Broad Agency Announcement
Call #001

Final Report

Contract Number: 692M15-20-C-00001

UAS Integration Office

Program & Data Management Branch

(AUS-410)

Project Title: Enabling Unmanned Aircraft Systems Beyond Visual Line-of-Sight Flight Operations with FlightHorizon Detect-and-Avoid and Air Traffic Situational Awareness System

Company Name: Vigilant Aerospace Systems, Inc.

Submitted By: Zach Peterson, Project Coordinator;

Kraettli Epperson, Project Manager

Report Date: September 3, 2021

Contract Period of Performance: 02/03/2020 – 09/03/2021

[INTENTIONALLY LEFT BLANK]

TABLE OF CONTENTS

1. EXECUTIVE SUMMARY

This report is for the project titled “Enabling Unmanned Aircraft Systems Beyond Visual Line-of-Sight Flight Operations with FlightHorizon Detect-and-Avoid and Air Traffic Situational Awareness System,” carried out by Vigilant Aerospace Systems, Inc. in partnership with the Alaska UAS Test Site operated by the Alaska Center for Unmanned Aerial Systems Integration (ACUASI) under the Federal Aviation Administration’s (FAA) contract #692M15-20-C-00001.

The unmanned aircraft system (UAS) industry needs an effective and affordable detect-and-avoid (DAA) system to safely enable the integration of unmanned aircraft into the national airspace system (NAS) and allow UAS to fly beyond the visual line of sight (BVLOS) of the remote pilot on a routine basis. This critical function would allow remote pilots to detect-and-avoid other aircraft while their UAS is BVLOS.

Recent relevant research and development in the industry around this problem exists in two primary areas: (1) the detection and tracking of aircraft using active radar systems; and (2) the development, testing, and use of algorithms and software to automatically track aircraft, predict potential conflicts, and calculate and deliver avoidance commands or “resolution advisories (RA).”

Small radars that are viable for DAA systems for commercial applications, including equipage on smaller UAS, have advanced significantly in recent years. There are multiple options for these radars on the market. However, the implementation and use of these devices and underlying DAA system technology is still at an early stage. The industry has a need for practical application of these new radar technologies via software and DAA systems to further the safe integration of UAS into the NAS.

Outlined below is the testing approach, overall participant observations, data analysis, lessons learned and recommendations regarding the use of the DAA system and sensing technologies throughout the 18-month preparation and testing process for the contract period starting February 3, 2020 and ending on September 3, 2021.

Significant preparation was undertaken prior to the first demonstration / flight test in January 2021, and the impacts of COVID-19 on safety, changes to public health policy at the local and federal levels, and the reduction in normal logistics resources all presented unique challenges to this project. Successful coordination between the teams and companies committed to overcoming these barriers and executing this project led to the completion of all the required demonstrations / flight tests.

Each day of this project and the cumulative demonstration / flight testing process built progressively on the previous day’s testing, resulting in operations becoming sequentially more advanced as the project progressed.

The first day of testing included a basic understanding of the performance capabilities of the radars, supporting hardware and primary unmanned test aircraft, the X6. The last day of testing included the X6 performing true BVLOS flights while equipped with an onboard radar, ADS-B In receiver, and a beta version of the FlightHorizon PILOT DAA system onboard the aircraft, while both manned and unmanned testing aircraft were flown for observation and tracking simultaneously by six radars.

The results of the demonstration / flight tests included advancements to the FlightHorizon DAA system and data logs showing that the radars being tested could be a viable component of a DAA system. The analysis produced by this project suggests that a carefully selected and deployed suite of the tested radars would be a good fit for a variety of UAS mission-types and locations, including especially analysis of expected air traffic, encounters and flight locations. Analysis also indicates that careful use of software and hardware data filters with the radars to reduce the detection of false tracks would be necessary in both mobile and permanent DAA system deployment with radars. In all cases of DAA and radar use, experience and training played key roles in setup, use, troubleshooting and interpretation of real-time information. Also, environmental conditions such as magnetic deviation, RF interference and local climate all impacted performance. The performance of the radars generally agreed with manufacturer performance claims.

2. INTRODUCTION

This project conducted research, development and especially flight-testing of a system to provide remote pilots of UAS with the capability to detect-and-avoid other air traffic and to avoid conflicts. The DAA software tested during this project attempted to correlate data from a variety of sources including flight controller telemetry, aircraft transponders and ground-based or onboard radar and used this data to predict trajectories, detect potential conflicts and provide avoidance guidance to the testing team and to remote pilots.

The flight testing program tested the data correlation model, trajectory prediction and avoidance model of the DAA software and also the remote pilot user interface of the DAA software over numerous aircraft encounters. By detecting and tracking both cooperative aircraft (with transponders) and non-cooperative aircraft (without transponders, tracked using radar), and providing trajectory prediction and avoidance advisories to remote pilots and the testing team, this project was able to demonstrate the potential of a DAA system with radar, like the product tested, to make significant contributions to the advancement of the UAS industry towards safe, routine BVLOS flights.

The flight-testing plan utilized the resources of an unmanned aircraft systems test site, manned aircraft to simulate air traffic encounters, multiple radar systems and other sensors, an unmanned aircraft to carry onboard radar, and the detect-and-avoid software both on the ground and onboard a UAS. The project was designed to advance the state of the UAS industry and to provide for safer, easier, and faster integration of UAS into the US national airspace.

As a part of the project, Vigilant Aerospace Systems (Vigilant) engaged ACUASI at University of Alaska Fairbanks (UAF) to assist in demonstration and validation of the ability of various radars to contribute to a DAA system at the ground control station (GCS) and onboard the UAS to provide the UAS remote pilot with the capability to detect other air traffic and to avoid conflicts by following maneuvering guidance. This effort involved the demonstration / flight tests and further development of a DAA system, with special emphasis on performance, interoperability, and efficacy, by conducting flights in partnership with the UAS Test Site.

The tested system implemented data correlation across a range of sensors and sources, especially including portable radars; validation of the system's avoidance advisory process; and especially extensive flight testing to validate the overall performance and suitability of the system to support the safe integration of UAS into the NAS.

Throughout this report, "Well-Clear" (WC) is referenced as a safety standard for horizontal and vertical separation between aircraft. For the purposes of this testing and in the DAA software, the WC definition used was that defined in the U.S. multi-agency Science and Research Panel (SARP) of the UAS Executive Committee (EXCOM) report titled, *Well-Clear Recommendation for Small Unmanned Aircraft Systems Based on Unmitigated Collision Risk* (Journal of Air Transportation, Vol. 26, No.3, July 2018; Weinert, Campbell, Vela, Schuldt, and Kurucar). The recommended well-clear distance for small UAS is a simple "hockey puck" definition of simultaneous horizontal separation of 2000 feet and vertical separation of 250 feet.

The ultimate goal of this project was the flight-testing, documentation, and validation of a radar-enabled DAA system utilizing the data from radar in combination with other data sources to detect and track targets, calculate conflicts, and issue avoidance advisories to remote pilots of UAS to maintain well-clear (WC) distances and successfully self-separate from manned aircraft. The project sought to make several determinations:

- Determining that specific commercially affordable radar models can be a viable sensor in the detection and tracking of non-cooperative (non-transponder equipped) intruder manned aircraft;
- Determining that such radar input can be fused into existing detection processes and used for intruder aircraft tracking in software;

- Determining that such radar data can be used to calculate intruder aircraft's closest point of approach (CPA) to ownship;
- Determining that such radar data can be used by the detect-and-avoid software to calculate potential loss of well-clear; and
- Determining that such radar data can be used by the DAA software, in combination with other data sources, to calculate an avoidance maneuver for the unmanned aircraft ownship to successfully maintain well clear.

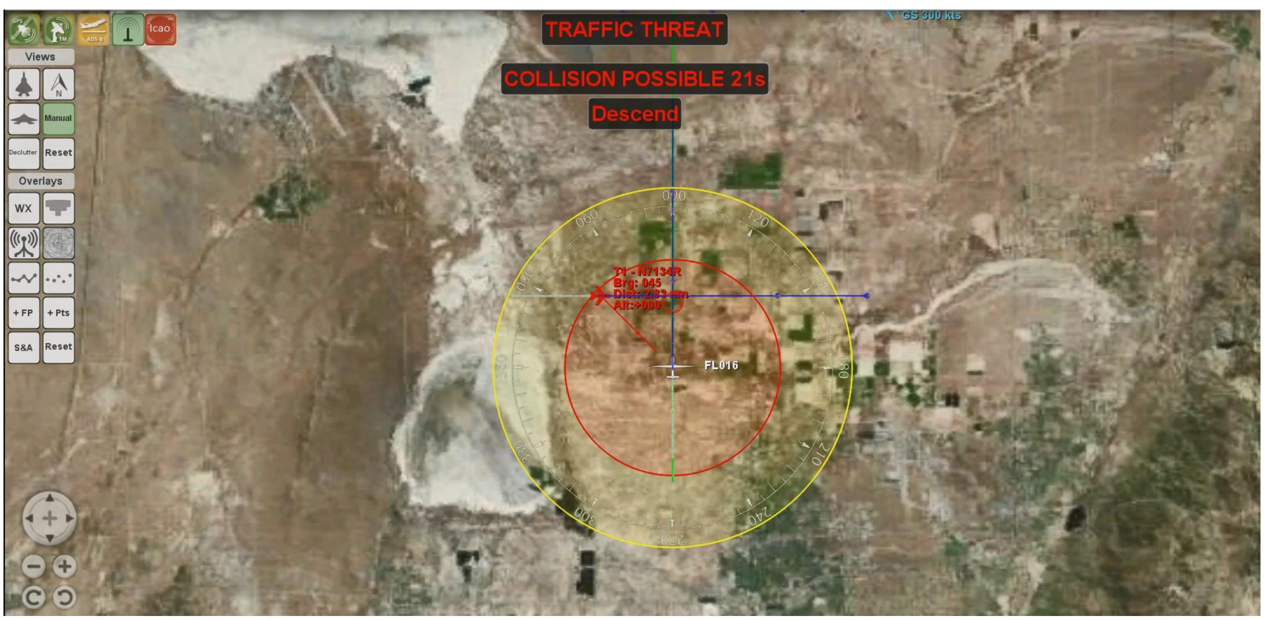
3. APPROACH

A. Overview of DAA Technologies Used

The DAA system used in this project was the FlightHorizon detect-and-avoid system developed by Vigilant Aerospace Systems, Inc. The FlightHorizon software product is designed to help unmanned aircraft remote pilots to "see and avoid" other aircraft, to maintain separation from air traffic and to avoid mid-air collisions. The software is based on an exclusively licensed NASA patent (#9,405,005) and prototype which has been the subject of published NASA research.

For remote pilots and airspace managers, the software provides a 2D map-based view (as shown in Figure 1 below) as well as offers a 3D synthetic cockpit view of the airspace, air traffic with data and sensor correlation using aviation transponders and UAS location telemetry, including "ownship" location directly from the onboard flight controller (MAVLink via network or telemetry radio) and/or from an onboard transponder when a UAS onboard transponder is allowed.

Figure 1



FlightHorizon user interface with a 2D map view.

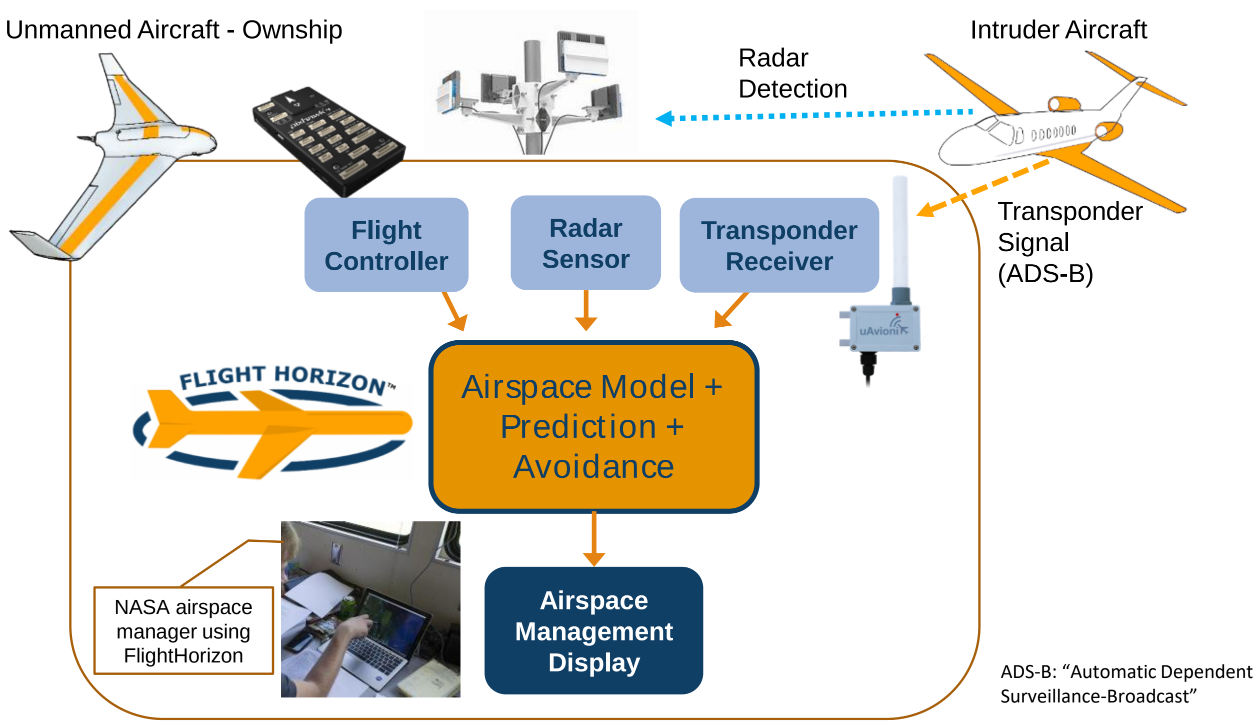
The system is designed to help operators maintain situational awareness, avoid conflicts, fly safely and achieve beyond visual line-of-sight flight authorizations. The software utilizes NASA algorithms to track aircraft, predict trajectories, detect conflicts and provide specific avoidance maneuvers to be taken by the unmanned aircraft.

During the demonstrations / flight tests, the FlightHorizon DAA system that was tested correlated data from a variety of sources including aircraft transponders and ground-based or onboard radar and used this data to predict trajectories, detect potential conflicts and to provide avoidance guidance. The system designated the remote pilot's aircraft as ownship using the Pixhawk autopilot telemetry feed and monitored the airspace around ownship continuously through the use of data from a uAvionix pingStation ADS-B In receiver and radar.

When data from an integrated sensor(s) caused FlightHorizon to predict that the trajectory of an intruder might cause a loss of well-clear (LoWC), the system triggered an alert and issued resolution advisories (RA's).

The telemetry feed from the Pixhawk autopilot onboard the test sUAS was transmitted to the ground control station (GCS), which used MAVLink software to conduct flight operations. The flight controller software provided a one-way transmission of the UAS ownship telemetry feed (in MAVLink format) that was ingested by FlightHorizon to display the ownship icon and its location on the map. The pingStation ADS-B In data and EchoGuard radar data were fed to FlightHorizon through both network connections. The diagram in Figure 2 below provides a visual representation of how FlightHorizon works with these DAA system components.

Figure 2



FlightHorizon equipment and systems data integration diagram

The equipment used throughout the four demonstration / flight test campaigns included but was not limited to several core components:

- One or more laptops running FlightHorizon COMMANDER while data logging.
- One or more small, single-board PCs (Udoo Bolt V8 models) running FlightHorizon PILOT while data logging.
- Three Echodyne EchoGuard portable radars.
- Two Echodyne EchoFlight portable radars.

- Multiple dedicated laptops running Echodyne software while connected to radars and data logging.
- One O.W.L. GroundAware GA9120 radar with portable System Control Module (SCM, a portable PC server) with data logging.
- One laptop dedicated to the O.W.L. GroundAware GA9120 radar and the SCM.
- uAvionix pingStation ADS-B In receiver.
- Ground-to-air radio transceiver radio and antenna system for transmitting EchoFlight data to Echodyne laptop (Ubiquiti brand).
- Ground-to-ground long-range radio transceiver (dish antenna system) for remote radar stations (Ubiquiti brand).
- Multiple portable inverter generators for powering remote radar stations (Honda brand).
- "X6" custom UAV built by ACUASI, with onboard EchoFlight, FlightHorizon PILOT, Pixhawk flight controller and Orange Cube ADS-B In receiver for Pixhawk.
- DJI S1000 UAV with targeting sphere as unmanned intruder aircraft.
- Skyfront Perimeter 4 UAV as unmanned intruder aircraft.
- Multiple handheld controllers for manual operation of UAV's.
- Multiple GCS laptops with GCS software (Mission Planner) providing a moving map for telemetry tracking and control of UAV autopilots.
- Multiple UAV battery backups and charging stations.
- Cessna 206 Stationair as manned fixed-wing intruder aircraft (cooperative).
- Helio Courier as manned fixed-wing intruder aircraft (cooperative).
- Robinson R44 as manned rotor-wing intruder aircraft (non-cooperative, no ADS-B transponder).
- Garmin WAAS GPS handheld navigator carried in intruder aircraft for truth positioning data.
- Experimental supplemental WAAS GPS tracker (built by ACUASI) carried in intruder aircraft for truth positioning data.
- Handheld RTK GPS unit used for high-accuracy position location of radars and pingStation (when WIFI available).
- Portable WAAS GPS used for position location of radars and pingStation (when WIFI unavailable).
- Demonstration / flight test command trailer with portable Honda generator and support equipment.
- Extensive system networking and connectivity equipment.
- Extensive support, repair and improvisation equipment, hardware, tools and replacement parts.

B. Overview of Demonstrations / Flight Tests

The demonstrations / flight tests involved four, five-day campaigns and were carried out with the support of ACUASI using a combination of unmanned and manned aircraft. Excluding preparation work and pre-testing, there was approximately 1,536 person hours for the flight test team, 53 hours of crewed intruder aircraft over 25 flights, 64 hours of ownship UAS flight time over 128 flights, 24 hours of intruder UAS flight time over 28 flights and 245 total unmanned-to-unmanned and unmanned-to-manned encounters.

Multiple actions were taken prior to and during the demonstration / flight tests to ensure safety, especially the safety of the crewed aircraft pilots.

To ensure safety of flight operations and to mitigate an unintentional LoWC, well-clear distance plus a 50% additional distance buffer was used as a minimum separation distance between manned and unmanned aircraft at the closest point of approach (CPA) between encounter aircraft.

In addition, verbal communication was continuously maintained with manned aircraft and remote pilots through 2-way radio for position reporting of aircraft and coordination of flights and encounters.

Flight test teams included participants from Vigilant Aerospace as well as ACUASI. Vigilant Aerospace team members operated the testing systems and software while ACUASI team members operated the manned and unmanned aircraft and some of the sensing and testing equipment.

i. Flight-Test Campaign #1

The first flight test campaign was carried out the week of January 25-29, 2021 at the Poker Flat Research Range in Chatanika, Alaska. Vigilant and ACUASI personnel met at the University of Alaska Fairbanks on January 21st to review equipment, configuration and software and prep for equipment testing. This was an essential step for efficient time management to ensure the best use of field time at the Research Range engaged in testing flights, and similar preparation work was carried out before each flight test.

Vigilant collaborated with members of the flight test team at ACUASI to coordinate and conduct a full-scale equipment and systems test outdoors at the University of Alaska Fairbanks of all systems to be used during the demonstration / flight tests, on January 22nd. This invaluable activity allowed test engineers to troubleshoot system configurations, which were being configured in ways that were new to the testing team, with the resources of UAF nearby to

Figure 3

Setup and pre-testing of systems and equipment at the University of Alaska Fairbanks.

assist as needed. Pictured in Figure 3 above, is the flight test team setting up the equipment for pre-flight test systems checks at UAF.

Flight tests went according to schedule, despite some difficulties related to extreme cold temperatures. The coldest temperature recorded by Vigilant Project Coordinator, Zach Peterson, was -36° F. These flight tests were carried out at the Poker Flat Research Range, with equipment being set up each morning and then stored in an on-site building each evening.

This flight test campaign included testing three predicate radars, radar data capture and logging to the DAA system and secondary laptops and software, sUAS and manned aircraft, GPS data logging and a variety of photo, video and notational data collection.

The primary purpose of demonstration / flight test 1 was to advance our understanding of the operational capabilities of the overall test system and specific hardware and software to be tested. Additionally, we sought to establish a baseline of expected equipment performance to measure against improvements throughout the rest of the demonstration / flight tests. The flight tests were designed to make an initial evaluation of system performance during calibration, then evaluate simple flight maneuvers to assess expected performance and finally advance to more complex flight maneuvers to stress the systems, all of which was completed daily and built upon.

During regular intervals of flight testing, data log validation was carried out to ensure that data was being captured. Vigilant also provided a shared cloud file storage location for flight test team members to upload their data in a consistent manner, by source, by category, by day, to ensure accurately captured data. As was controllable, daily time syncing of digital clocks on all equipment occurred and was confirmed.

ii. Flight-Test Campaign #2

Building on demonstration / flight test 1, the second flight test campaign was carried out the week of February 26-March 3, 2021. Vigilant and ACUASI personnel met at UAF ahead of Demonstration / Flight Test 2 to review new equipment, radar configuration, GCS and FlightHorizon software improvements, and test new equipment.

Two of the five days of testing were postponed due to inclement weather below safe minimums These two days of testing were later completed in Alaska prior to commencing demonstration / flight test 3. Of the remaining three days, two days of testing took place at Poker Flat Research Range, and the last day was conducted on the campus of University of Alaska Fairbanks.

Testing the range and accuracy of the radars, and specifically the airborne EchoFlight radar, and detect-and-avoid systems after software and hardware adjustments were made to improve performance was conducted. Testing was advanced to include specific encounters with an intruder sUAS and intruder manned aircraft simultaneously (pictured below in Figure 4).

ACUASI personnel made suggestions to enhance telemetry broadcasting from the Ground Control Station laptop to the FlightHorizon laptop, based on previous testing conducted in partnership with NASA. ACUASI also upgraded hardware used to transmit radar data from the EchoFlight onboard the test UAS to the ground-based receiver, increasing the transmission range.

The last day of testing at the campus of University of Alaska Fairbanks tested the radar and detect-and-avoid systems in an urban environment where there were a greater number of targets and radar system filtering was applied to help mitigate the number of false targets.

Figure 4

The unmanned aircraft (ownship) photographed during scripted encounters with the two manned aircraft used during the flight test.

iii. Flight-Test Campaign #3

Building on demonstration / flight test 1 & 2, the third flight test campaign was carried out the week of April 23 -29, 2021.

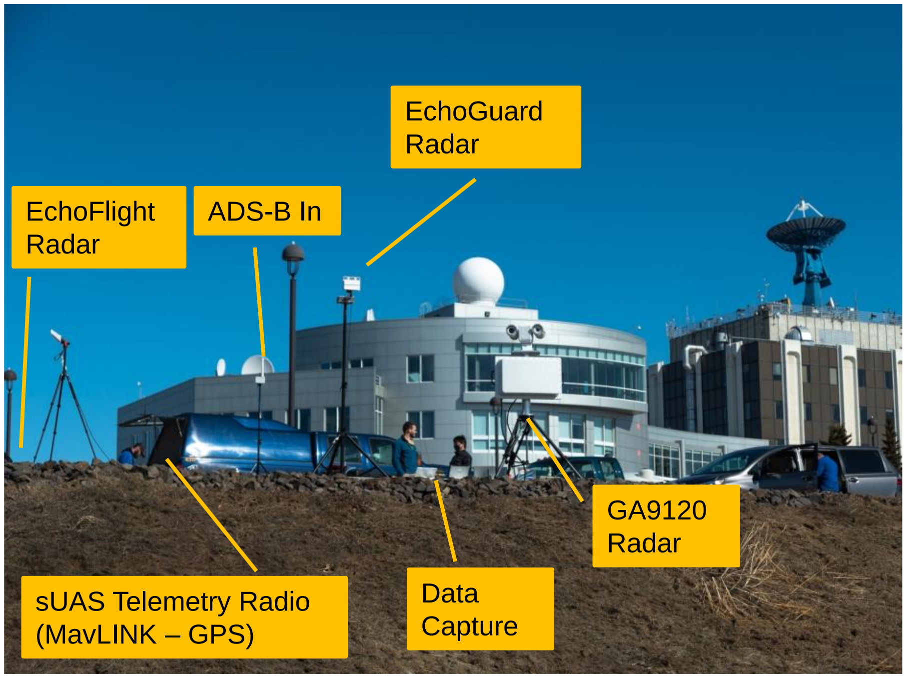
The first three days of testing included observations of radar and DAA system performance with additional filtering, while operating in an urban environment. An intruder sUAS flying specific encounters to generate alerts, warnings, and RA’s was introduced on two days and a manned aircraft was also introduced to further stress the system.

The remaining two days of Demonstration / Flight Test 3 were conducted on the campus of the University of Alaska Fairbanks as EVLOS operations using a trained visual observer who was in constant communication with the two-person flight crew operating the sUAS.

EVLOS flights were conducted to further test the onboard version of FlightHorizon while connected to the autopilot to receive ownship telemetry, as well as the signal integrity between EchoFlight radar and ground-based receiving station when the sUAS was beyond the visual line of sight of the remote pilot in command. A manned intruder aircraft was introduced on the last day of EVLOS testing.

Figure 5 below shows the equipment setup for flight testing at the university campus.

Figure 5



Equipment and system setup for flight testing at the University of Alaska Fairbanks.

iv. <u>Flight-Test Campaign #4</u>

Building on the previous demonstration / flight tests, the fourth flight test campaign was carried out the week of June 7-11, 2021 along the Trans-Alaska Pipeline System (TAPS). Alyeska Pipeline Services granted a request to conduct demonstration / flight test 4 along a designated area of the Trans-Alaska Pipeline System, using UAF Waiver number 107W-2020-04368, for BVLOS operations.

There were five days of testing that included deploying four ground-based Echodyne radars and one ground-based OWL GA9120 radar (shown below in Figure 6) on a daily basis. The four ground-based Echodyne radars were used to comply with the UAF Waiver requirements for BVLOS flights.

The primary purpose of demonstration / flight test 4 was to advance the cumulative progress from the previous tests and apply them toward an actual BVLOS flight, with specific safety mitigations, in a real-word environment whereby a use case of UAS for long-linear inspection of the TAPS could be simulated.

Two sUAS were used during the tests while conducting true BVLOS operations; one designated as ownship with onboard radar, ADS-B In, and a minicomputer running FlightHorizon PILOT, and the other acting as an intruder sUAS. There was a manned aircraft participating that was also acting as an intruder.

On the fifth day of testing, both the intruder sUAS and manned aircraft were used simultaneously. Staff from Vigilant, ACUASI, and Alyeska Pipeline Services were present during all days of testing. The test area was in a secure location with gated entry and restricted access.

Figure 6

View of the GroundAware 9120 ground-based radar unit pointed towards the designated encounter airspace at the Alyeska Pipeline flight testing location.

4. OBSERVATIONS / RESULTS

A. Discussion of Goals Achieved and Successes

Noted in the Project Plan were the following project goals:

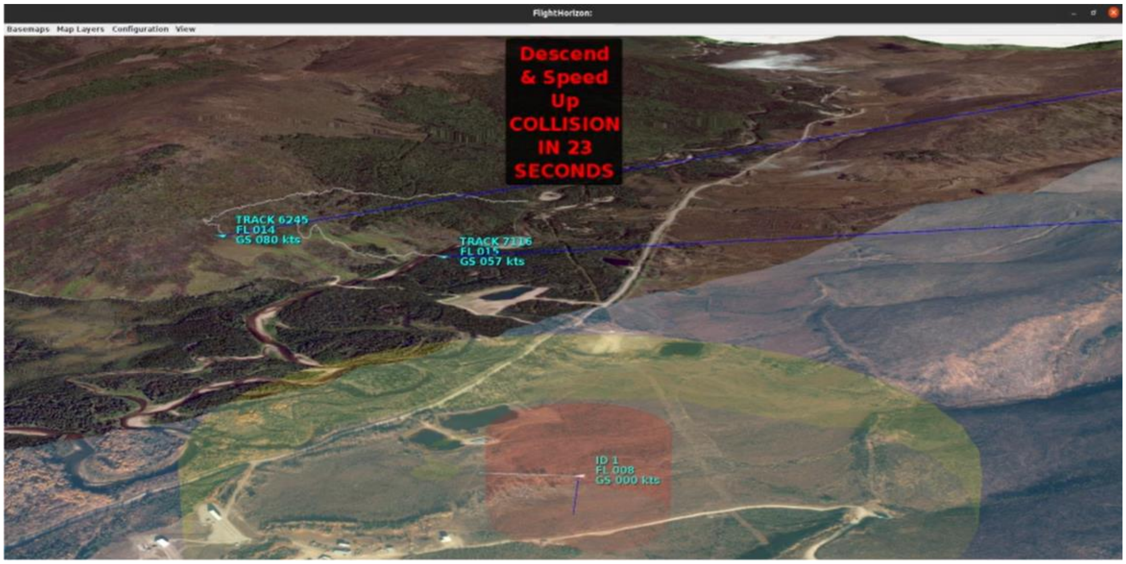
- Determining that specific commercially affordable radar models can be a viable sensor in the detection and tracking of non-cooperative (non-transponder) intruder aircraft;
- Determining that such radar input can be fused into existing detection processes and used for intruder aircraft tracking in software;
- Determining that such radar data can be used to calculate intruder aircraft's closest point of approach (CPA) to ownship;
- Determining that such radar data can be used by the detect-and-avoid software to calculate potential loss of well clear; and
- Determining that such radar data can be used by the DAA software, in combination with other data sources, to calculate an avoidance maneuver for the unmanned aircraft ownship to successfully maintain well clear.

The following analysis sections of this report were arrived at based on several processes:

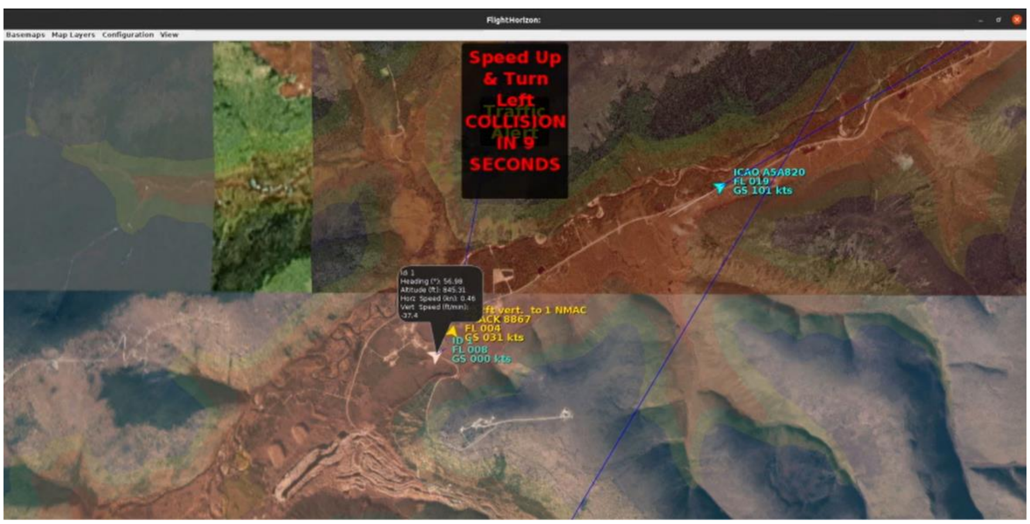
- Multiple in-depth conversations between Vigilant Aerospace and Echodyne radar manufacturer staff, and Vigilant Aerospace and O.W.L. radar manufacturer staff, especially on configuring and tuning the radars.
- Significant testing of the radar systems prior to and between demonstration / flight tests. This was useful to further integration, filtering, calibration and tuning steps.
- Observation of the vendor radar UI software and the FlightHorizon COMMANDER user interface by Vigilant personnel during testing. Using the FlightHorizon COMMANDER software was especially useful because it combines ownship telemetry, ADS-B In tracks and radar tracks into a single unified display with track correlation for ownship tracks.
- Post-test review of data logs and simulated replay of the flights using the data logs in the FlightHorizon COMMANDER software, allowing for careful review of the data in a detailed visual environment.
- Actual radar integration with FlightHorizon COMMANDER and PILOT, so that simultaneous data logs were made and kept for multiple sensors and could be replayed together.

The Echodyne EchoGuard and EchoFlight radars, as well as the O.W.L. GA9120 radar are viable sensors for detecting and tracking non-cooperative intruder aircraft and can be combined and correlated into existing detection processes and used for intruder aircraft tracking in FlightHorizon software.

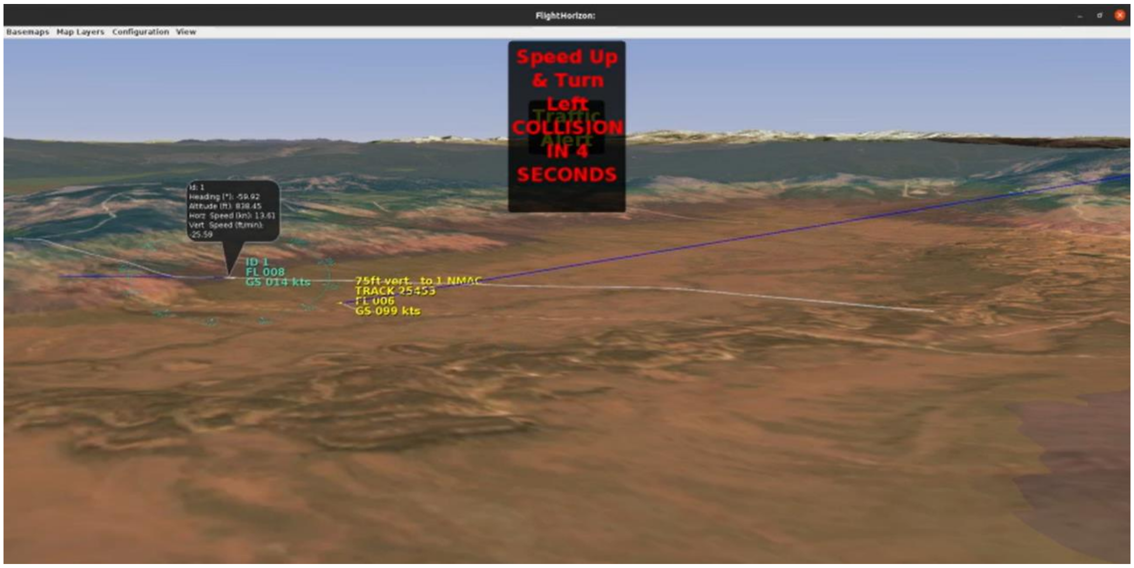
For example, in the representative screenshot below, from Flight Test #1, Day 5, the FlightHorizon software is using both live radar data from an Echodyne radar, data from the ADS-B In receiver and ownship telemetry to generate and display aircraft tracks on the moving 3D map. The aircraft trajectories are being predicted and one radar tracked intruder is causing the software to issue a resolution advisory to prevent a possible loss of well-clear and, eventually, an NMAC condition. The yellow well-clear boundary around the UAS ownship is displayed and the red NMAC boundary around the UAS ownship is also displayed. (No actual loss of well-clear or NMAC condition occurred during this or any flight test during this project.)



Similarly, in this screenshot from live flight testing at Poker Flat, the system is displaying data from radar, ownship telemetry and an ADS-B In target, in which an intruder aircraft tracked by radar is generating an NMAC condition warning and resolution advisory in the DAA software based on the projected trajectories of both ownship and the intruder aircraft. (No NMAC condition occurred during this flight. The inconsistency in the underlying aerial photography is caused by either slow internet download speeds or different resolutions of available photography, but does not effect the function of the DAA system and can be turned off or pre-cached, if distracting to a remote pilot using the system.)



In this screenshot from live flight testing at the Fox Operating Area of the Trans-Alaska Pipeline, FT#4, Day 5, the system is displaying data from radar tracking of the intruder aircraft and ownship telemetry in which an intruder aircraft tracked by radar is generating an NMAC warning and resolution advisory in the DAA software based on the projected trajectories of both ownship and the intruder aircraft. The relatively high speed of the intruder aircraft during this encounter is generating a long trajectory prediction within the time bounds of the DAA function (No NMAC condition occurred during this flight.)



In addition, further analysis of the specific radar tracks recorded is provided in Section 8 - Appendix.

B. Comparative Radar Design and Function

The Echodyne EchoGuard and EchoFlight, as well as the O.W.L. GA9120 were all used throughout the four demonstration / flight test campaigns. The use and selection of a particular model of radar for DAA purposes should consider the UAS flight intent, location, concept of operations, risks and mobile versus permanent deployment. Also, the need for continuous airspace management versus intermittent use should be considered in selection of the radar for DAA.

When properly calibrated and operated by an individual familiar with the respective radar, all of the radars used in this project were observed to perform to the standards claimed by the manufacturers on multiple occasions, including detecting manned aircraft reliability, precisely enough for DAA purposes and with a range sufficient for performing DAA maneuvers by the UAS being used for testing, if actual DAA maneuvers had been required.

See Section 8 – Appendix, for detailed diagrams of target tracking by the radars and brief analysis of the performance of the individual radars.

Below, each radar is listed with advantages and limitations. Note that the comments about the radars are based on manufacture specifications, obvious physical characteristics and qualitative observations.

i. EchoGuard Ground-Based Radar

The EchoGuard from Echodyne is a ground-based, ultra-low SWaP MESA radar that detects and tracks both manned and unmanned aircraft. Advantages of the EchoGuard include ease of deployment, lightweight, compact, user-friendly UI. Limitations include max range of 5km and durability of metamaterial.

ii. EchoFlight Onboard Radar

The EchoFlight radar from Echodyne is an airborne radar designed for inflight DAA on unmanned aircraft. Advantages of the EchoGuard include ease of deployment, lightweight, compact, user-friendly UI. Limitations include lack of integrated software to process IMU data for inflight heading orientation and durability of metamaterial.

iii. GA9120 GroundAware Ground-Based Radar

The GroundAware GA9120 from Dynetics / O.W.L. is a 3D digital multibeam-forming, ground-based radar system for long-range manned and unmanned aircraft detection and ground surveillance. Advantages include radar coverage within 12km, advanced filtering, alert zones, classifier and durable construction. Limitations include larger size and weight (still portable) and specialized tuning / calibration requirement for deployment in new environments.

As noted above, the radars were observed to perform as stated by the manufacturers.

During flight testing, the function of the FlightHorizon DAA system in consuming and using the live radar detection and track data for the ownship and intruder aircraft was visually compared to the tracks being displayed in the Echodyne and GA9120 vendor software to ensure that the tracks were being processed and displayed consistently and correctly across all systems.

In addition, when manned aircraft targets were beyond VLOS, approximate location was validated via two-way radio communication between a ground observer and the PIC of the manned aircraft. When unmanned aircraft targets were beyond VLOS (in either EVLOS or BVLOS operations), location was validated by observing the GCS laptop, which displayed location of UAS based on GPS fed through telemetry.

C. Discussion of Improvements between Demonstrations / Flight Tests and Best Practices

Personnel from Vigilant Aerospace and ACUASI made up the flight test team and routinely collaborated on opportunities for improvement and best practices prior to commencing the first demonstration / flight test and throughout the duration of the testing. There was also an effort to find or create as many efficiencies as possible to maximize the available test time. Each campaign included advanced planning and discussion of backup plans and / or possible relocation contingencies if there were issues with the planned test site.

The following best practices were applied before, during and after testing, as applicable.

Practical Best Practices:

- Advanced planning, equipment testing and setting expectations (no surprises).
- Attention and adherence to COVID-19 safety protocol.
- Arriving one to two days in advance of tests to do setup and pretesting.
- Proper outfitting of clothing and gear for personal safety in extreme environment.

Operational Best Practices:

- A daily action plan available to all team members to plan and prepare.
- A clear chain of command for operational and emergency situations.
- Discussion and identifying clear zones around operational radars.
- Advanced communication of flight test plan with manned aircraft personnel.
- Pre-flight safety & execution briefings, delegation of duties, clear call-outs and communication.
- Limiting unnecessary chatter during critical phases of flight (sterile cockpit procedures).
- Organize and secure all test equipment and clear test site.
- Post-flight de-brief, recap, discussion of improvements and review plan for next test day.

Technical Best Practices:

- Consistent and sequenced daily hardware setup, activation and teardown routine.
- Security / isolation of network connections and links to test computers and UAV equipment.
- Regular check-in on time syncing and data logging at all stations.
- Regular check-in with flight crew to assess equipment performance.
- Backup data logs, notes & other media.

Following the best practices noted above, we were able to identify efficiencies to daily setup and tear down, to maintain emphasis and focus on execution of actual testing.

Note that, due to testing delays as a result of COVID-19, many advancements to FlightHorizon software were completed prior to testing, that were otherwise scheduled to take place between the flight tests.

Below are specific examples of improvements made during the demonstration / flight tests:

- Between demonstration / flight test 1 and 2, ACUASI personnel made suggestions to enhance telemetry broadcasting from the Ground Control Station laptop to the FlightHorizon laptop, based on previous testing conducted in partnership with NASA. ACUASI also upgraded hardware used to transmit radar data from the EchoFlight on board the test UAS to the ground-based receiver, increasing the transmission range. Vigilant and ACUASI personnel met at UAF ahead of demonstration / flight test 2 to review new equipment, radar configuration, GCS and FlightHorizon software improvements / debugging, and test new equipment.

- Between demonstration / flight test 2 and 3, software improvements to FlightHorizon COMMANDER for ingesting the IMU data from the UAS-mounted EchoFlight radar were made. To address connection stability between the EchoFlight radar and FlightHorizon during long-range LOS, EVLOS and BVLOS flights, a minicomputer with FlightHorizon PILOT installed was mounted to the sUAS. The onboard version of FlightHorizon received telemetry data from the sUAS autopilot, and further integration was required to receive a data feed from the EchoFlight radar, and ADS-B In from a uAvionix PingUSB receiver.
- To facilitate more advanced testing and connection stability between the EchoFlight radar and FlightHorizon, a minicomputer with updated FlightHorizon PILOT software was tested prior to Demonstration / Flight Test 4. The updated onboard version of FlightHorizon received telemetry and GPS data from the sUAS autopilot, a data feed from the EchoFlight radar, and ADS-B In from a Pixhawk Orange Cube device attached to the Pixhawk autopilot.

D. Basic Reporting & Analysis of Human Factors Performance

i. Review of User Interface and Feedback

Throughout the demonstrations / flight tests, the following was reported during use and observation of the FlightHorizon DAA system. The comments were also checked against logged flight data during post-flight test analysis.

On introduction, the remote pilots commented that the graphical user interface (GUI) seemed intuitive. One remote pilot noted, “It was intuitive at first glance, (pointing at the screen) here’s our aircraft, NMAC and well clear rings.” The 3D view also received positive feedback for adding enhanced situational awareness with a graphical view of the horizontal separation between aircraft. The remote pilots added that they had previous experience with GUI’s of other systems that, while not providing DAA capabilities, had a similar screen appearance. One remote pilot mentioned a subtlety to their comments was that they understood what they were looking at because of previous exposure to the system, which may be a drawback for providing feedback.

Additional comments included that ownship tracking and ADS-B In performed as expected in the user interface. FlightHorizon displayed a constant track of the test sUAS on the GUI. ADS-B targets consistently populated on FlightHorizon and were confirmed with visual observation. Tracks displayed from radar appeared less consistent than ADS-B In at close range. It should be noted that the ADS-B In receiver in these tests uses an omnidirectional antenna capable of tracking the ADS-B Out signals from any direction including cooperative aircraft above or behind the field of view of the radar units.

Summarizing additional observations from users during testing, the ground-based radar provided a supplemental view of cooperative targets and enhanced situational awareness of non-cooperative targets. Airborne radar provided a supplemental view of cooperative targets and enhanced situational awareness of non-cooperative targets while stationary. When the airborne radar was in motion, duplicate radar target tracks would be display, lessening the effectiveness of onboard radar tracking. Improvements to IMU integration to the software should reduce this duplicate track problem in the future.

ii. Remote Pilot Reported Effectiveness of DAA and Recommendations for Improvement

The remote pilots reported that the FlightHorizon DAA system was effective in enhancing situational awareness by generating alerts (resolution advisories) embedded in a 3D display of the airspace they were operating in.

Recommendations for improvements to the FlightHorizon DAA system included:

- Having available a “quick-start” text user guide to review before initial use and to reference as needed.
- Enhancing the software filtering capabilities to mitigate a distracting number of false tracks from radar.
- The ability to change common radar and sensor settings in the GUI, versus in the code.
- Update alerts (RA’s) to prevent them from “talking over” each other, such as when an intruder changes course or a second intruder enters the picture.
- Tweak directional icons to orientate in the actual or predicted path of flight, versus displaying a directional icon that appears to slip or skid in normal unaccelerated forward flight.
- Formalized in-depth training for performing actual mitigation of safety concerns and enhanced situational awareness. There would be an operator need to understand things such as false tracks.

iii. <u>Remote Pilot Reported Workload & Timing Issues</u>

There were two remote pilots in each flight team and multiple flight teams that were able to make observations when not acting as PIC. Potential issues with timing were discussed and observations made while the FlightHorizon DAA system was in use. (Due to the inherent complexity of the demonstrations / flight tests, safety of flight operations and policy, the remote pilot-in-command (PIC) was not able to directly observe a screen displaying FlightHorizon while in control of their aircraft or monitoring the GCS.)

While the remote pilots acknowledged that an additional screen to monitor would add to the workload of normal airborne operations, comment was also made that if a DAA screen were located in close proximity to the GCS screen, it would become part of the regular instrument scan and additional workload would be limited.

Note: The FlightHorizon DAA system would not add to high workload operations such as takeoff and landing, which would continue to be conducted visually, within visual line-of-sight or with a high-resolution camera at the landing location, with manual remote pilot control.

A concluding consensus was that the most effective method of mitigating additions to workload or timing issues would be to have the FlightHorizon DAA system merged into the GCS software so the display was on one screen. This may be implemented in future versions of the software.

E. Analysis of Well-Clear

All testing was conducted with safety of the flight test team and participating vendors as the priority, and in accordance with ACUASI and UAF policies. As such, there were no flight test plans for encounters that included an intentional LoWC, nor was there an unintentional LoWC at any point during the testing.

Typical encounters between unmanned to unmanned aircraft and unmanned to manned aircraft were performed at horizontal and / or vertical well-clear plus an additional 50% or greater spatial separation. For example, horizontal separation was typical during unmanned-to-unmanned encounters whereas vertical separation was used during unmanned to manned encounters. When both an unmanned and manned intruder were present for the testing, horizontal separation was used with the unmanned aircraft and simultaneous vertical separation was used between the manned intruder and unmanned aircrafts.

Review of the flight data logs from FlightHorizon after the fields yielded these safety observations:

i. Well-Clear for Non-Cooperative Aircraft

Scripted encounters were planned such that test aircraft approaching a potential LoWC were previously scheduled to deconflict. During the flight tests well-clear was always maintained. When a scripted encounter with a non-cooperative aircraft was approaching LoWC, well-clear was maintained through planned deconfliction.

ii. Well-Clear for Cooperative Aircraft

Scripted encounters were planned such that test aircraft approaching a potential LoWC were previously scheduled to deconflict. During the flight tests, well-clear was always maintained. When a scripted encounter with a cooperative aircraft was approaching LoWC, well-clear was maintained through planned deconfliction.

F. Analysis of Performance of DAA System and Software in Avoidance Advisory Functions

The version of FlightHorizon software ultimately used in these flight tests for DAA was significantly more advanced than the software originally planned for this project due to delays in flight testing dates caused by the COVID-19 pandemic and the additional software development time available.

Additionally, local flight tests, as well as equipment and radar tests, outside and independent of this contract, were conducted before the demonstration / flight tests commenced. These factors all contributed to the core functions of FlightHorizon performing as expected as a DAA system.

These observations emerge from review of data logs and simulated replay of the flights using the data logs:

i. Data Correlation Process, Track Matching, Track Prediction, Traffic Alerts, Warnings, and Avoidance Timing

The data correlation process, track matching, and track prediction all performed as expected. The timing Resolution Advisories generated during encounters were sufficient to allow a remote pilot to conduct a resolution advisory (RA) to avoid a collision. On average, the RAs provided the remote pilot with at least 10 seconds or greater warnings before a collision could occur.

ii. Remote Pilot Actions

Due to the scripted nature of the encounters during the demonstrations / flight tests, ACUASI / UAF policies and the experimental nature of the FlightHorizon COMMANDER DAA software, the flight test crew observed but did not use FlightHorizon COMMANDER as the primary flight display. All remote pilot actions and autopilot courses were pre-scripted to automatically vector to deconflict after a planned encounter was initiated to trigger the FlightHorizon DAA system.

5. DATA ANALYSIS

Reviewing the data logs and doing a quantitative analysis provided useful statistical results that could potentially be used for improving setup and calibration procedures, software, enhanced training for operation and / or a better understanding of mission specific filters.

The demonstrations / flight tests took place in three unique environments across five months with temperature variances of 118 degrees Fahrenheit and daylight ranging from less than 4 hours during the first test to over 22 hours during the last test. There were also other conditions that could have affected the performance of the systems being tested and the resulting data logs.

The qualifications to performance are important in assessing the robustness of the radars and DAA systems, which as previously noted, were all observed performing as expected when adequately calibrated, filtered correctly and free of interference.

The radars did not perform well when initial calibration was inaccurate, there was inadequate performance tuning for different test locations or unexplained interference was present. These factors could skew the resulting radar data generated.

Addressed here are some of the potential factors that could have caused inconsistent performance of the radar systems being tested. This is followed by a high-level overview of the results from the radar data.

A. Environmental Factors Impacting System Performance:

i. <u>Magnetic Deviation:</u>

One of the challenges noted when calibrating radar heading was dramatic variance in magnetic compass headings. When operating at Poker Flat Research Range, University of Alaska Fairbanks, or nearby the Trans-Alaska Pipeline System, compass heading deviations of 18° were observed over some 50 m traversals. Because the headings had high variance between locations, calibration of radar heading was predominantly accomplished by either having a target vehicle traverse a known path or sight the radar's heading visually by using an object in the distance. Sometimes magnetic headings were used, and because of the data's sensitivity to initial calibration this could be a significant source of error. In one case, Vigilant staff also observed a momentary approximate 20° magnetic heading swing while stationary on the ground and troubleshooting radar heading.

ii. <u>Electromagnetic Interference:</u>

Intermittently, at all test sites, EM interference was monitored within the communication bands of the UAV's. EM interference was **not** monitored within the bands utilized by the radars except for any monitoring built into the radars themselves. When setting up the EchoGaurd radars, care was made to minimize interference between sensors. Depending on the terrain, a selection of time and frequency separation was selected to minimize interference between ground radars; however, for ownship radar, only frequency separation could be used. This had a limited ability to minimize interference, so it is suspected a large number of false tracks in the EchoFlight data may be caused by the ground radars. Future work using radars for DAA will address this with specific RF technical mitigations, if multiple radars are to be used.

iii. <u>Radio Frequency Interference:</u>

There were two specific days during testing, one each at Poker Flat Research Range and the University of Alaska Fairbanks, during which all systems did not perform as expected. This included devices that otherwise operated as expected at all other times, such as cellular phones, laptop computers and radio transmitters. RF scans were completed by ACUASI personnel, and the areas were confirmed to have intermittent higher amounts of RF “noise” than was typical. The “noisy” frequencies did not overlap the frequencies being used by the radars. Nonetheless, there were radar performance issues that could not be explained or rapidly debugged. These anomaly days were bookended by testing days on either side during which systems performed as expected, and without significant modifications to how the system was setup and operating. A variety of unknown government or private sector transmissions could have been the source of the RF interference.

iv. Additional Noteworthy Comments:

- Vigilant’s Project Coordinator became aware of Military activities within the vicinity of the demonstration / flight tests, for planned GPS jamming tests. The nature and specifics of these tests were not clear, however the timing overlapped almost all of demonstration / flight test 3.
- While the demonstration / flight tests did not specifically include a climatological study of the impact on the systems being tested, there were differences in performance observed depending on temperature. In particular, days at -20 degrees Fahrenheit or colder had adverse effects on some test equipment, although radars continued to perform as expected.
- O.W.L. recommends deployment height of the GA9120 radar system at approximately 20’ AGL. When this is not possible, O.W.L. recommends deploying as high as possible in areas with minimal obstacles directly in front of the radar. While it was not possible to deploy the GA9120 on a mast 20’ AGL, the radar was elevated to heights that were sufficient to achieve performance as expected. It is possible that excessive false tracks from low-level objects such as animals (a moose was observed on more than one occasion) and trees moving in the wind could have been filtered out of the data if the radar system could have been further elevated.

B. Overview of Radar Data Analysis:

The data picture from review of the radar logs after testing tended to align with the observations made during the live demonstration / flight tests by Vigilant’s flight test team. While there were some limitations to radar consistency, it is our perception that these environmental factors can be mitigated with advanced filtering techniques. Some generalizations can also be made about radar efficacy and utility as part of a DAA system in a practical application.

Initial calibration and tuning of the radar system to perform optimally in the environment in which it is located is essential to efficacy. Our expectation is that a form of “self-calibration” during radar initialization will emerge as the technology advances, but as of now it is necessary to manually calibrate and re-calibrate the radars to achieve expected performance.

All the radars were observed, and then later confirmed through radar data logs, to have consistently limited performance when a target was at a low altitude, near the radar and moving slowly. The radars also reported decreased or low target confidence of any nearly motionless or slow velocity targets along the XYZ axis. For the practical application of radar in a DAA system, the limitation of performance when a target is low in altitude, nearby and moving slowly, usually represents a lower level of hazard for the UAS than faster moving aircraft. Such a target may be more easily mitigated by other sensors, such as an onboard high-resolution camera used by the remote pilot. See Section 8 – Appendix, Part C, for additional information.

6. LESSONS LEARNED

There were several lessons learned that would benefit future testing and that would help to increase future quality and quantity of testing that can be completed in a given period of time or with a particular budget.

Noteworthy lessons learned were several:

- Exceptional investment in pre-planning and pre-testing is a necessity to ensure the best possible outcome of actual tests. Ideally, this would be accomplished as close to onsite as is practical and / or in similar environmental conditions (pre-testing in North Dakota in the winter has some similarity to actual testing in Alaska in the winter). It is important not to assume that equipment will perform in an environment it hasn't been previously tested in.
- Clear and concise communication with all team members, including those in the field, the office and providing ancillary support, regarding the plan and near-term activities, is critical. "Need-to-know," should not be assumed or considered an acceptable practice unless there is a stated or formal level of confidentiality or secrecy required by the nature of the tests. The more team members who understand what the project goals are, the more likely that problems and delays can be spotted and smoothed out in advance.
- Set expectations for an even, measured cadence during test days, sometimes referred to as, "Go slow, to go fast." There is a great benefit to setup and teardown efficiency by maintaining a structured routine that all team members understand and adhere to. When everyone is where they need to be on time and are performing the tasks that have been previously communicated, the likelihood of missteps is lessened, and mental fatigue is reduced.
- Lessons for daily test activities include to plan ahead and prepare, start early and stop early, encouraging a policy of "if you see something, say something," and knowing the facts of the operation through verbal confirmation and not assuming that facts are already known.

Additional lessons learned included responding to environmental challenges and metering progressive testing complexity.

- Ideally, the testing environment would progress from the most favorable to increasingly harsh conditions to limit the number of factors that could adversely impact the testing. Due to the impacts of COVID-19 and the ensuing delays, demonstration / flight test 1 that was originally scheduled for mid-2020 was delayed until January 2021. While all safety risks were satisfactorily mitigated, the extreme cold temperatures impacted the testing efficiency, and efficacy of some equipment. The flight test team was able to compare the overall impact of testing in January versus testing in June. Had the initial tests been conducted in more moderate weather conditions first, identifying the cold temperatures as the most likely variable impacting the performance of the equipment would have been more evident. Instead, when a "bug" was causing poor or unexpected performance of the test equipment, isolating the cause was less straightforward as the cold temperature was one of several possible variables.
- Each demonstration / flight test campaign and the individual days making up the campaigns were progressive in nature, each building upon the last and becoming increasingly complex. There were two notable lessons learned from this approach, and while the following comments are not meant as guiding principles for future tests or suggestions of best practices, consideration should be taken and openly discussed.
    - Since the demonstration / flight tests were all subsequently more complex, were carried out with portable equipment that was re-installed each day, and each day built on the last, there were no two test days that were identical. Even when the same test was repeated multiple

times throughout one day of testing for purposes of comparison, there was not the opportunity to compare testing results between days. There were some cases where immediate post-test data analysis would have benefited from an immediate end-of-day analysis to allow for changes to testing conditions immediately.

- As each day of testing became more complex, there were new and sometimes unique barriers to overcome. One such barrier that became evident during demonstration / flight test 1 was the physical distance used for EVLOS and BVLOS testing, which created disconnections between payload radios and the ground control station. This was especially problematic for the EchoFlight radar, which required continuous, positive control from a computer. The issue was initially resolved by swapping in a longer-range radio. However, increasing testing distances required a better solution. For FT#4, the onboard FlightHorizon PILOT system was successfully used to control the onboard radar, providing continuous positive control of the radar as well as data logging and onboard DAA system testing.

7. RECOMMENDATIONS

In general, Vigilant Aerospace recommends that continued, regular and ongoing demonstrations / flight tests take place to help facilitate the integration of UAS into the NAS. Vigilant also suggests careful consideration and adoption of practices to improve the results of future tests as noted above in Section 6 – Lessons Learned.

Thank you for partnering with the Vigilant Aerospace Systems on this contract. We look forward to opportunities to work with the Federal Aviation Administration again in the future to help ensure the ongoing safety of our National Airspace System.

8. APPENDIX

A thorough analysis of the data from the four demonstration / flight tests was conducted and used to generate the figures in the Appendix. Through the data, we were able to add a quantitative component to our observations while using the equipment in the field. There are several important factors to note about the figures when reviewing:

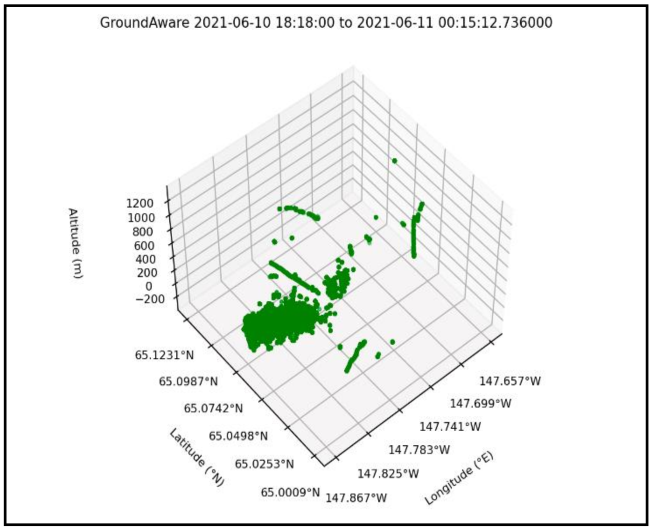
- There are occasional negative altitude values in the radar target data, which accurately reflect the data logged by the radar(s). These values could occur when targets were at lower altitude than the radar(s); or could be noise (for example, caused by reflection off the ground).
- Due to daily setup and teardown, it was not practical to calibrate an exact radar heading. This, combined with potential drift of truth data, resulted in minor lat/long discrepancies on some figures.
- Accuracy and precision of altitude, in the radar data particularly, was very limited and has mostly been excluded from our analysis because the data was highly inconsistent. This was caused both by the need to reset and re-install the radar units each day, but also by magnetic and other anomalies noted previously in the report that may be unique to this far Northern testing location or governmental operating environment.
- Further IMU and GPS integration is necessary to optimize use of the Echodyne EchoFlight radar when it is mounted on a UAV and airborne. Due to the experimental nature of the onboard system and its immediate need to control the onboard radar during longer-range flights, only rudimentary logging of this IMU data was attempted as a part of these tests.
- The figures presented below represent an entire day of testing data, not an instantaneous picture or snapshot of a particular flight or encounter.

The chart below provides an estimated number of data logs captured during the demonstration / flight tests.

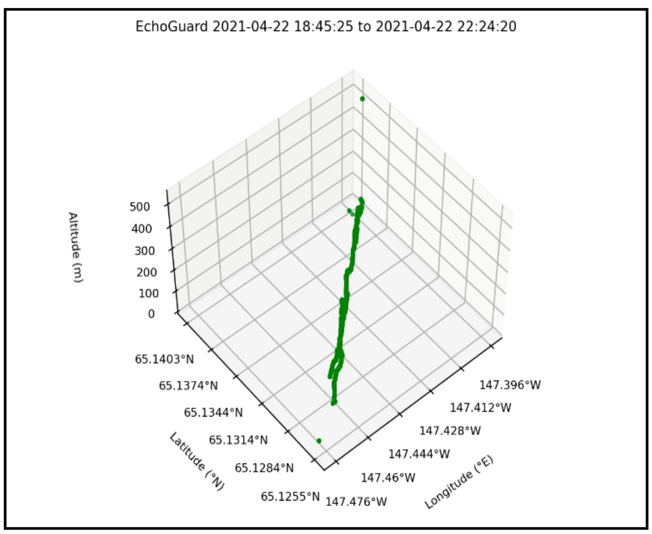
	GPS Recorder Logs	Radar Data Logs	ADS-B In Logs	Ownship Telemetry Logs	GA9120 Raw Radar Data Logs
Flight Test 1	18	70	62	63	9690
Flight Test 2	12	58	58	58	12255
Flight Test 3	6	59	59	59	71582
Flight Test 4	2	57	0	55	47080

PART A: We found that optimum radar performance occurred on days when confidence in initial radar calibration was high, system tuning was optimized and there was limited to no interference experienced or observed. The typical results that could be expected aligned with manufacture claims about radar performance and generally resulted in a consistent picture of targets with reported high radar confidence in targets.

Below are some representative figures:

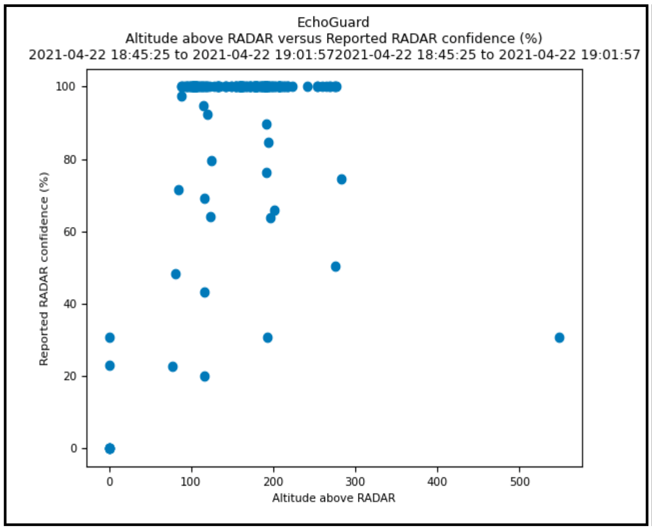


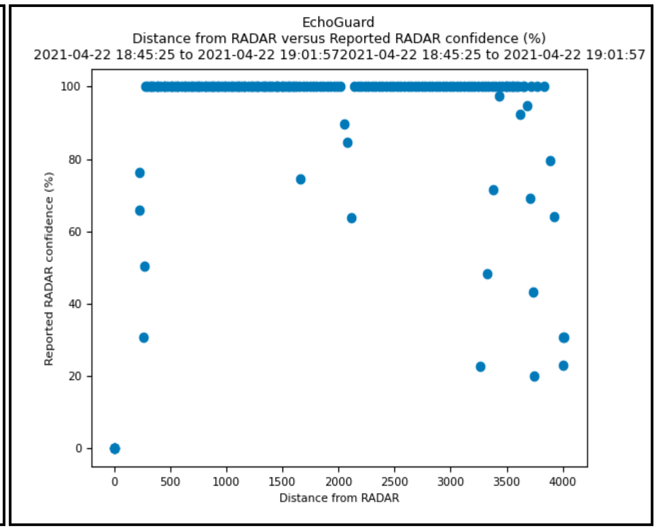
In this figure created from the O.W.L. GroundAware GA9120 data logs, there is a clear picture during demonstration / flight test 4, day 4, during which an unmanned intruder is present and flying against ownship. The large green cluster in the middle of the diagram shows the points at which the intruder and ownship had repeated encounters. The small green cluster is the maximum range at which ownship would turn around. The solid green lines are likely the detection of boats on the Chatanika River.



The figure above shows the Echodyne EchoGuard tracking ownship during demonstration / flight test 2, day 4, during which the radar was able to successfully track a particularly straight recurring flight path. This figure demonstrates what a clear radar picture might look like in a rural setting, when properly calibrated with appropriate filters applied. In this day of testing, the EchoGuard was consistently able to detect and track the ownship aircraft, as expected and with little noise and few false tracks, in these circumstances.

Additional figures generated from the EchoGuard during demonstration / flight test 2, day 4, show the reported radar confidence in targets while measuring altitude above radar, distance from radar, and XYZ dimensional velocity. The figure below on the left shows the target confidence, as reported by the radar, of targets in altitude above the radar, and the second figure below on the right displays target confidence in distance from the radar.



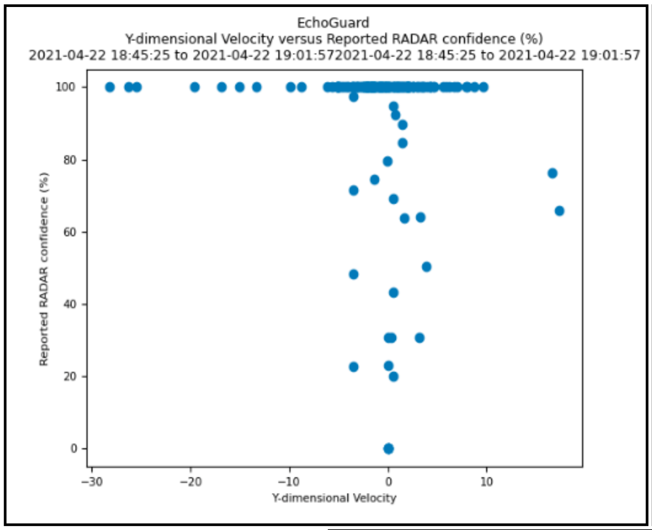


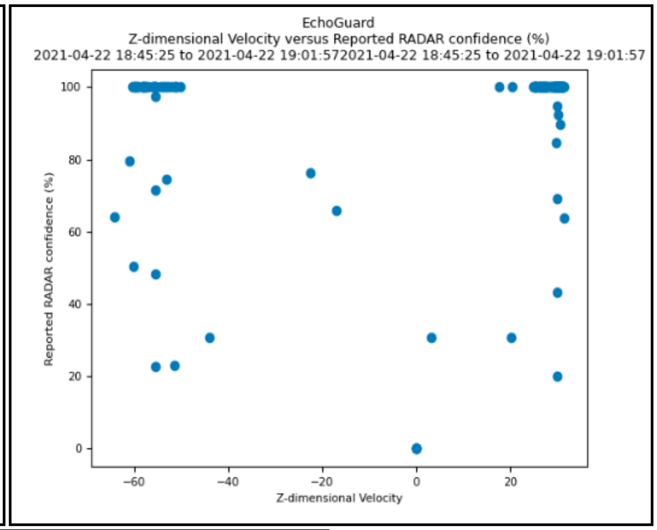
In both figures, ownship and the unmanned and manned intruders are coming in and out of the field of view (FOV) of the radar through the duration of the data log, and are discernible based on altitude and distance, the unmanned aircraft being lower and closer and the manned aircraft being higher and traveling further.

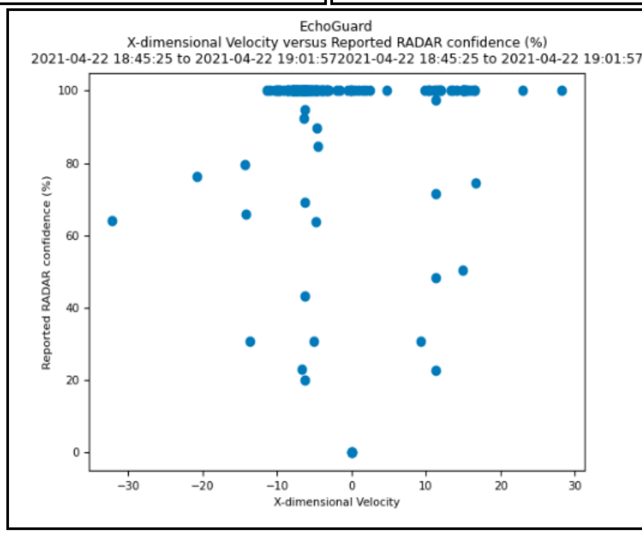
Notice that the closer the target is to the radar in both distance and height, the lower the radar confidence out to approximately 250 meters in distance and 100 meters in height, at which point radar confidence becomes steady near 100%.

This is a strong indication that the EchoGuard functions best for targets that are further away from the radar and that confidence is lower for closer and lower targets. Implications for DAA use and UAS operations are that other mitigations, like a camera operated by the remote pilot, may provide better mitigation for very nearby targets, especially targets at low altitude, but that the radar provides confident target tracking at 250 meters or more.

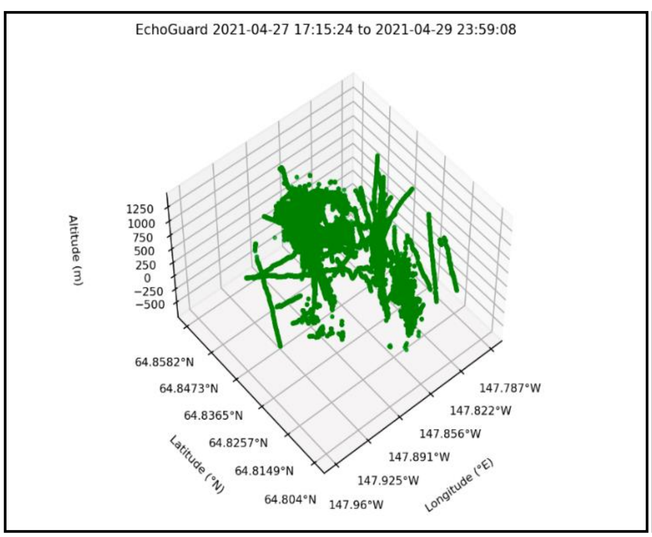
The figures below are an alternate view of the same data. The unmanned aircraft were generally operating in the X-dimension of the FOV as indicated by the slower velocity, whereas the manned aircraft was generally operating in the Z-dimension of the FOV as indicated by the faster velocity. All aircraft were operating in the Y-dimension of the FOV and generally maintained a static altitude. Notice that the lowest levels of radar confidence occur at minimal levels of velocity and sporadically oscillate thereafter. It is our hypothesis that the decrease in radar confidence of a target on the periphery of velocity occur when the aircraft is making a multidimensional maneuver or course shift. An example would be an unmanned multi-rotor or manned rotorcraft that slows to momentary hover before reversing course, or a fixed-wing aircraft that makes a rapid turn or 180 degree turn, momentarily shifting primary velocity from one dimension to another.

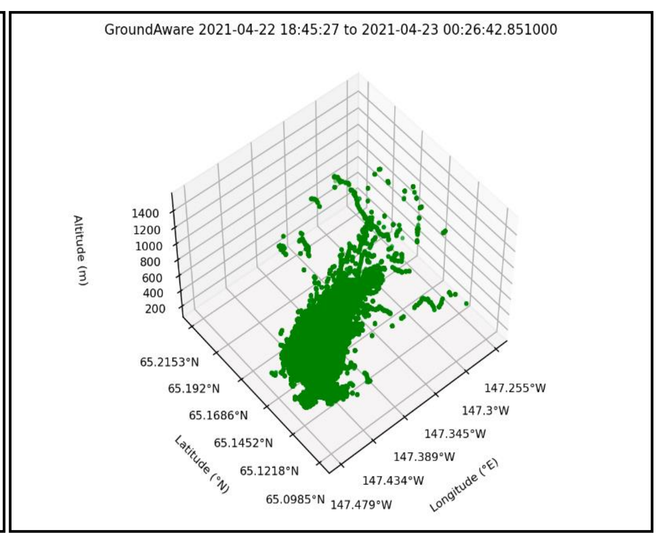






PART B: We found that radar performance was not optimum on days when confidence in initial radar calibration was low, additional system tuning was required and there was environmental interference experienced or observed, and not easily isolated. The typical results that could be expected on these days were sporadic targets, the absence of targets when they would be expected and / or the existence of unlikely (false) targets.



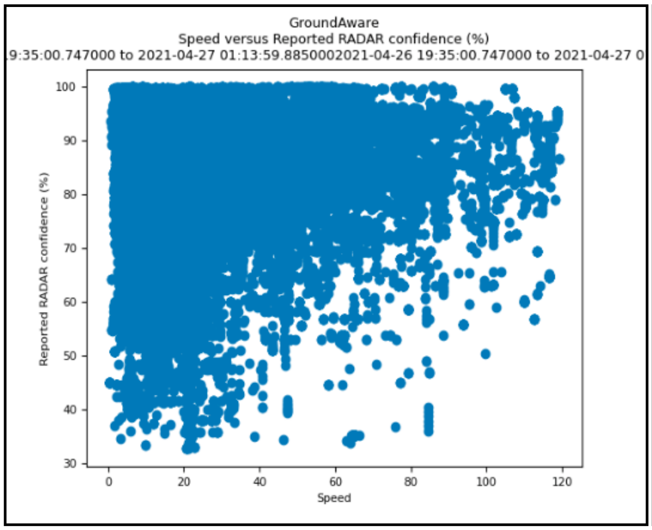


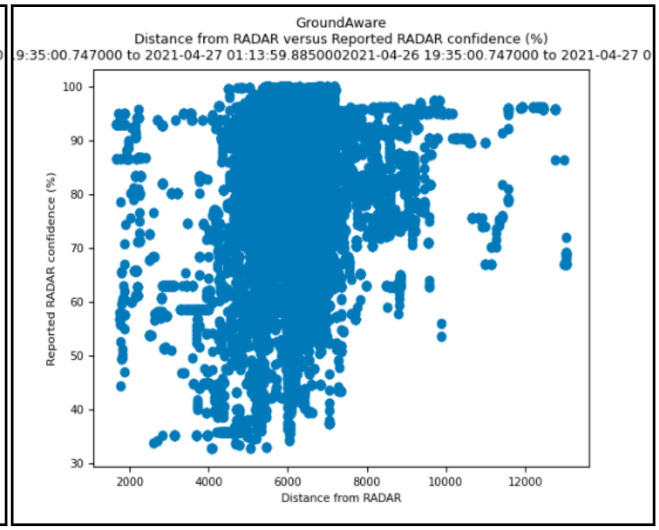
The figure above on the left is from demonstration / flight test 3, day 3 and is an example of sub-optimal performance. It is hard to say what may have caused the interference in this case. We suspect that a combination of environmental factors impacted the performance. It also seems possible there was other unexplainable RF interference given the erratic changes in target altitude. The figure above on the right is from demonstration / flight test 2, day 4. Here again, the cause of the interference is not clearly discernable. The flight test team observed expected performance from the EchoGuard on this day, but not the GroundAware radar. In this case, we suspect that the most probably cause was a mis-calibration during initial setup. These figures have been included to illustrate the impacts to the radar when initial calibration was inaccurate, or environmental interference was present.

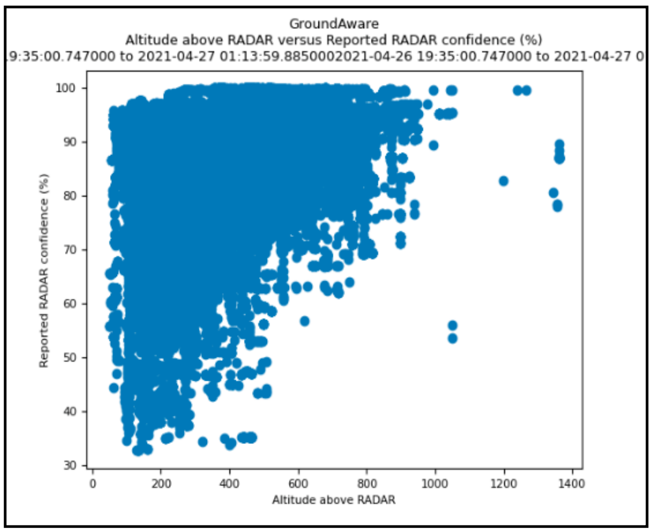
PART C: During the testing, it was observed that incremental improvements to the performance of the radars could be achieved primarily through fine-tuning of the system for the operating environment and the use of filters for speed, altitude, distance and 3-dimensional velocity. With regards to a radar system in motion, such as the airborne EchoFlight mounted to the primary test UAV, the X6, we believe that additional incremental improvement can be achieved with advancement of IMU and GPS data collection and streaming for dead-reckoning calculation.

Further improvement can be achieved when radar data is processed through the FlightHorizon DAA system. Note that FlightHorizon (as shown in prior screenshots in this report) displays only a filtered subset of radar data to the end-user, when that data creates a coherent track. Upstream in the sensing process, the radar might use data to build a track, even if not all that data will pass the FlightHorizon display filter. Radar data points only create tracks in FlightHorizon when they occur close together spatially and temporally. Since noise is generally random, the probability that noise will associate into a track is low. Therefore, when using a DAA system like FlightHorizon, most radar noise does not reach the DAA process or increase RPIC workload, because it does not create tracks and thus does not lead to DAA advisories in FlightHorizon. The result is a reduced workload for the RPIC and better rejection of noise, false tracks and other interference. Examples of FlightHorizon's advanced filtering capabilities can be seen by comparing the relatively quiet EchoGuard figures in Part A, generated from FlightHorizon radar logs, to the noisier raw radar data from the GA9120 that was used to produce the figures below. If processed through FlightHorizon, we expect that data from the GA9120 would appear similar to that of the EchoGuard.

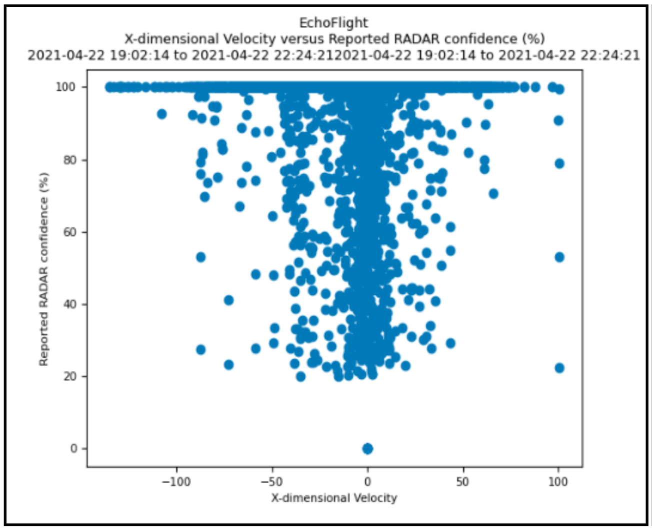
The figures below are from demonstration / flight test 3, day 2. Notice the trend from the GA9120 in reported radar confidence. The greater the target speed, altitude and distance from the radar, the higher the confidence. In this case, filters could be used to improve the radar picture. In circumstances where the mission was specific and routine, an airspace corridor could be created with filters that would exclude all targets above and below certain speeds, altitudes and distances. While filtering was used during flight testing, urban environments such as where these sample figures come from at the University of Alaska Fairbanks, which has a higher altitude than much of Fairbanks and overlooks FAI, can still be very congested, even with the use of filters to mitigate sensing in the areas without aircraft, like city streets.

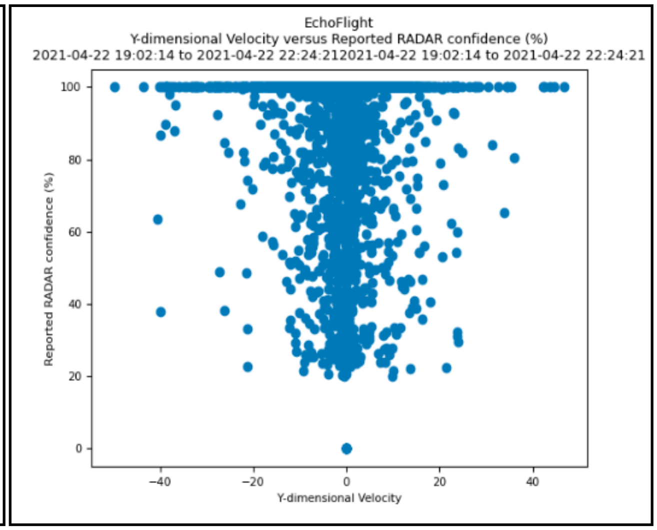


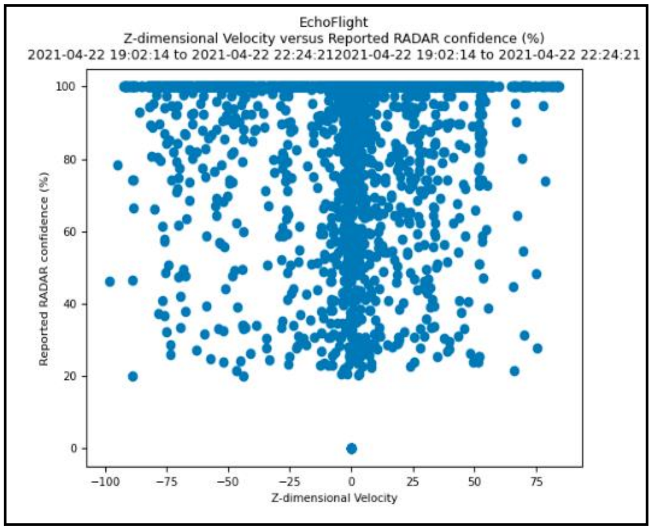




Additional filtering can be applied to dimensional velocity to reduce the number of potential false targets, such as targets that in fact are present and real, but pose low or limited risk, such as trees or small birds. Below are figures from demonstration / flight test 2, day 4. The EchoFlight is tracking a number of targets with reduced confidence in those with low dimensional velocity. If filters were applied to limit the targets being tracked at or near zero dimensional-velocity, a number of false targets would be eliminated and overall confidence in targets would increase. More sophisticated filters could also be developed for permanent deployment of these radars, and could utilize algorithms or machine learning to identify and remove regular noise such as vehicle or foot traffic that changes altitude across areas with diverse topography.







We found that each tested radar (EchoGuard, EchoFlight, GroundAware) exhibited more noise when sensing targets traveling at lower speeds compared to higher speeds. For EchoGuard and EchoFlight, the speeds are split into three dimensions (X, Y, Z) in the reference frame of the radar. For GroundAware, the speed is given as a single 3D magnitude.

- For EchoGuard, the majority of noise occurs at speeds less than ~35 meters/second in the X-dimension; less than ~18 meters/second in the Y-dimension; and less than ~22 meters/second in the Z-dimension.
- For EchoFlight, the majority of noise occurs at speeds less than ~25 meters/second in the X-dimension; less than ~15 meters/second in the Y-dimension; and less than ~25 meters/second in the Z-dimension.
- For GroundAware, the majority of noise occurs at speeds less than ~50 meters/second.

As mentioned in Part A, this implies the radars will have more difficulty tracking objects as they slow or turn around, if their velocities decrease or from dimensional shift during the turn.

Each tested radar also exhibited more noise at lower altitudes. With all three radars, when the field of view included negative altitude, namely objects below the elevation of the radar, especially large amounts of noise were exhibited.

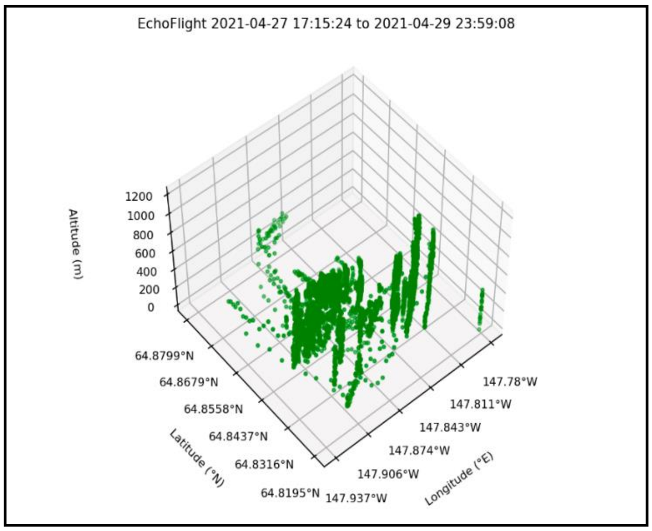
- For EchoGuard, the majority of noise occurs below ~340m.
- For EchoFlight, the majority of noise occurs below ~325m, with the worst noise occurring below ~100m.

- For GroundAware, the majority of noise occurs below ~460m.

Each tested radar also exhibited more noise at different ranges of distance. The distance-dependent noise trends are less obvious than the speed-dependent trends, in our data. Note also that distance dependent noise could have been an isolated result of environmental factors such as diverse topography and varying altitudes across the radars FOV.

- EchoGuard exhibits more noise at less than 2000m distance or past 5000m distance.
- EchoFlight exhibits some noise at all distances.
- GroundAware exhibits most noise at less than 4000m distance.

In the figure below from demonstration / flight test 3, day 3. Notice how the targets the EchoFlight is tracking appear vertically, and to a lesser degree, horizontally jittery or "bumpy." We believe additional advancements to IMU and GPS integrations would smooth the tracks and create a more stable picture. This figure emphasizes the need for advanced development of IMU and GPS integration to achieve incremental increases in performance of an airborne radar while in motion.



PART D: One of our primary objectives of the demonstration / flight tests was to assess how the radars being tested could be used as a sensor for a detect-and-avoid system. As was previously noted in this report, choosing a particular radar(s) would be highly dependent on the objectives of the intended mission. This could include ground-based versus airborne DAA, deconfliction actions being executed by an RPIC or autonomous system, permanent versus mobile deployment, ease of setup versus range or FOV and other concerns. Based on the observations and data gathered during the demonstration / flight tests, and the resulting data discussed above, we observe that the three radars tested are all suitable sensors that could be used as part of a DAA system individually or together, and in conjunction with other data sources and sensors such as telemetry and ADS-B. This is especially the case with the additional filtering function provided by the DAA system to only present established tracks in the remote pilot DAA display and only add remote pilot workload when a potential LoWC is predicted by the DAA system.

Below are examples of possible uses of the radar as part of a DAA system. The scenarios are not meant as a suggested or exclusive use but are intended to be examples of real-world applications.

When mounted on a UAV, the EchoFlight offers a diverse opportunity for conducting BVLOS flights in areas both with and without ground-based DAA infrastructure, when paired with an onboard DAA system, such as was demonstrated is possible during flight test 4. Without the constraints of staying within the coverage area of a ground-based radar system, or the necessity to set up a portable, use-specific and temporary system, the EchoFlight could be used for both routine and rapid-response applications, including BVLOS applications.

The EchoGuard is easily portable and offers the user an option to rapidly deploy a ground-based radar for missions where a RPIC needs a DAA system for a variety of applications. Routine uses could be inspection of long-linear infrastructure or surveying farmland where the possibility of encountering non-cooperative aircraft is greater than in an urban setting. Specific uses could include disaster response for areas impacted by flooding or fires, as well as search and rescue operations where some aircraft are cooperative and others may not be.

The Ground Aware 9120 is a long-range radar that could be an ideal choice for airspace management in a permanent location such as a droneport, vertiport, airport or sprawling medical campus in an area with congested airspace, and regular air traffic patterns. Three GA 9120 radars can be combined to create a radar system that provides 360-degree coverage over a 20 to 24 square-kilometer area. A system such as this could be used for DAA at enterprise scale, enabling coverage of a metropolitan area where UAV's are simultaneously leveraged for small package delivery, medical support and law enforcement while operating in airspace routinely shared by manned aircraft.