD)
    - Mission Commander (MC)
    - Scribe

During flight testing the ownship utilized the instrument approach procedures for KCVH. This provided a realistic approach path for the aircraft to use and provided a reproducible baseline for encounters. KCVH has two runways: runway 13/31 and runway 6/24. Runways 13/31 have established RNAV IAPs. For runways 6/24 no RNAV IAPs have been established so notional ones were created by NASA for use in this project.

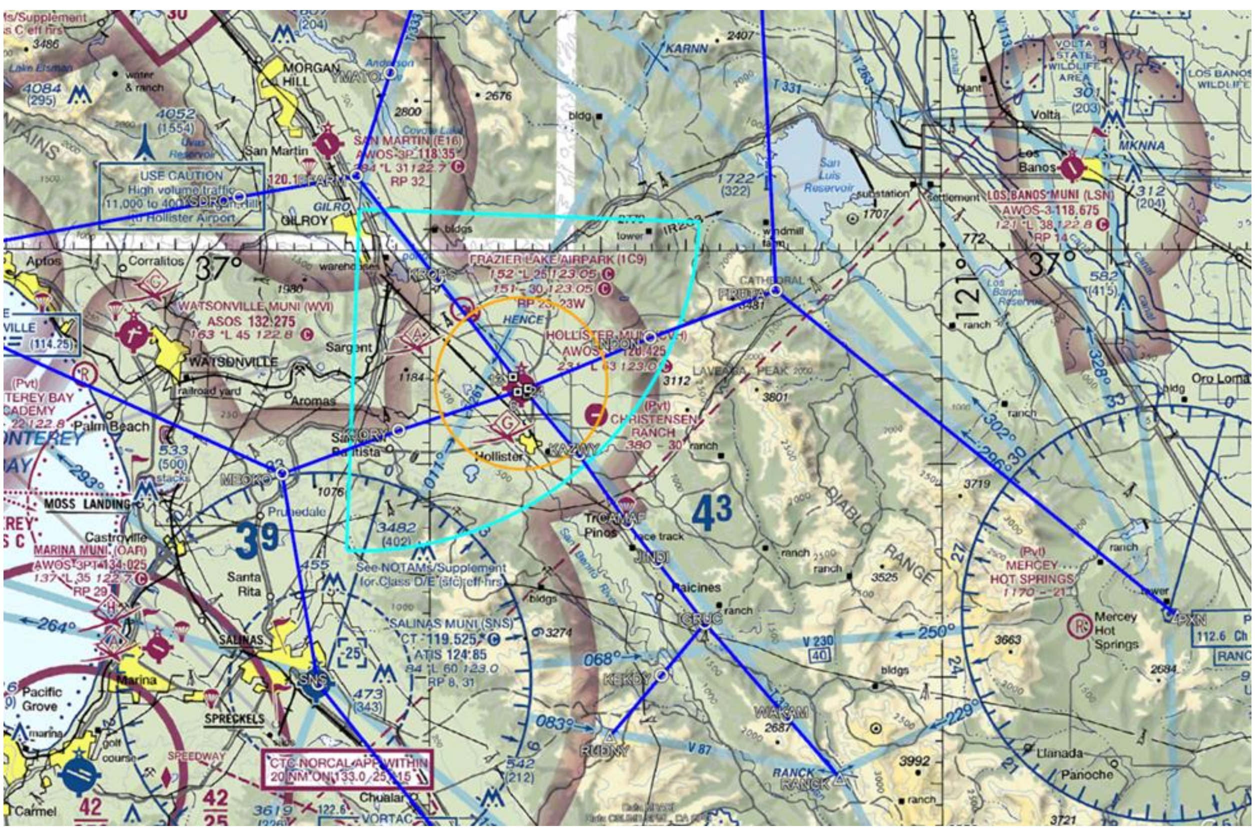

Figure 5. Test area around Hollister Municipal Airport (KCVH). The DAA Terminal Area (DTA) around KCVH is shown in orange. The GBSS surveillance volume is shown in cyan. All four instrument approaches are shown in dark blue.

2.4.2 DAA Terminal Area Definition

The DAA terminal area (DTA) was defined based on recommendations found in Appendix C of DO-365. The recommended DTA radius is 4-5 nautical miles with an altitude above the typical turbine VFR traffic pattern and below the typical Class D airspace height. For Hollister the DTA was set to 4 nautical miles with an altitude ceiling of 2,000' AGL. The lower radius was chosen as the runways at Hollister are smaller than the NASA study that produced the 4-5 NM range, which should result in smaller traffic patterns. The ceiling altitude was set to be between the turbine traffic pattern (1,500') and below the standard class D altitude (2,500').

2.4.3 Encounter Design

The encounters were designed to be realistic of the airspace and to sample the design space of ACAS-Xr. When designing the encounters it was assumed that the ownship would fly the instrument approach and the intruder would fly pre-determined paths to cause a predicted conflict.

Due to the changing logic of ACAS-Xr's alerting inside or outside of the DTA meant that encounters challenging the appropriate switching behaviour around the DTA boundary were of particular interest.

Encounter sets were generated for all the instrument approaches and were divided into three categories: En-Route, Boundary and Terminal. These were used to test ACAS-Xr inside, outside and near the edge of the DAA Terminal Area. Table 1 shows the breakdown of the test cards. The encounter sets were also designed to test different encounter geometries as shown in Table 2.

Table 1. Breakdown of test card types by intruder and ownship location.

		Intruder	
		In DTA	**Outside DTA**
Ownship	**In DTA**	Terminal Test Cards (TC10 - TC12)	Not tested
	Outside DTA	Boundary Test Cards (TC6 - TC9)	En-Route Test Cards (TC1 - TC5)

Table 2. Breakdown of test cards by encounter geometry.

Encounter Type	Test Cards
Head-On	1, 6, 12
Overtaking	3, 5, 7, 8

Crossing	4, 9, 10, 11
Converging	2

The DWC definitions used by ACAS-Xr are shown in Table 3 as described in DO-365C. Encounters were planned to have a predicted WC violation, but safe separation between the test aircraft must be maintained. It was determined that by utilizing scripted test cards the two aircraft could have an actual closest point of approach of 2,500 feet horizontally. For encounters outside the DTA this is sufficient to cause a DAA well clear violation. For encounters inside the DTA the flight paths were designed to show a predicted DAA well clear violation, however the aircraft will maneuver and stop the encounter before maintaining at least 2,500 feet of separation.

Table 3. DAA Well Clear Parameters.

	En Route Well Clear	Terminal Well Clear
Vertical Displacement	450 Feet	450 Feet
Modified Tau	35 Seconds	0 Seconds
Horizontal Miss Distance	4000 Feet	1500 Feet

2.4.4 Test Cards

From these encounter sets, detailed test cards were made for each encounter. An example test card is shown in Figure 6.

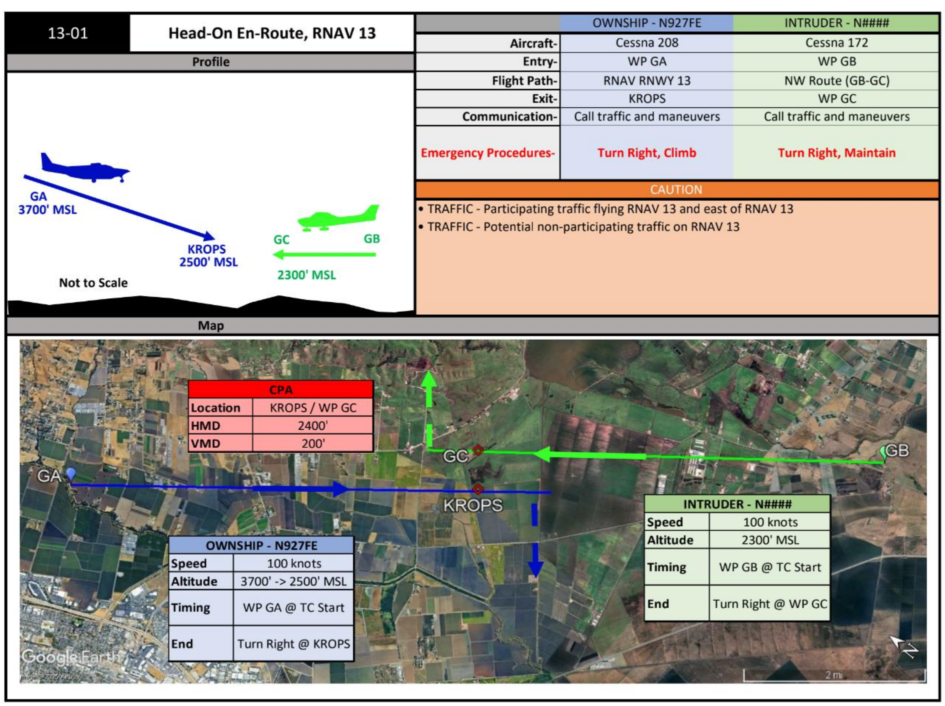

Figure 6. Example test card showing card #13-01.

Similarly, the sUAS test cards were designed as seen in Figure 7.

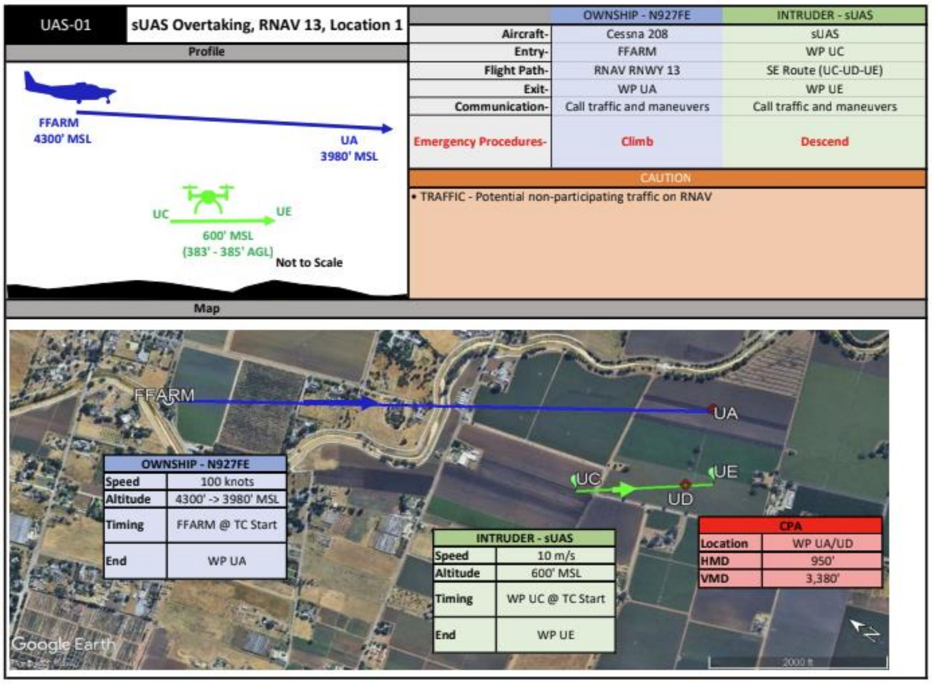

Figure 7. Example sUAS test card showing card UAS-01.

Like many of the crewed intruder test cards that all shared 12 nearly identical encounter geometries, the sUAS test cards also had two sets of similar test cards. Flexibility was needed in this regard due to the sUAS' requirement to fly under Part 107 which could be affected by both ground and air traffic at the primary site.

Test cards UAS-01 and UAS-02 were designed to operate at the primary flight location where the sUAS would have been located approximately four nautical miles away from the San Martin ground-based radar. Test cards UAS-01 and UAS-02 represented an ownship overtake of the sUAS and a head-on approach of the two aircraft, respectively. Test cards UAS-03 and UAS-04 then represented the same encounter geometries only at a different flight location approximately 1.75 nautical miles further south of the San Martin radar installation.

2.5 Data Analysis Plan (DAP)

The data collection plan for the flight testing is outlined in the Data Analysis Plan document, but is summarized here. To meet the objectives of the project, several data metrics were identified, shown in Table 4. Further details on data analysis can be found in the Data Analysis Plan deliverable.

Table 4. Flight test data metrics and sources.

Data Metric	Source	Responsible Party
GBSS Track Logs	Skyler Cloud	Collins
Ground Based ADS-B Logs	Skyler Cloud	Collins
Ground Based ADS-B Logs	FAA ADS-B Receivers	FAA/Reliable
Ground GBSS Messages	Display & Comms Computer	Reliable
Ground Received ACAS Alerting & Guidance	Display & Comms Computer	Reliable
Airborne Received GBSS Messages	Airborne Comms Computer	Reliable
Airborne ADS-B Messages	Sagetech DAA Processor	Sagetech
Airborne SSR Messages	Sagetech DAA Processor	Sagetech
ACAS Alerting and Guidance Messages	Airborne Comms Computer	Reliable
DAA Equipped Aircraft Navigational State	Airborne Comms Computer	Reliable
Participating Aircraft Position Data	Onboard Data Logger	Reliable
Remote Pilot Display Video Recording	Remote Pilot Display Computer	Reliable
Remote Pilot Survey	Survey	Reliable

2.6 Hardware-in-the-Loop (HITL) Testing

Hardware-in-the-Loop (HITL) testing was conducted by Reliable Robotics to validate the GBDAA system prior to live flight testing. The HITL setup replicated the full flight hardware configuration, integrating simulated intruder aircraft. These tests were designed to evaluate the system's alerting behavior and ensure readiness for live flight trials.

Overall results from the HITL testing were positive, but did reveal several issues that were addressed prior to live flight. The two largest issues addressed during HITL testing were:

- Reevaluation of Boundary and Terminal Area Test Cards - Several test cards, especially in the boundary and terminal areas did not trigger the correct alerts during HITL testing. Two additional Terminal Area test cards were created to fly encounters with a closer CPA in the terminal area.
- Addressing remaining Sagetech device issues - Several issues with the Sagetech ACAS-Xr device were identified, including startup instability, delayed alerting, and limitations in processing multiple intruder inputs. These have since been addressed by Sagetech. All HITL tests have been re-run with fixes implemented.

2.7 Flight Testing

Flight testing was performed over a four week period beginning Aug 4th and concluding Aug 28th. Flight tests occurred on August 6, 8, 11, 13, 14, 18, 25 and 28th. In total 56 encounters were performed. An initial assessment of all encounters showed that 52 of these encounters sufficiently meet criteria to be considered successful, while the other 4 had CPAs that were outside of our prescribed tolerances due to timing.

Test cards were split into en-route, terminal and boundary based on the transition into the DAA Terminal Area (DTA). Encounters were performed on the 13, 06 and 31 RNAV approaches. Due to traffic in and around the airport during testing the decision was made by the flight test and operations team to omit the 24 RNAV approach. The breakdown of encounters flown by encounter type and RNAV approach is shown in the tables below.

Table 5. Encounter totals by encounter area and RNAV approach.

Encounter Area	RNAV Approach			TOTAL
	13	31	06	
En-Route	5		9	**14**
Boundary	14		4	**18**
Terminal		17	7	**24**
TOTAL	**19**	**17**	**20**	

Table 6. Number of encounters by encounter type.

Encounter Type	Number of Encounters
Head-On	17
Crossing	14
Overtaking	21
Converging	4

For each encounter, the ownship and intruder aircraft time calls at predetermined CPA points were used to determine if the test point was flown successfully in real-time. ADS-B data was used as an auxiliary live source for test point success. Post-flight analysis was performed on positional logs to compute realized CPA metrics.

2.6.1 Crewed Intruder Flight Testing

Crewed intruder testing was performed on August 6, 8, 11, 13, 18, 25 and 28th. All crewed testing utilized a Cessna 182 intruder. 50 test points were completed in a crewed configuration.

Before testing each day, preflight checkout procedures for the Reliable Autonomy system, DAA system, and aircraft were performed. DAA system preflight checks confirmed subsystem health and healthy communication, not necessarily normal function. After the successful completion of the preflight procedures, crew briefings were held for all personnel involved with the operation to run through the test card selections for the day and brief any pertinent information (NOTAMS, weather conditions, etc.). Completion of checkouts and the crew brief were followed by final aircraft checks and ferry flights from Reliable Robotic's hangar in San Martin to the Hollister airspace to begin testing.

After completing testing for the day and returning to base, a debrief meeting was held each day to assess the completion of the test points and capture actions to be resolved before the next day of flight testing. After this debrief, logs would be collected from each aircraft and uploaded to a fileshare server for post-flight analysis.

2.6.2 sUAS Intruder Flight Testing

sUAS intruder testing was performed on August 14 and was flown by MAAP. A total of five test point attempts were made with four deemed acceptable to count towards the final tally. A location was selected for the flight that was along the RNAV 13 approach and in close proximity to the San Martin Skyler installation.

The sUAS intruder is limited to flying under 400' AGL. To bring the encounter close enough in altitude between the ownship and the intruder aircraft along the RNAV approach into runway 13, a simulated 3600' vertical altitude offset was applied to all Skyler tracks on the day of testing.

Due to heavy ground traffic on the day of testing near the identified location for UAS-01 and UAS-02 test cards, UAS-03 and UAS-04 were performed.

During the first attempt at test card UAS-03, the sUAS experienced high winds at its target altitude, 379' to 385' AGL. After returning to base, the decision was made to remove the radar reflector to allow for safe operation in the higher winds. Continuing on without the radar reflector, an additional two attempts at UAS-03 were then made with acceptable timing at the CPA before moving on to test card UAS-04.

The first attempt at test card UAS-04 resulted in an abort, however, due to unaffiliated traffic in the path of the ownship. The ownship was able to communicate with the other traffic and clear the airspace before another attempt was made. A second attempt was completed as both aircraft again reached their CPAs with appropriate timing. It was at this time the decision was made to end testing for the day after four good sUAS points were captured; three at UAS-03 and one at UAS-04.

3.0 Data Analysis

3.1 Methods

3.1.1 Encounter Log

The Encounter Log contains a list of all encounters flown, with test card #, timing information, Test Card CPA and Measured CPA. These are duplicated in the Flight Test and Data Collection daily reports.

3.1.2 Encounter Reports

Reliable has developed tooling to take logs from flight testing and generate graphical analysis reports. For each encounter flown, one report has been generated. Details are expanded on below.

3.1.2.1 Primary data sources for encounter plots

Data for these plots is aggregated from 4 different sources:

- Recorded ownship state from Reliable Systems
    - Ownship position & velocity vectors
    - System time (UTC time)
- Recorded intruder state from GPS logger onboard 182 intruder vehicle
    - Intruder aircraft position & velocity vectors
    - UTC time
- Recorded alerting and guidance messages received from Sagetech ACAS device
    - Display reports:
        - Relative guidance bands
        - System time (UTC time)
    - Intruder reports:
        - Intruder alert status
        - Estimated relative state
            - Relative altitude
            - Range
            - Bearing
            - Relative velocities
        - Selected data source
        - System time (UTC time)

3.1.2.2 Computed metrics

From these primary data sources, computed metrics are derived. These metrics are derived by aligning time sources between logs and computing metrics that are combinations of different log sources:

- Estimated absolute intruder state
    - Source: ownship state log, estimated intruder relative state log
- Ground truth intruder relative state
    - Source: ownship state log, intruder ground truth log
- DAA Terminal Area Ownship State
    - Source: ownship state log, KVCH DAA Terminal Area definition
- Terminal Area Intruder State
    - Source: ground truth intruder state log, KVCH DAA Terminal Area definition
- Intruder reports track selection
    - Intruder reports received from the ACAS device with an ICAO address that matches the 182 intruder aircraft were considered to represent the intruder aircraft. These reports were assigned an "ICAO" track selection source.
    - Not all intruder tracks that pertain to the 182 intruder aircraft were received with an ICAO address. To associate non-ICAO-address tracks, all tracks received from the ACAS device were compared against ground truth data in time alignment, relative altitude, and range. Tracks from the ACAS device with sufficiently low error were considered to represent the intruder aircraft. These reports were assigned an "Position" track selection source.

- Ground Truth DWC Criteria from Appendix C.5 Mathematical DWC Definition in DO-365C
    - Range
        - Source: ownship state log, intruder ground truth log
        - (Same as ground truth intruder relative state)
    - DMOD
        - Source: ground truth intruder relative state, DO-365C Table 2-25 Parameters for Enroute DWC Alerting Requirements, DO-365C Table 2-26 Parameters for Terminal DWC Alerting Requirements
    - Closing Rate
        - Source: ownship state log, intruder ground truth log
    - Modified Tau
        - Source: ownship state log, ground truth intruder relative state, Appendix C.5 Mathematical DWC Definition
    - Modified Tau Threshold
        - Source: ground truth intruder relative state, DO-365C Table 2-25 Parameters for Enroute DWC Alerting Requirements, DO-365C Table 2-26 Parameters for Terminal DWC Alerting Requirements
    - Horizontal Miss Distance (HMD)
        - Source: ownship state log, ground truth intruder relative state, Appendix C.5 Mathematical DWC Definition
    - Horizontal Miss Distance Threshold

        - Source: ground truth intruder relative state, DO-365C Table 2-25 Parameters for Enroute DWC Alerting Requirements, DO-365C Table 2-26 Parameters for Terminal DWC Alerting Requirements
    - Vertical Separation
        - Source: ownship state log, ground truth intruder relative state, Appendix C.5 Mathematical DWC Definition
    - Vertical Separation Threshold
        - Source: ground truth intruder relative state, DO-365C Table 2-25 Parameters for Enroute DWC Alerting Requirements, DO-365C Table 2-26 Parameters for Terminal DWC Alerting Requirements

3.1.2.3 Common Symbology

Across plots and pages of the reports, common plotting colors and symbology are kept consistent for easy comparison.

- Ownship state is plotted with colors mapping to traffic alert status. Color mapping is listed below:
    - None: Dark Blue
    - Guidance Alert: Green
    - Corrective Alert: Yellow
    - Warning: Red
- Intruder ground truth state is plotted with a black dashed line
- Estimated intruder state as is plotted with a pink dashed line.
- Closest Point of Approach (CPA) is marked with an orange star, and an orange dashed time axis line.
- Ownship Terminal Area Crossing is marked with a cyan "plus" icon, and a cyan dashed time axis line.

3.1.2.4 Report Page 1

The first page of the encounter report includes encounter metrics and 2D top-down plot. An example report page 1 is shown in Figure 8.

<u>Encounter Metrics</u>

- Ownship Aircraft: Identifies the primary aircraft undergoing testing (e.g., C208 N927FE).
- Intruder Aircraft: Identifies the intruder aircraft during flight testing (e.g. C182 N71298).
- Horizontal Separation at Closest Point of Approach (CPA) (ft): The minimum horizontal distance between the ownship and intruder at their Closest Point of Approach (CPA), measured in feet.
- Vertical Separation at Closest Point of Approach (CPA) (ft): The minimum vertical distance between the ownship and intruder at their CPA, measured in feet.

- Max Closing Speed (ft/s): The maximum rate at which the ownship and intruder were approaching each other, measured in feet per second.
- En-Route Cooperative DWC Breached: Indicates whether the cooperative DAA Well Clear (DWC) criteria was breached during the enroute region of the encounter. A "True" value signifies a breach.
- Terminal DWC Breached: Indicates whether the terminal area DWC criteria was breached during the encounter. A "True" value signifies a breach.
- Duration (s): The total duration of the recorded encounter, measured in seconds.
- Time Range: The specific UTC timestamp range during which the encounter occurred.
- Alert Types: Lists the types of alerts for the intruder during the encounter (e.g., Warning, Guidance, None, Corrective).

2D Top Down Plot

The 2D plot follows the color/symbology convention detailed in the Common Symbology section above. In addition to those conventions, the plot includes the following specific elements:

- Trajectory start and end are marked by triangles aligned to direction of flight.
- Relevant waypoints from the test cards are plotted as purple squares with labels.

Flight Test: HITL Convergence at Fix, RNAV 31
Date: 2025-06-23

Encounter Metrics

Ownship Aircraft	**C208 N927FE**
Intruder Aircraft	**C178 Nxxx**
Horizontal Separation at CPA (ft)	**3722.25**
Vertical Separation at CPA (ft)	**41.70**
Max Closing Speed (ft/s)	**207.53**
En-Route Cooperative DWC Breached	**True**
Terminal DWC Breached	**False**
Duration (s)	**209.90**
Time Range	**2025-06-13 21:38:25 - 2025-06-13 21:41:55**
Alert Types	**Warning, Guidance, None, Corrective**

2D Top-Down Plot

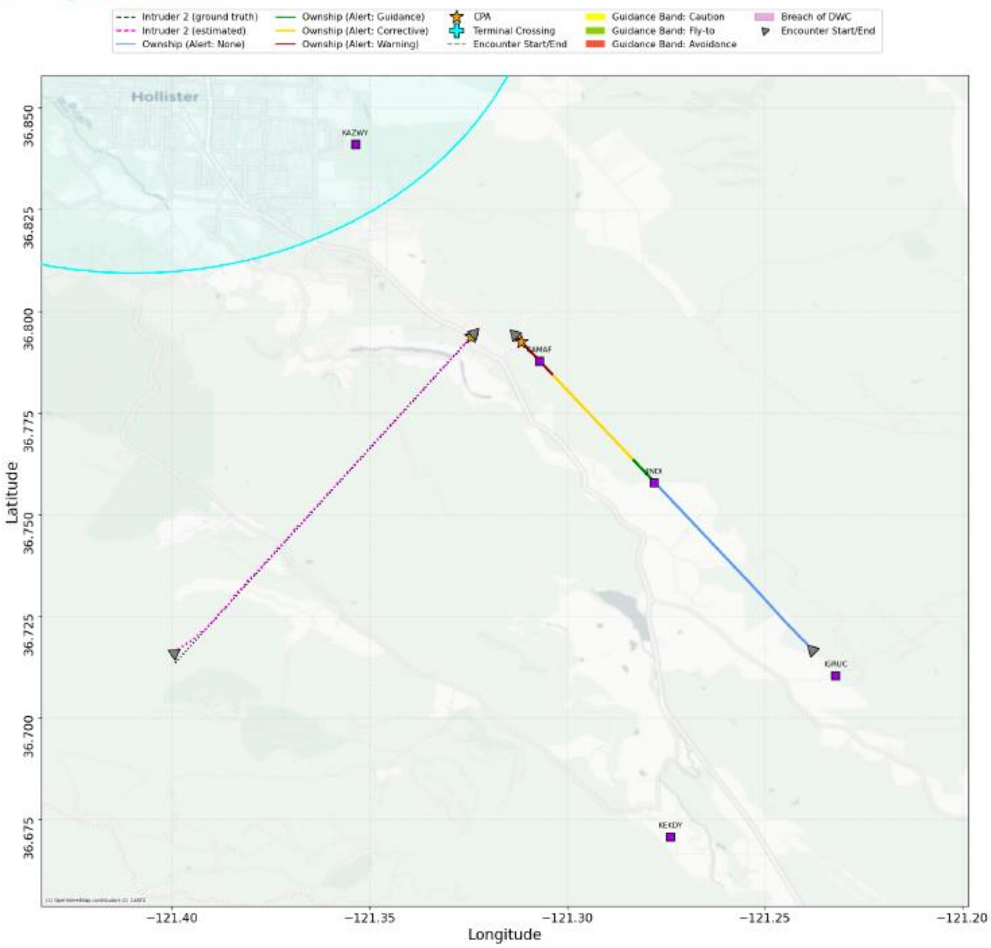

Figure 8. Example Report – Page 1.

3.1.2.5 Report Page 2

The second page of the encounter report includes a variety of plots including altitude, vertical speed, bearing and DAA well clear plots. An example report page 2 is shown in Figure 9.

Altitude, Vertical Speed, Bearing, Range plots

The Altitude, Vertical Speed, Bearing and Range plots follow the color/symbology convention detailed in the Common Symbology section above. In addition to those conventions, the plot includes the following specific elements:

Guidance Bands as received from the ACAS Device are overlaid onto the plot:

- Caution Band: Yellow
- Fly-To Band: Green
- Avoidance Band: Red
- Altitude, Vertical Speed, Bearing, RangePlots

Track Source plot

The Track Source plot reports the track source received from the ACAS device. Note that this source is selected by the ACAS-Xr algorithm as the highest integrity source from all received/associated sources. See ACAS-XR ADD TrackSourceSelection (Algorithm 223). For the equipment onboard the intruder aircraft, the possible options are one of 2 sources:

- Absolute Geodetic Track (AGT) (GBSS source).
    - This source indicates the validation of the onboard ADS-B out equipment with an AGT track.
- Mode C
    - ACAS Xr considers Mode C SSR tracks to be higher integrity than unvalidated ADS-B reports, so in absence of a GBSS AGT track, the intruder will have a Mode C track.

Match Method plot

As detailed in the intruder reports track selection item in the Computed Metrics section, intruder report tracks are associated with the intruder aircraft for plotting from either “ICAO” address source or “Position” source. This plot reports the method used to select the intruder report track used for plotting.

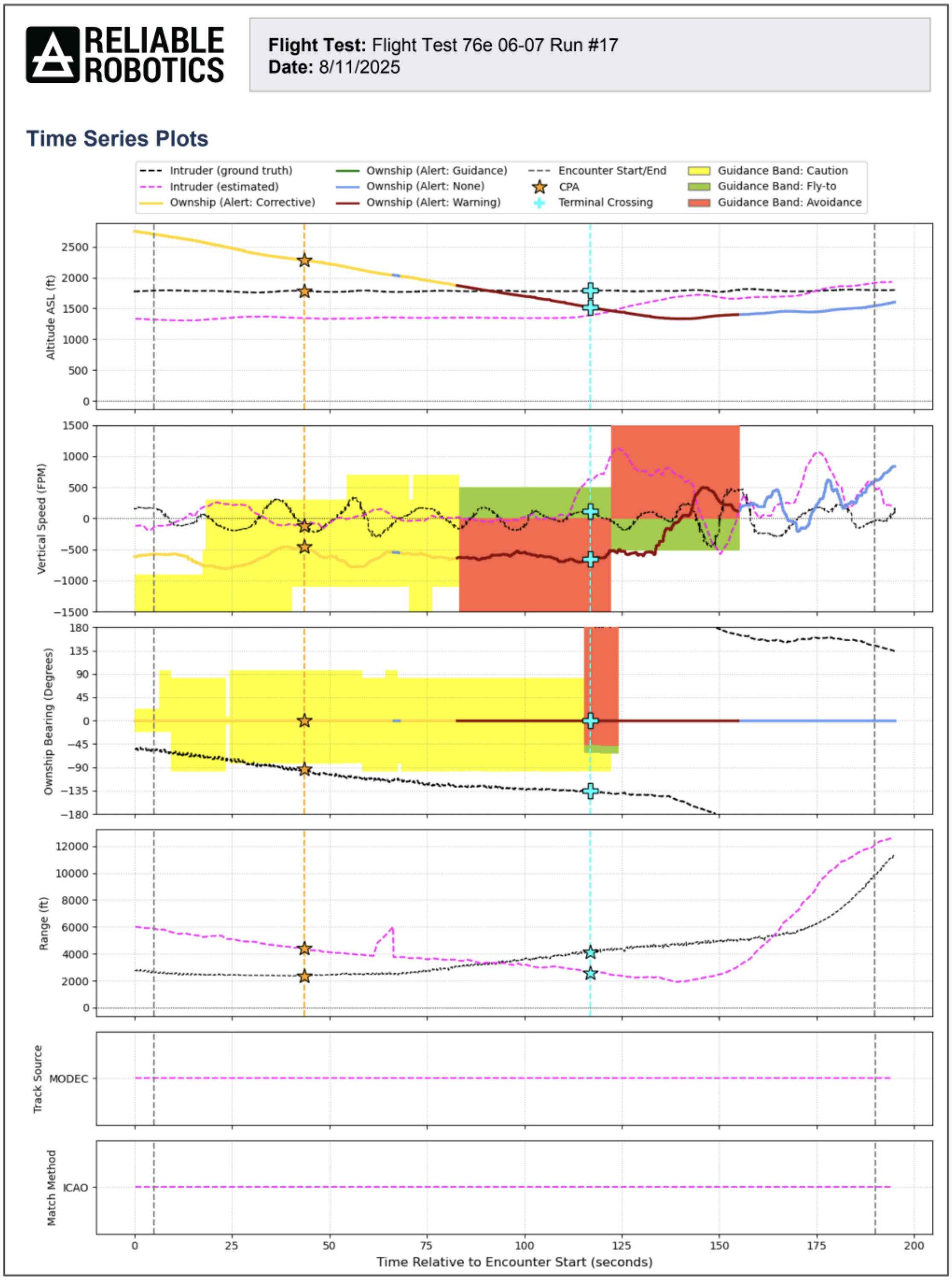

Figure 9. Example Report – Page 2.

3.1.2.6 Report Page 3

The third page of the encounter reports includes plots pertaining to the loss of DAA Well Clear. An example report page 3 is shown in Figure 10.

DAA Well Clear Criteria Plots

The DAA Well Clear (DWC) plots track each of the three criteria for a breach of DAA Well Clear. Each plot includes the metric, plotted in a solid black line, and the corresponding threshold, plotted in a dotted black line. When all three thresholds are broken concurrently, a purple band is shown across all three plots to indicate a breach of DWC.

DO-365C: Section 2.2.4.3.6: Alert Parameters by DWC considers two sets of parameters for DWC criteria: En Route DWC Alerting, and Terminal DWC Alerting. Thresholds for En Route DWC Alerting are used when the ownship is outside of the terminal area, and thresholds for Terminal DWC Alerting are used when the ownship is within the terminal area.

Modified Tau (T_{Mod}) Plot

Modified Tau is calculated from the definition in DO-365C: Appendix C: Section C.5: Mathematical DWC Definitions. The Enroute threshold used is 35 seconds, from DO-365C: Table 2-25 Parameters for En Route DWC Alerting Requirements. The Terminal Area threshold used is 0 seconds, from DO-365C: Table 2-26 Parameters for Terminal DWC Alerting Requirements

Horizontal Miss Distance (HMD) Plot

Horizontal Miss Distance (HMD) tracks the projected closest horizontal distance between the aircraft if they continue their current trajectories. This is calculated from the definition in DO-365C: Appendix C: Section C.5: Mathematical DWC Definitions. The Enroute threshold used is 4,000 feet, from DO-365C: Table 2-25 Parameters for En Route DWC Alerting Requirements. The Terminal Area threshold used is 1,500 feet from DO-365C: Table 2-26 Parameters for Terminal DWC Alerting Requirements.

Altitude Offset (DH)

Altitude offset tracks the difference in altitude between the aircraft. The Enroute threshold used is 450 feet, from the Corrective Alert Type in DO-365C: Table 2-25 Parameters for En Route DWC Alerting Requirements. To keep the plot clear, only the Corrective Alert Type threshold is used for the En Route environment. Manual inspection may be used to check against other Alert type thresholds. The Terminal Area threshold used is 450 feet from DO-365C: Table 2-26 Parameters for Terminal DWC Alerting Requirements.

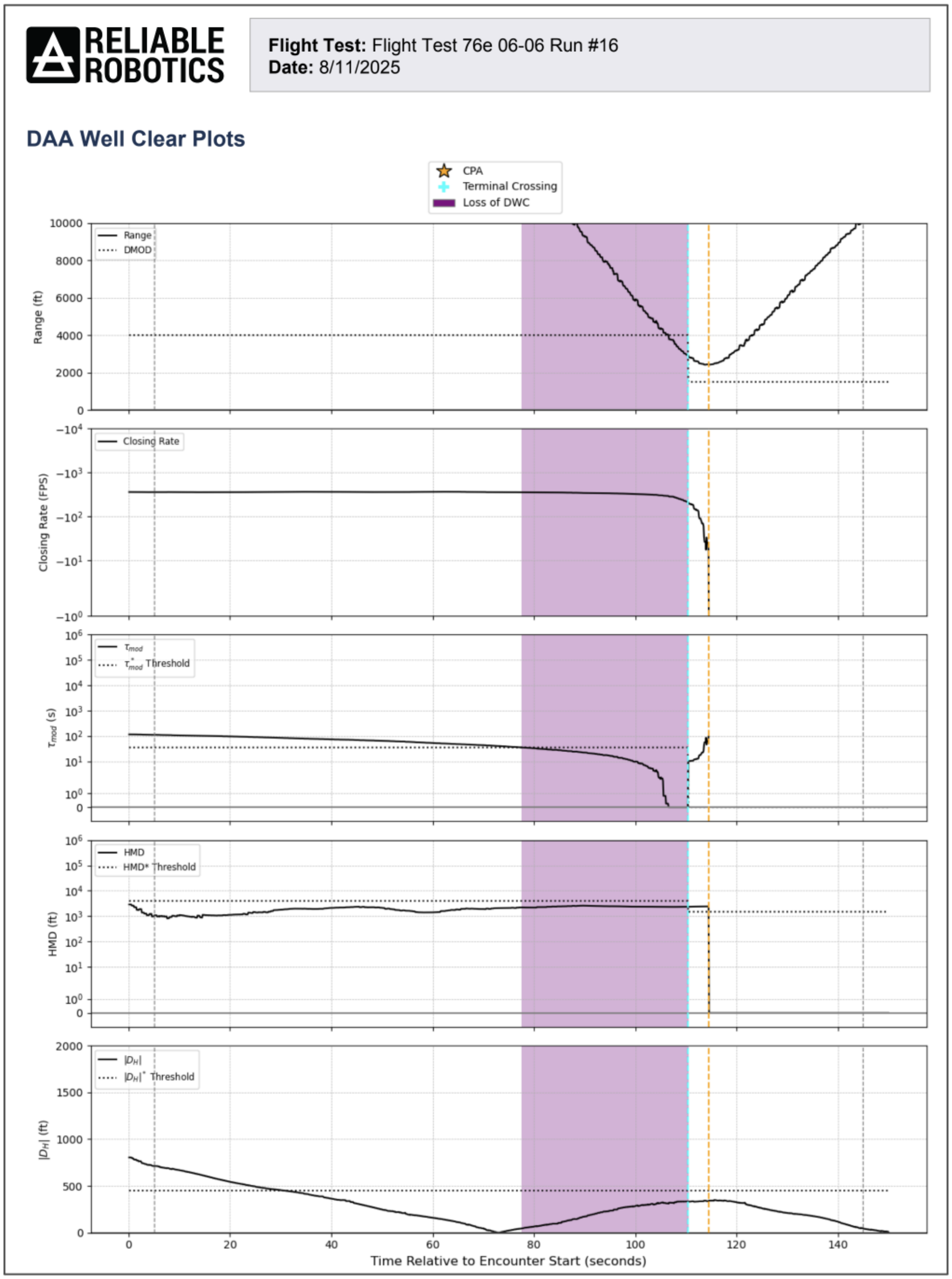

Figure 10. Example Report – Page 3.

3.1.3 Collins GBSS Track Analysis

Collins has provided aggregated GBSS track error calculations and plots against ADS-B tracks for all days of testing. These are collected within the Skyler Analysis folder. Each day of testing includes a folder for each radar under consideration. Each radar folder contains a sub folder for each aircraft ICAO address under consideration. The ICAO for the ownship vehicle is ACD8AD.

The ICAO address for the intruder aircraft is A9872F. Each aircraft folder includes a text file with analysis and a number of collected plots. Note that in some analysis text files, the range metric unit is mislabeled as nautical miles. The metric is expressed in feet.

3.1.4 uAvionix Uplink Reports

Uplink reports provide quantitative Quality of Service (QoS) metrics and plots for performance of the uplink of GBSS AGT tracks over the uAvionix C-Band CNPC data link. Metrics are calculated from the start time of the first encounter of the day to the end time of the last encounter of the day, bounding the QoS metrics to only times when the ownship was airborne and within the coverage volume of the uAvionix link.

3.1.4.1 Data Sources

Each message sent over the uAvionix uplink is tagged with a UUID. Logs are recorded of all packets when they are sent to the uAvionix ground system, and when they are received from the uAvionix airborne radio. In post processing, UUIDs and timestamps of messages are used to compute message reception and latency metrics.

Ownship aircraft positions are associated to packets by UTC timestamps from both logs.

3.1.4.2 Report Page 1

Uplink Performance Metrics

- Packets Sent
  - Total count of packets sent up to the aircraft over uAvionix link
- Packets Received
  - Total count of packets received on the aircraft
- Percent Received
  - Percentage of packets received / packets sent across all packets
- Average Latency (s)
  - Mean latency between send and receive across all packets
- Median Latency (s)
  - Median latency between send and receive across all packets

Packet Sequence vs. Time Analysis Plot

Packet sequence number is plotted against packet sent time. Packets dropped are plotted in red, while packets received are plotted in green.

3.1.4.3 Report Page 2

Packet Status over Flight Path

Packet receipt is plotted over the flight path of the ownship aircraft. Packets dropped are plotted in red, while packets received are plotted in green.

Uplink Latency over Flight Path

Packet latency is plotted over the flight path of the ownship aircraft. Packet color is plotted based on latency of receipt on a gradient scale with zero seconds of latency corresponding to green, and latency or one second or more corresponding to red.

3.1.5 Sagetech ADS-B / Mode C Analysis

Sagetech has provided a data analysis spreadsheet for each day of flight testing, along with exported CSV versions of their device logs. The spreadsheet includes tabs with analysis for each type of track received.

Each tab includes a *report_time* column which is used to sync against other logs. This column corresponds to seconds after midnight of the current day in UTC; to convert to UTC time,

InputWgs84Observation

Timeseries log of all ownship position messages received by the device from Reliable's airborne systems.

stmDisplayStruct

Timeseries log of all display reports generated by the device.

receivedModeCReplies

Timeseries log of Mode C reports received by the ACAS device from Sagetech's MXR interrogator.

receiveDF0

Timeseries log of DF0 reports received by the ACAS device from Sagetech's MXR interrogator.

positionReport

Timeseries log of intruder reports output from the device

AGT

Timeseries log of Absolute Geodetic Track (AGT) reports received by the ACAS device. AGT reports encode tracks from the Skyler radar system.

stmTRMOwnInput

Timeseries log of ownship position input into the ACAS-Xr TRM.

3.1.6 Remote Pilot Surveys

For each encounter with the ownship under control of the Remote Pilot, a survey was completed by the remote pilot for each encounter. This survey captures the following fields:

- Encounter # (First of the day is 1, second encounter is #2, etc.)
- Test Card #
- An ACAS Xr alert was necessary in the previous encounter
    - Answered on a scale from 1-5, with 1 corresponding to "Disagree Completely" and 5 corresponding to "Agree"
- The DAA system provided sufficient information to determine an appropriate course of action.
    - Answered on a scale from 1-5, with 1 corresponding to "Disagree Completely" and 5 corresponding to "Agree"
- The guidance issued by ACAS Xr successfully ensured safe separation from all nearby aircraft
    - Answered on a scale from 1-5, with 1 corresponding to "Disagree Completely" and 5 corresponding to "Agree"
- The guidance issued by ACAS Xr was appropriate given known airspace constraints
    - Answered on a scale from 1-5, with 1 corresponding to "Disagree Completely" and 5 corresponding to "Agree"
- The timing of the guidance issued by ACAS Xr was:
    - Answered on scale from "Too Early" to "Too Late"
- Would you have responded to the previous encounter differently if you did not have ACAS Xr? If yes, please explain.
    - Free response.
- Do you have any additional thoughts about this encounter? If yes, please explain.
    - Free response.

The "Appropriate Guidance Provided" metric is considered to be a positive affirmation (answer of 4 or 5) to "The DAA system provided sufficient information to determine an appropriate course of action.", "The guidance issued by ACAS Xr successfully ensured safe separation from all nearby aircraft", and "The guidance issued by ACAS Xr was appropriate given known airspace constraints"

3.2 Data Notes

3.2.1 C-Band CNPC Uplink

3.2.1.1 Ground station switchover.

Initially, the intention was to use both uAvionix ground stations installed in San Martin and in Hollister. uAvionix's Skyline link management system was to be used to handle switchover between the two ground stations. Preliminary functional flight testing showed that switchover between the two ground stations did not function properly. As such, all testing was performed exclusively with the Hollister ground station and ground station switchover was not performed during this test campaign.

3.2.1.2 System Upgrade on Aug 14th

Uplink reports and remote pilot feedback indicated poor performance of the uAvionix system on the RNAV 13 approach on 2025-08-06 and 2025-08-08. See Uplink reports for 2025-08-06 and 2025-08-08. uAvionix provided a system update, which was applied after the flight on Aug 14th. This update was expected to fix switchover, provide better coverage and reduce packet drops. Link analysis plots show improved performance after this date, but are not conclusive as the flown routes after Aug 14th do not include RNAV 13. The San Martin ground station was not brought online and ground station switchover was not performed during this test campaign.

3.2.2 ACAS Xr Alerting and Guidance

3.2.2.1 Terminal Area Behavior

The Sagetech ACAS device did not adhere to ACAS-Xr terminal area logic. In discussions with the team during data review, Sagetech provided the causes. There are two considerations for terminal area function: intruder position in relation to the terminal area, and ownship position in relation to the terminal area. For Mode C tracks, intruder terminal area position cannot be determined with non-bearing tracks. For ownship terminal area state, Sagetech had not implemented terminal area designation for Mode C tracks. This was not caught earlier in HITL testing as HITL testing was performed with ADS-B and AGT track sources feeding the ACAS device.

4.0 Results and Discussion

4.1 Ground-Based Surveillance System (GBSS)

The Skyler radars in San Martin and Gilroy were configured for data collection on six of the flight test days. Four of the days utilized the radar installed in San Martin, CA and two of the days utilized the Gilroy, CA and San Martin radars. For all flight days, radar tracks associated with the ownship aircraft were analyzed. For a subset of days, radar tracks associated with the intruder aircraft were analyzed.

Table 7. Skyler GBSS vs. ADS-B analysis performed

	San Martin, CA		Gilroy, CA	
	Ownship	Intruder	Ownship	Intruder
8/6/2025	X	X		
8/8/2025	X	X		
8/14/2025	X			
8/18/2025	X	X		
8/25/2025	X	X	X	X
8/28/2025	X	X	X	

4.1.1 Probability of Detection and Track Reliability

Overall the track reliability of the Sklyer radar was mixed. At times the radar would reliably track the aircraft when it was in the field of view, other times it would drop the track. It is difficult to determine the cause of the varying track reliability. An example of this discrepancy is shown in Figure 11 and Figure 12. As expected, the probability of detection and track reliability decreased with increased range. The two days that utilized the Gilroy radar had reduced track reliability, but due to the limited data set it is difficult to say this contributed.

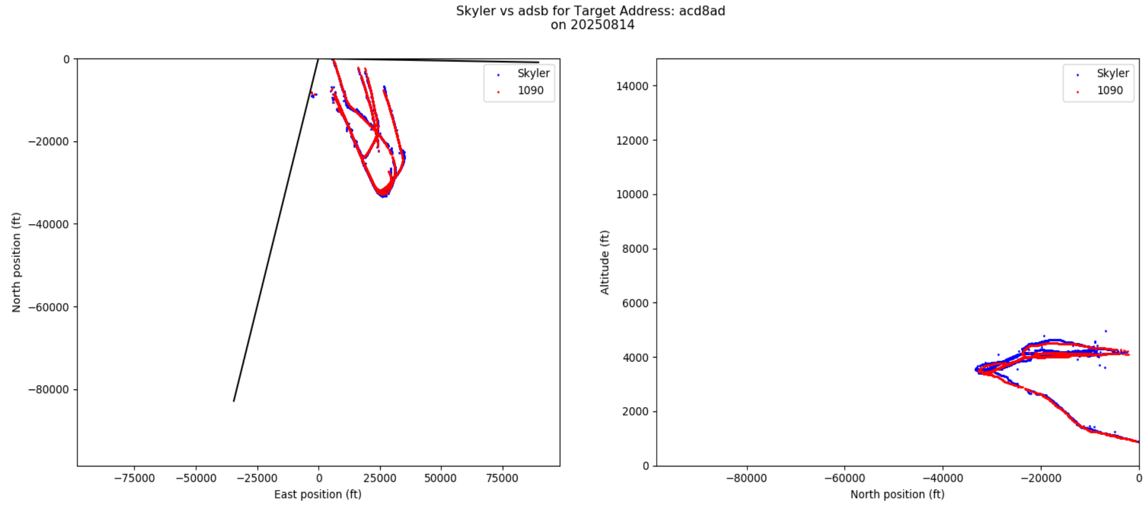

Figure 11. Radar and ADS-B data from 8/14/25 showing decently good tracking reliability.

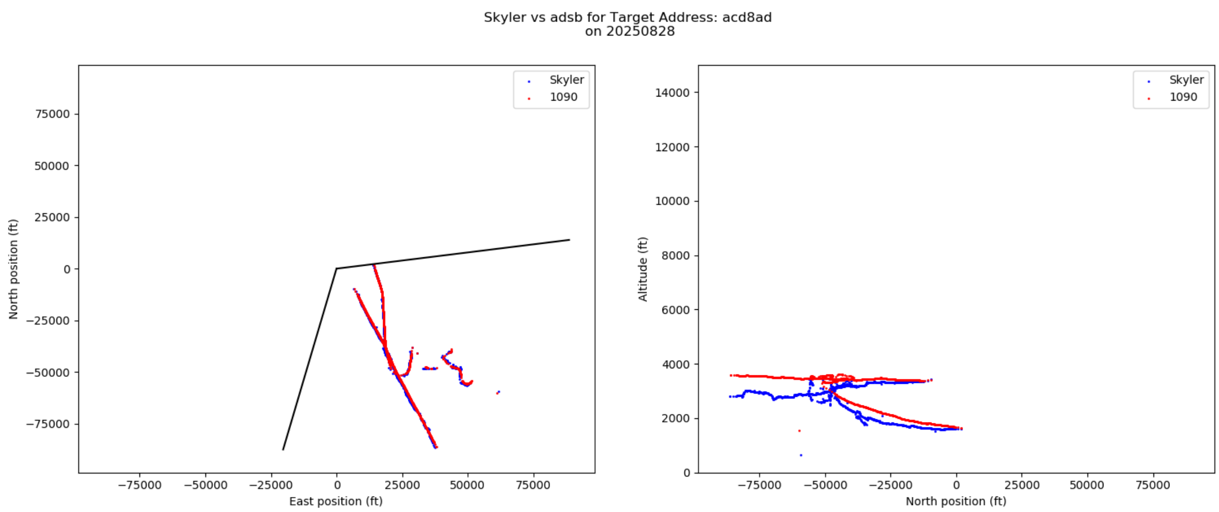

Figure 12. Radar and ADS-B data from 8/28/25 showing poor tracking reliability.

4.1.2 Range Performance

A majority of test points were flown within the radar's advertised surveillance boundary, but effects of range limitations were likely still felt after review of the provided data.

All results were reported back to the team from Collins as only ADSB-confirmed data. This means that any tracks formed by the radar without a corresponding ADSB signal were left out. Unfortunately, gaps in the data therefore could not be confirmed to be an issue of the radar or one of an unconfirmed ADSB signal.

Given that the surveillance volume of the Skyler radar has a range of 16 NM, many encounters were designed to lie well within that volume, but certain encounters, such as those of the 31 RNAV terminal area, did push the range limitations of the radar installed in Gilroy. Figure 13 shows the range error for a RNAV 31 flight that shows tracks out to 16 NM. While this shows that the radar can track at these distances, more data collection and processing would be required to provide a probability of detection at range.

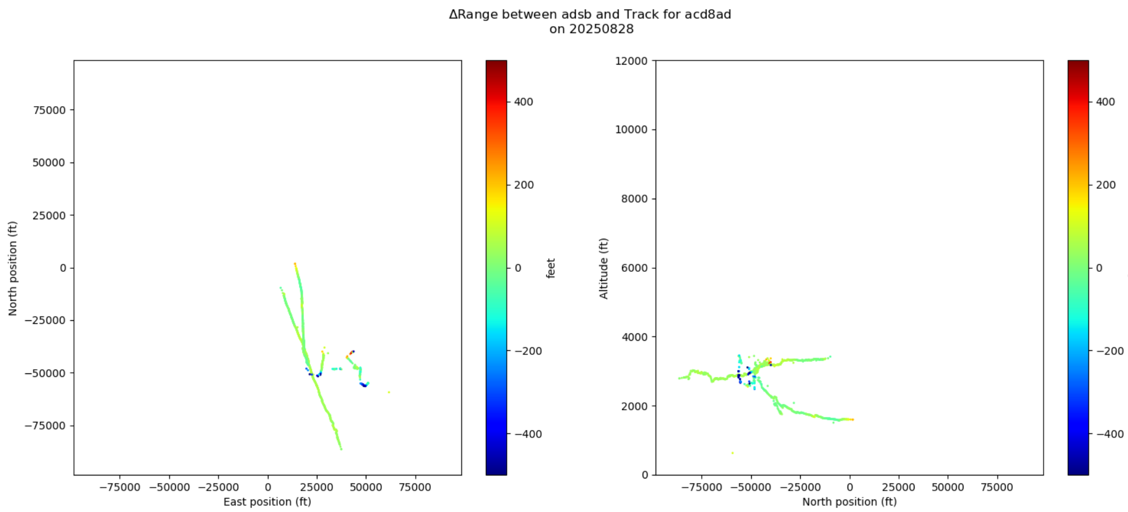

Figure 13. Delta range values between Skyler radar data and ADSB over distance from the Gilroy Skyler radar.

4.1.3 Accuracy

Overall during testing the radar showed fairly good accuracy. The average azimuth and elevation root mean square error (RMSE) were 0.72 and 0.42 degrees, respectively. The average 3D range RMSE was 120 feet. Figure 14 shows the azimuth, elevation and range RMSE over all test days. While this accuracy is sufficient for most GBDAA applications, there were periods of increased error, especially on 8/18/2025. These errors may be sufficient to degrade ACAS guidance. There were no determined accuracy differences between the San Martin and Gilroy radars.
Collins has defined an internal requirement of 2 degree limitation for azimuth, and 0.1 degrees for elevation. Azimuth performance generally meets this requirement, whereas elevation does not. The radar's range accuracy also lies well within their defined limit of 500 feet RMSE with an actual observed average RMSE of only 120 feet.

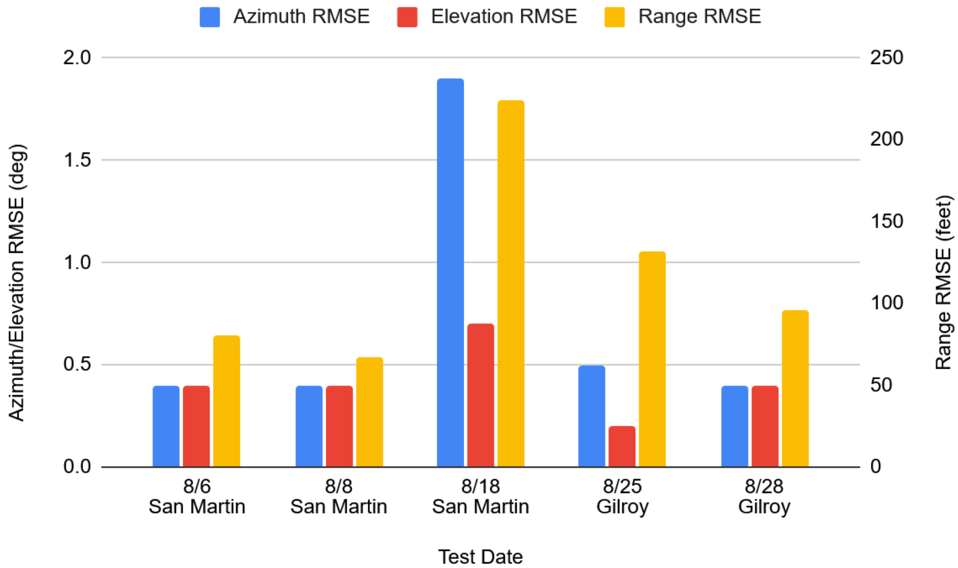

Figure 14. Azimuth, elevation and range root mean square error (RMSE) over all test dates.

Absolute track position performance is worse when farther away from radar. A MOPS conforming positional error of 500ft at 5nmi increases to ~1000ft at 10nmi. The 06 RNAV approach tested is roughly 15nmi from San Martin, which is testing the system at the limits of reception. Tracks even further out were still provided by the Skyler system, with resulting high absolute position error.

It is suggested that tracks provided by GBSS systems be limited to their declaration volume. Tracks produced by the radar system for long ranges may result in high positional error, even if the radar meets the MOPS within its declaration volume.

4.1.4 Time Base Considerations

GBSS AGT track input to ACAS Xr requires a “Time of Applicability” in a time base which matches the time base provided to Xr. Maintaining a common reference for Time of Applicability (ToA) is relatively simple onboard the UA, but when interfacing with a ground based system (GBSS, ground based DAA processor, etc), keeping the two time sources in sync becomes a much harder problem. In the scope of this campaign, time synchronization was achieved by running both airborne and ground systems based off of UTC, with a method for time synchronization during pre-flight procedures and calculations for worst case clock desynchronization. This is likely untenable for a MOPS conforming integration, and a better time synchronization method will need to be determined. There are also external factors that may disrupt time source syncing (GPS-out, variable comms latency, etc.). Considerations should be made for required time synchronization requirements and methods between ground and airborne systems.

4.1.5 sUAS Test Points

Preliminary remarks from the RPIC after the day of sUAS testing indicated that no display was provided for the sUAS, and the intruder triggered no ACAS-Xr Alerts or Guidance during any of the test points, either with the radar reflector mounted or not. Encounter reports confirmed this result post-test. With or without a radar reflector, the small drone was not picked up by the Skyler Radar.

While the radar cross section of the DJI Inspire without the radar reflector is unknown, and therefore the test points performed without a radar reflector are in a grey area in regards to the MOPS, a 9sqm reflector has roughly the same radar cross section as a Cessna 172 (per DO-381). The sUAS was flown at ~6 nmi from the San Martin installation, a distance and location that is expected to be within the declaration volume of the installation (if one was defined by Collins). As such, a track should have been produced for the target.

4.2 Control and Non-Payload Communication (CNPC) Datalink

Data was collected on the CNPC datalink performance during the eight days of flight testing. Figure 15 shows the flow of uplinked GBSS tracks from the Skyler radar up to the ACAS device, along with the locations of logging.

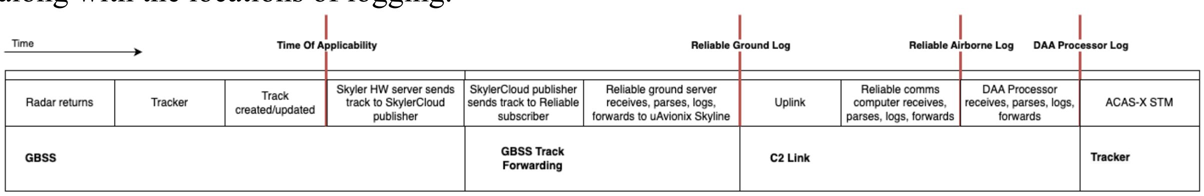

Figure 15. GBSS AGT track uplink flow

As the figure details, logs are recorded of all messages sent to the uAvionix link directly before sending the UDP packet on the ground and immediately after receipt on the airborne system. Each uplinked packet includes a UUID. Packet UUIDs are compared between ground and airborne logs in post-processing to determine link continuity. Ground and airborne systems are time-sync'd, so timestamps of message send and message receipt are used along with UUIDs to compute latency.

Figure 16 shows the packet receive percent and the average latency on all flight test days. Overall, the average percentage of packets received was 91.6% and the average latency was 414ms.

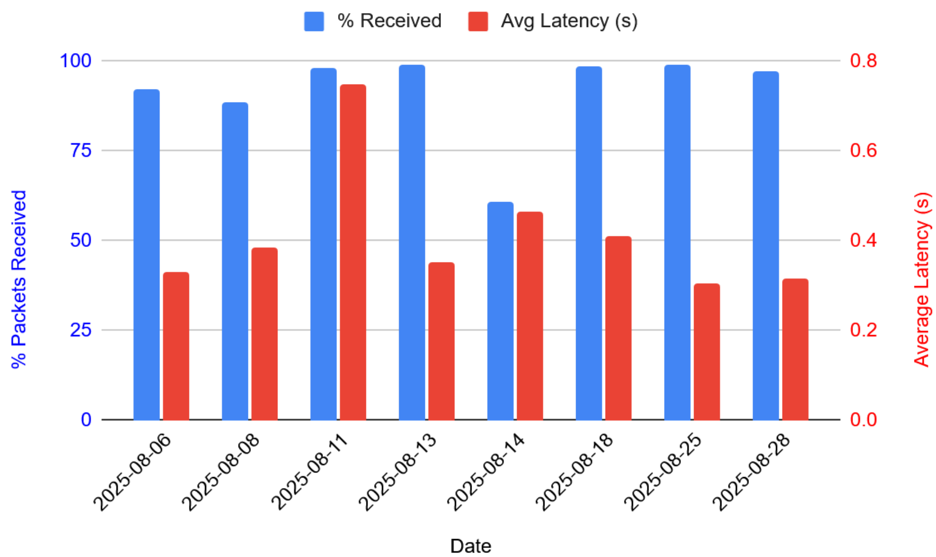

Figure 16. Percent packets received and average latency for the CNPC radio by test date.

DO-377 requires a link latency less than 1000ms, and internal analysis by Reliable Robotics has derived that a link continuity of 98.2% is required of the C-Band CNPC when used in combination with other data links to hit the overall link availability requirement of DO-362A. Across all tests, the measured average latency of 414ms meets the requirement. The average link continuity of 91.6% did not meet the derived requirement.

Geographical regions of link dropout were identified on the RNAV 13 approach. An example of this is shown in Figure 17. These dropouts could last up to a few seconds, resulting in no GBSS tracks passed to aircraft. This link dropout was also noted in the downlink as well, resulting in traffic disappearing from the remote pilot display. It appears from the data that these periods of dropouts are largely location dependent, appearing in the same places on the RNAV 13 approach each time. Regions of dropout do not appear to have any correlation with identifiable obstructions or interference sources.

Flights performed on August 14 had significantly worse performance for packet continuity than other days. These flights were exclusively on the RNAV 13, which may play a contributing role to the poor performance. Other causes have not been identified.

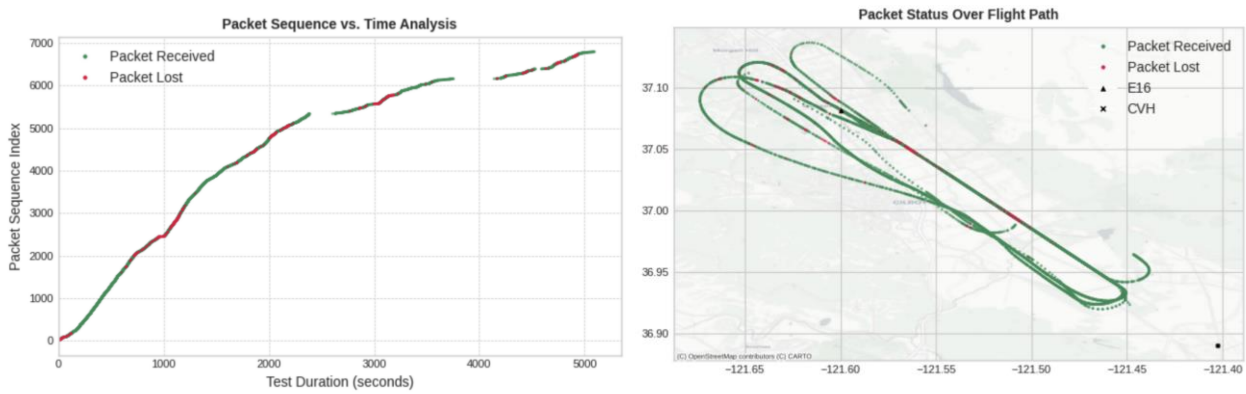

Figure 17. CNPC data from the flight along RNAV13 from August 8 showing periods of link dropout.

Assessing and mitigating these regions of coverage dropout will be integral to successful deployment of a C-Band radio system. As a ground based radio system, it is expected that both natural and man-made obstacles will affect the coverage of the system. Future deployments of these systems should likely entail assessment of the operational area for adequate coverage of the intended flight path. Additionally, if link drop-outs are expected and not directly mitigated by other data links, user interface changes may be considered to display to the pilot the status of the latency and staleness of the data presented.

Looking at only the final three days, the average continuity improves to 98.2%. The tests performed on these days were after the uAvionix system upgrade, and on RNAV 06 and 31 approaches. Link performance reports for RNAV 06 and 31 approaches do not show consistent regions of dropout. This suggests that with future improvements and in a conforming installation, both latency and continuity will be sufficient to meet the MOPS for this data link.

4.3 ACAS Xr Alerting and Guidance

4.3.1 Encounter Assessment

During the test campaign, a Remote Pilot controlled the aircraft for 36 encounters. From the Remote Pilot Surveys, Alerting and/or Guidance was determined by the remote pilot to be necessary in 31 encounters.

Table 8. Percentage of encounters where alerting was necessary.

	Remote Pilot Encounters	Encounters with Alerting Necessary
Count	36	31
Percentage	100%	88.6%

In the 31 encounters where the remote pilot deemed alerting necessary, the ACAS system failed to provide a response in 4 cases, or 12.9% of the 31.

Table 9. Percentage of encounters where alerting was necessary and provided/not provided.

	Alert/Guidance NOT Provided	Alerting/Guidance Provided
Count	4	27
Percentage of Encounters with Alerting Necessary	12.9%	87.1%

For encounters where an ACAS response was deemed necessary and an Alert or Guidance was provided, the Remote Pilot determined that the "correct" response was provided in only 21 of the encounters, 77.7% of alerted encounters, or 67.7% of encounters where guidance was deemed necessary.

Table 10. Pilot feedback on quality of alerting guidance.

	Appropriate Guidance Provided
Count	21
Appropriate ACAS Response out of RPIC Identified Encounters	67.7%
Appropriate ACAS Response out of Alerted Encounters	77.7%

Out of the same set of encounters where Alerting or Guidance was determined to be necessary, the ACAS response was determined to be on-time in 17 encounters, somewhat late in 6 encounters, and too late in 8 encounters.

Table 11. Pilot feedback on timeliness of alerting guidance.

	Alerting/Guidance On-Time	**Alerting/Guidance Somewhat Late**	**Alerting/Guidance Too Late**
Count	17	6	8
Percentage of Encounters with Alerting Necessary	54.8%	19.4%	25.8%

Selected Remote Pilot notes:

- During Test Card 13-08, encounter #11, the ACAS device provided guidance would have taken ownship toward/into terrain.
- In two encounters (#34, #38) for test card 06-02, the Remote Pilot noted that they would have turned in a different direction than what was suggested by guidance bands. These encounters were determined by the remote pilot to otherwise have provided guidance which was on time and would have mitigated the situation.
- Remote Pilot never answered that any alerting/guidance was "Somewhat Early" or "Too Early"

4.3.2 Remote Pilot Display

Across the test campaign, the traffic map on the remote pilot display appropriately showed traffic and guidance to the remote pilot. No negative feedback was received from the remote pilot regarding issues with the display implementation or traffic map. However, three items were identified as areas of improvement:

Bearingless Track Display

The majority of tracks provided by the ACAS device were Mode C bearingless tracks. These tracks do not have a display element on the traffic map, and as noted in the Remote Pilot Display section of Reliable Robotics Ground Infrastructure, the text based display prescribed by DO-365C was not implemented on the remote pilot interface. The remote pilot consistently wrote in the survey that no display element for the intruder was present, and that they expected a display element to indicate the intruder.

Intruder Absolute Position Conversion

On Reliable's ground system, relative bearings to intruders are converted to absolute position using ownship heading for display on the north-up map. Misalignment between the time of reporting of ownship heading and the intruder bearing reports can introduce error into the resulting absolute position of the intruder, especially at longer ranges. In both HITL testing and in flight testing, it was noted that intruder tracks on the display would rotate slightly around the ownship when the ownship changed heading. It is unknown whether this is caused by the variable latency in the data links, or the intruder position error identified initially during HITL testing.

Absolute position conversion issues caused by misalignment of heading and bearing could be addressed by including the heading used in the bearing calculation as part of the intruder report. Alternatively, DO-365C could allow manufacturers to use an alternate intruder report type, where relative position of intruders are provided in ownship relative North-East-Down (NED) coordinates instead of bearing/range.

ACAS-Xr Performance in the Context of SSR Performance

Given the poor performance of the SSR Tracks as one of the primary sources feeding ACAS-Xr in this testing campaign, the poor performance of Xr could be explained by the source data. Previously completed HITL testing, detailed in the HITL report, showed timely and appropriate alerting and guidance when fed from simulated track sources.

Data Integrity & Remote Pilot Decision Making

Ultimate authority for safe operation of an uncrewed system resides in the remote pilot, even when they are in a control center far from the physical location of the aircraft. As such, the remote pilot in a UAS operating in the NAS must make maneuvering decisions to maintain DWC and avoid NMAC based on the information available to them. In this test campaign, multiple factors came together to degrade the information available to the remote pilot: track position error detailed in the SSR performance section, dropouts in the uAvionix link detailed in the C-Band CNPC section, and instances of missing or inappropriate alerting and guidance detailed in the alerting and guidance section. When integrity of these systems are degraded, situational awareness of the remote pilot is lost precipitously and assessing correct course of action becomes much more difficult or impossible.

4.4 Secondary Surveillance Radar (SSR) Performance

Data review shows that the primary selected track source across the scope of testing was Mode C Non-Bearing tracks. As such, metrics for ACAS provided tracks can be used to show the upper bound for the performance of Mode C tracks alone. Sagetech has provided track analysis against ground truth data for four flight test days: 2025-08-13, 2025-08-18, 2025-08-25, and 2025-08-28. Track source makeup of each encounter can be found in the included "Track Ground Truth Error Calculation" folder of analysis data attached.

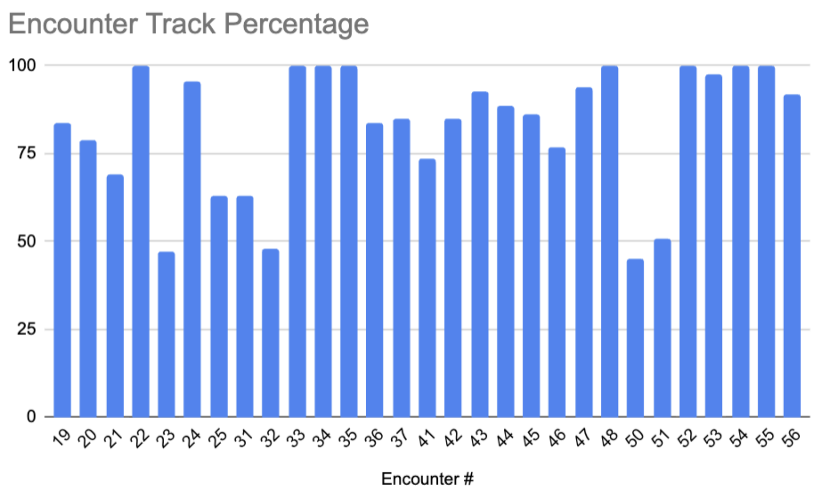

Figure 18. Encounter Track Percentage.

Figure 18 shows track percentages across encounters. These are determined by dividing the length of time under which an intruder track was provided which estimated the ground truth state of the intruder, by the total length of the encounter. Tracks are expected to be provided all for each encounter for the length of the encounter. For two encounters, TC 06-06 Run #15 and #16, which were not considered in Sagetech's analysis, encounter reports show no track was able to be associated with the intruder aircraft for the whole encounter. Other runs such as TC-10 Run #20 have only a very small track percentage.

Figure 19 shows error rates for range and altitude across the encounters under consideration. Qualitative error rates can also be seen in the range and altitude plots in encounter reports.

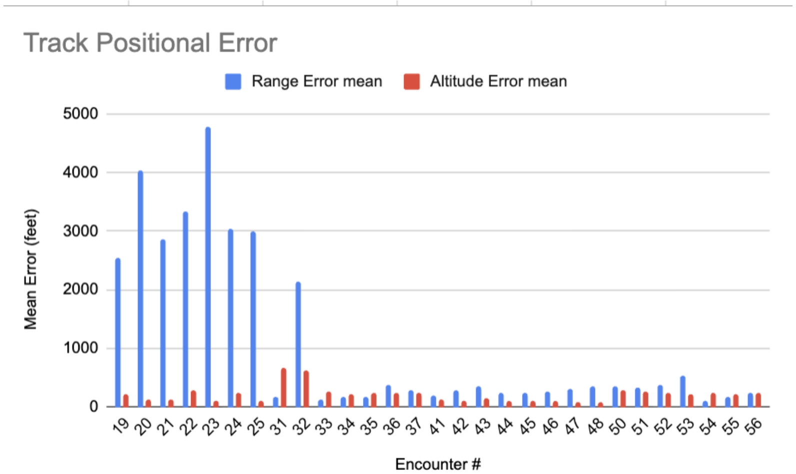

Figure 19. Track Positional Error.

Across all encounters, ICAO address associated tracks showed much higher error rates than tracks associated by position. Examples of this can be seen in Figure 20 and 21, one showing a ICAO associated track and one showing a position associated track, both pure Mode C tracks.

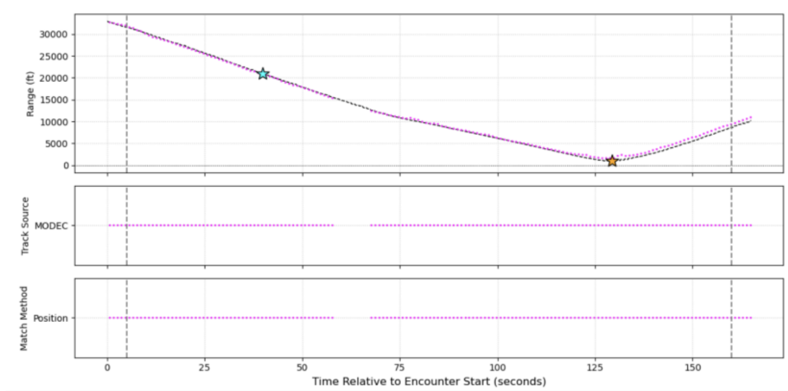

Figure 20. Encounter #22 Position associated ModeC track.

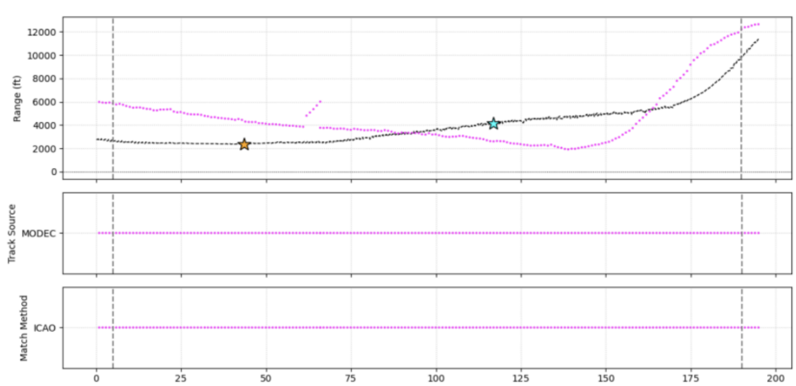

Figure 21. Encounter #17 ICAO associated ModeC track.

To move towards a certified DAA system, performance of SSR Mode C tracks must be improved. This would fall under Sagetech's prototype MXR interrogator unit. It is unknown at this time whether the problem lies in the cooperative surveillance algorithms themselves or the implementation.

5.0 Conclusion and Recommendations

5.1 Conclusions

5.1.1 Objective 1: GBSS Performance

Test results of the two Skyler radars located at San Martin and Gilroy show that their accuracy metrics within their surveillance volume could be satisfactory, but unknown causes of lost tracks of non-instrumented targets of opportunity have the effect of decreasing confidence in the system as a whole. Some tracks provided over a testing day have shown that the radars could reliably track the target aircraft over the course of its flight path within its boundaries, but other tracks, even those well within the same boundaries of further targets, have been lost and dropped from recorded tracking but further testing would be required to understand that behavior.

Average accuracy of the tracks that were recorded throughout the testing campaign show root mean square errors of 0.72 and 0.42 degrees for their azimuth and elevation, respectively. These numbers fall within Collins' defined 2 degree limitation for azimuth, but not within its tighter constraint of 0.1 degrees for elevation. The radar's range accuracy also lies well within their defined limit of 500 feet RMSE with an actual observed average RMSE of only 120 feet.

5.1.2 Objective 2: C-Band CNPC Datalink Performance

The C-Band CNPC link performed well throughout the campaign. The system functioned with low uplink latency averaging 414 ms, which is well within the 1000ms latency requirement of DO-377. The average link continuity performance of 91.6% does not meet Reliable's DO-362A derived requirement of 98.2%, but that requirement was not an objective of this contract and uAvionix was not given it as a requirement. Looking at a subset of testing within identified full coverage regions, continuity performance improves to be sufficient to meet the DO-362A derived continuity requirement. It is suggested that C-Band CNPC link installations should include comprehensive link characterization testing as obstacles may result in loss of coverage over isolated regions.

5.1.3 Objective 3: ACAS-Xr Alerting and Guidance

Based on feedback from the Remote Pilot and Safety Pilot, the ACAS system provided an appropriate course of action to maintain safe separation in 67.7% of encounters determined to require intervention. Across encounters determined to require intervention, guidance was determined by pilot judgement to be provided too late in 25.8% of cases. ACAS-Xr alerting and guidance can only be as good as the source data; it is hypothesized that the degraded performance in some encounters is a result of the poor performance of the Mode C Omnidirectional SSR tracks.

Based on remote pilot feedback and results, there are considerations to be made for DAA displays. It is suggested that display elements beyond the text based display in the MOPS are evaluated for bearingless tracks. Additionally, if north-up displays are to be allowed, options may be pursued to mitigate the issues resulting from the conversion between bearing/range relative positions and absolute positions.

5.1.4 Objective 4: Omnidirectional SSR

Review of encounter reports shows range error in thousands of feet and altitude error in hundreds of feet across the majority of encounters. Two encounters do not have any track which can be associated with the intruder aircraft, and others only have a small region with a track provided. The implementation of omnidirectional SSR surveillance prototype used during this test has room for improvement, and further development work to improve performance is suggested.

5.2 Future Testing and Recommendations

5.2.1 Recommendations

Recommendations from each section are collated below.

<u>GBSS System</u>

1. Tracks provided by GBSS systems should be limited to within the Declaration Volume of a MOPS compliant installation to eliminate tracks with higher uncertainty.
2. Considerations should be made for time synchronization requirements and methods between ground and airborne systems.

<u>C-Band CNPC Data Link</u>

3. Installation of C-Band radio links should include comprehensive coverage testing to identify and mitigate geographical regions where consistent link interruption is observed.
4. User interface elements may be considered to notify the remote pilot when the C2 link is experiencing decreased performance, especially when concerned with ACAS-Xr alerting and guidance.

<u>SSR Cooperative Surveillance</u>

5. Development work should be undertaken to improve the performance of SSR tracks on Sagetech's prototype MXR interrogator unit.

<u>ACAS-Xr Alerting & Guidance</u>

6. Non-bearing track traffic display elements (beyond text based) should be investigated for DAA traffic display.
7. If a north-up traffic map is allowed, consideration should be made for this implementation. This could include passing ownship bearing with display messages, or allowing a alternate intruder message set whose position is provided in ownship relative NED coordinates (akin to the current velocity data).

5.2.2 Future Testing

Reliable expects that many of the recommendations provided will require further HITL or flight testing as a part of solution space exploration, investigation and/or resolution verification.

Additionally, in the continued development of DAA solutions for existing and new stakeholders in the National Airspace System, Reliable expects the following systems to require HITL or flight testing for standards development and validation in the near future:

- ACAS-Xr V5
- ACAS-Xr or Xu with Air-to-Air Radar non-cooperative surveillance
- ACAS-Xu with Terminal Area additions

Over the course of this contract Reliable Robotics has developed a number of capabilities for the purpose of performing comprehensive testing and analysis work for DAA systems onboard a OPA/UAS system. These capabilities include a HITL testing environment, an airborne platform, flight test planning & expertise, a DAA display, and a number of analysis tools.

Reliable Robotics intends to continue to utilize these developed capabilities to help our partners in industry, standards bodies, and regulatory bodies develop Detect and Avoid systems. Reliable is already in discussion with Sagetech to perform airborne testing of ACAS-Xr V5 in the near future. Reliable and our partners look forward to continue to contribute to the shared objectives of integrating UAS into the NAS with safety, security, and efficiency.

Appendix A: Acronym List

ACAS	Airborne Collision Avoidance System
ADS-B	Automatic Dependent Surveillance–Broadcast
AGL	Above Ground Level
AGT	Absolute Geodetic Tracks
BAA	Broad Agency Announcement
CA	Collision Avoidance
CNPC	Control and Non-Payload Communications
CPA	Closest Point of Approach
DAA	Detect and Avoid
DAP	Data Analysis Plan
DTA	DAA Terminal Area
DWC	DAA Well Clear
FAA	Federal Aviation Administration
GBDAA	Ground-Based Detect and Avoid
GBSS	Ground-Based Surveillance System
GPS	Global Positioning System
HITL	Hardware-in-the-Loop
HMD	Horizontal Miss Distance
IAP	Instrument Approach Procedures
MAAP	Mid-Atlantic Aviation Partnership
MOPS	Minimum Operational Performance Standards
MSL	Mean Sea Level
NASA	National Aeronautics and Space Administration
QoS	Quality of Service
RA	Resolution Advisory

RCC	Remote Command Center
RR	Reliable Robotics
RTB	Return To Base
RWC	Remain Well Clear
SSR	Secondary Surveillance Radar
STM	Surveillance Tracking Module
sUAS	Small Unmanned Aircraft System
UAS	Unmanned Aircraft System
UDP	User Datagram Protocol
UTC	Coordinated Universal Time
UUID	universally unique identifier
VMD	Vertical Miss Distance
VT	Virginia Tech