Transport Canada/LookNorth detect and avoid flight trials 2020/2021

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Transport Canada/LookNorth Detect and Avoid Flight Trials 2020/2021

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National Research Council Canada
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Canada

FLIGHT RESEARCH LABORATORY

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ABSTRACT

The National Research Council's Flight Research Laboratory has collaborated with Transport Canada and Look North to provide guidance, analysis, and recommendations regarding field trials of developmental Detect and Avoid technologies by three Canadian companies.

The systems employed in these trials are considered to be developmental as opposed to operational. The objectives of the testing were primarily to:

1. Inform system modelling activities such that the simulation can leverage the flight test data and estimate the system's performance under different circumstances
2. Assess the critical issues as relevant to the JARUS SORA process identified by Transport Canada
3. Identify and report on system deficiencies
4. Report on reliability
5. Assess whether the system is ready for operational test and evaluation
6. Assess the technical risk and evaluate the compliance with the specifications in respect to operational requirements
7. Assess human factors and identify limiting factors where possible
8. Establish a risk managed flight test planning philosophy that may be used by future DAA system developers, and will inform standards development (e.g. the ASTM's Test Guide)

This report describes the evolution of the flight test plans, custom instrumentation to provide intruder 'truth data', analysis techniques, as well as preliminary analysis of test results.

RESUME

Le Laboratoire de recherche en vol du Conseil national de recherches du Canada (CNRC) a collaboré avec Transports Canada et Look North pour fournir des conseils, des analyses et des recommandations concernant des essais sur le terrain de technologies de détection et d'évitement (DEE) à la phase de développement, essais qui ont été réalisés par 3 entreprises canadiennes.

Les systèmes utilisés dans ces essais sont considérés comme étant en cours de développement plutôt qu'opérationnels. Les principaux objectifs des essais étaient les suivants :

1. Éclairer les activités de modélisation du système de sorte que la simulation puisse tirer parti des données d'essai en vol et estimer le rendement du système dans différentes circonstances.
2. Évaluer les enjeux critiques pertinents au processus JARUS SORA déterminés par Transports Canada.
3. Cerner les lacunes du système et en faire rapport.
4. Faire rapport de la fiabilité.
5. Déterminer si le système est prêt pour l'essai et l'évaluation opérationnels.
6. Déterminer les risques techniques et évaluer la conformité aux spécifications par rapport aux exigences opérationnelles.
7. Évaluer les facteurs humains et déterminer les facteurs limitatifs dans la mesure du possible.
8. Établir une philosophie de planification des essais en vol incorporant la gestion des risques qui pourrait éclairer les futurs développeurs de systèmes DEE dans l'élaboration de normes (p. ex. des guides d'essai de l'ASTM).

Ce rapport décrit l'évolution des plans d'essais en vol, les instruments personnalisés servant à fournir des « données véridiques » sur les intrus, les techniques d'analyse et l'analyse préliminaire des résultats des essais.

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NOMENCLATURE

AGL	Above Ground Level
ASTM	American Society for Testing Materials
ATC	Air Traffic Control
AWGN	Average White Gaussian Noise
CARAC	Canadian Aviation Regulatory Advisory Council
CFAR	Constant False Alarm Rate
CSV	Comma Separated Value
CV	Computer Vision
CUAVs	Canadian UAVs
DAA	Detect and Avoid
FFT	Fast Fourier Transform
FOV	Field of View
FRL	Flight Research Laboratory
GBDAA	Ground Based Detect and Avoid
GCS	Ground Control Station
GMT	Greenwich Mean Time
GPS	Global Positioning System
HPBW	Half Power Beam Width
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
IMM	Interacting Multiple Model
JARUS	Joint Authorities for Rulemaking on Unmanned Systems
LED	Light Emitting Diode
MDS	Minimum Detectable Signal
MEMS	Micro Electro-Mechanical Systems
MTI	Moving Target Indicator
NM	Nautical Mile
NRC	National Research Council
NMAC	Near Mid-Air Collision
OGD	Other Government Departments
PDF	Probability Density Function
PIC	Pilot in Command
PPI	Plan Position Indication
PPS	Pulse per Second
PRF	Pulse Repetition Frequency
RCS	Radar Cross Section
RPA	Remotely Piloted Aircraft
RPAS	Remotely Piloted Aircraft System
RPM	Revolutions Per Minute
SFTP	Secure File Transfer Protocol
SNR	Signal to Noise Ratio
SORA	Specific Operations Risk Assessment
TC	Transport Canada
UAS	Unmanned Aircraft System
UTC	Universal Coordinated Time
UTM	Universal Trans Mercator
VLOS	Visual Line of Sight

1.0 BACKGROUND

The National Research Council Canada has established a technology demonstration and development program in the area of UAS/RPAS, with the objective of advancing UAS/RPAS technologies to foster higher economic activities in Canada. Through this initiative, NRC has consulted with and engaged the stakeholders and end-users in various industries, Other Government Departments (OGD) and aerospace Original Equipment Manufacturers (OEM). The program addresses the technology gaps while at the same time engages with the end-user industry to streamline the activities for a higher impact. NRC has been a regular contributor to the Canadian Aviation Regulatory Advisory Council (CARAC) and participated in the TC UAV Program Design working group at both the main and subgroup levels.

NRC has partnered with several government organizations (e.g., Canadian Coast Guard, Royal Canadian Navy, Correctional Services Canada, etc.) to conduct state-of-the art analysis and technical evaluation of the UAS/RPAS technologies for the applications in the clients' targeted operations. In 2018 the NRC's Flight Research Laboratory conducted trials and analysis of the Seamatica Aerospace Ltd 'GuardianEye' ground based detect and avoid system [References 1-3]. This testing established vital experience regarding the development of test methods for ground based Detect and Avoid systems, and leveraged FRL's considerable experience with the testing of airborne systems [Reference 4].

In 2019 TC announced a call for proposals to investigate DAA enabling technologies via flight test. Three Canadian companies (proponents) were selected to demonstrate their systems via flight test:

1. Canadian UAVs (ground based radar system)
2. Drone Delivery Canada (ground based radar system)
3. Pegasus (air based radar system)

During recurrent technical meetings between NRC and TC, the opportunity for NRC to provide support to the planned tranche of DAA exploratory trials emerged. There were particular concerns regarding the ability of the proponents to conduct testing and data collection of sufficient consistency and quality to enable TC to make informed decisions regarding the efficacy of the technologies being assessed.

NRC was uniquely positioned to address this challenge. The NRC Flight Research Laboratory had already been consulting with TC during early stages of the call for proposals to assess the applications and refine the flight test plans to ensure that the testing performed and data collected is of sufficient consistency and quality to make meaningful assessments of the viability of the candidate technologies. Most of the discussions focused around the collection of appropriate 'truth data' to assess the system's detection and tracking performance. The potential of using NRC aircraft as instrumented intruders, or supplying 'low cost' inertial navigation systems to serve as consistent high precision data sources for installation in contracted intruder aircraft were both explored. Initial attempts to convince the proponents to move their testing to the Ottawa area to facilitate the use of NRC aircraft were not favourably received, and thus the low cost INS approach was decided upon.

NRC was also well positioned to assist in the development of analysis/ground and flight plans for all of the proposed DAA systems. NRC has prior experience in conducting this sort of test using ground based DAA systems, as well as over a hundred hours of conducting airborne testing including flying near-miss intercepts. This experience was leveraged to provide guidance that shaped the proponent's test plans and ensured that the testing progresses in a consistent, controlled, and risk managed manner.

The systems employed in these trials are considered to be developmental as opposed to operational. The objectives of the testing were to:

1. Inform system modelling activities such that the simulation can leverage the flight test data and estimate system performance under different circumstances

2. Assess the critical issues as relevant to the JARUS SORA process identified by Transport Canada
3. Identify and report on system deficiencies
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8. Establish a risk managed flight test planning philosophy that may be used by future DAA system developers, and will inform standards development (e.g. the ASTM's Test Guide)

The objective of this collaboration between NRC and Transport Canada was to identify means of safely assessing DAA technology, to disseminate this information to Canadian RPAS operators looking to integrate/test DAA systems, and to provide guidance to TC regarding the level of maturity/readiness of the particular DAA systems under test.

The DAA systems assessed in these trials varied in their level of automation and integration into the complete RPAS system. The Pegasus A3S system included automatic threat classification and maneuver initiation and was intended for airborne operation, whereas the Canadian UAVs' Sparrowhawk system, as tested, was intended for ground based operation alongside a ground control station, and manual avoidance maneuver selection and initiation.

The focus of these DAA technology trials was on the ability of the system to detect and track an instrumented intruder aircraft using non-cooperative radar sensors; i.e. an assessment of sensor performance. Owing to travel restrictions imposed by the Covid-19 pandemic it was not possible to witness the flight trials, and conduct on-site human factors assessment as originally planned. During the conduct of the flight trials, the proponents performed additional testing of their systems, for example automatic maneuver initiation. The results of these additional tests were not assessed by NRC, and as such are not discussed in this report.

2.0 TEST OBJECTIVES AND PLANNING

This section presents an idealized list of requirements that should go into the development of a test plan. The proponents involved in the DAA trials had already developed their own test plans prior to NRC's involvement, and this did not benefit from all the factors described in this section. The proponent's flight test plans were, however, reviewed by an NRC Test Pilot who assessed the plans from a test safety perspective. The individual proponent flight test plans have not been included as part of this report since they are company proprietary, however the flight test plan reviews are included as Appendix A to this report.

The systems employed in these trials are considered to be developmental as opposed to operational. As identified in Reference 5, developmental test and evaluation cannot ignore the system's operational requirements, and therefore should not be so limited in scope that it is design only to test within the specification. Some operational "flavour" should be given to planning the development test and evaluation.

2.1 Test Plan Description

The following guidance regarding test plans has been extracted from Reference 5. Although this reference focuses on air to air radar testing it is believed that the general principles apply to ground to air testing.

A complete radar test plan should include the topics described below. They need not be in the exact order shown, but each should be addressed at some point in the document. A brief explanation of what each test plan topic should cover is included here.

Introduction:

- Background information such as the purpose of the test, the scope of the testing (e.g. whether it is to develop or evaluate a minor system change versus a major evaluation of a new radar system)
- Critical issues and questions to be addressed
- Test location, overall schedule, and any related tests

Test Objectives:

- Clear definition of general and specific objectives. A typical general radar test objective is "Evaluate the capability of the radar to detect airborne targets" while a specific radar objective is: "Evaluate the radar range-rate accuracy in single target track mode"
- Assurance that the objectives cover critical development, evaluation and operational concerns
- Requirements in applicable management directives and plans (e.g. regulations)
- Prioritize objectives

Success Criteria:

- Confirmation that the test has been properly performed and sufficient data collected to determine if the tests have been satisfactorily accomplished to evaluate the specific objectives
- May include measures of effectiveness (the performance expected to be seen) in terms of thresholds and goals

References:

- Other test plans
- Other test reports
- Specifications and test requirements document
- System modification and configuration documentation
- Operating limitations documents

Test Schedule:

- Any limitations imposed by test sites, agencies, production decisions, or deployments
- Estimate of required flight time and number of sorties

Participating Organizations and Responsibilities

- Including areas of administration, support, maintenance, logistics, data reduction, photo coverage, scheduling, briefing, and reporting
- Definition of lead organization responsible for coordinating each effort
- Agreements which have been reached with the required organizations

Aircraft Configuration:

- Definition of any requirement for a particular aircraft configuration (e.g. external fuel tanks) or particular configuration of other aircraft systems
- Brief description of the configuration control program and participants

Test Radar Configuration:

- Brief description of the radar system, the controls displays and the relevant interfacing with other systems
- Definition of peculiar/particular radar software configurations required, and a short explanation of the differences from a standard production unit
- Assurance that the specific radar test items are clearly defined and understandable

Test Methodology (Conditions, Procedures, and Techniques):

- Detailed test objectives and conditions/procedures/techniques organized by radar mode
- Ground and pre-flight testing requirements such as: EMC tests, Self-Test tests, harmonization/boresighting of the radar
- Detailed description of tests, including test and target aircraft parameters (such as configuration, altitudes, airspeeds, heading and maneuvering requirements) and environment (such as electromagnetic, weather, clutter, etc.)
- Number of test conditions, sample sizes, flights and flight time required, with each sample of each condition uniquely numbered in order to track test accomplishment and traceability of requirements to testing
- Description of retest (regression) conditions to be accomplished if changes are made to the radar. These can be detailed to the point of defining what runs will be accomplished for each type of system change
- Definition of test condition tolerances to allow the test conductor the flexibility to accommodate variables encountered during test (such as weather or conflicting air traffic), also define the to the crew the critical parameters which must be followed or which could be substituted for others which are less critical
- Usually written in the form of tables which describe the run in detail, the instrumentation requirements, the resources required, the maneuvers to be performed, the start stop conditions and initial points/conditions/ranges
- Written to ensure a logical technical sequence of planned testing
- Identification of the critical limits and the protection required to ensure they are not exceeded
- Description of the interrelationship between various tests (e.g. establishment of priorities and prerequisites) including ground tests, milestones, and production deadlines
- The sequence of modelling, simulation, lab, integration, EMC and ground tests to be accomplished prior to initial testing, and after significant system changes
- Rules and criteria for decisions whether or not to proceed with testing

- The criteria or philosophy used to determine the sample size and the required confidence level
- Requirement that the test conditions be controlled and the procedures designed to ensure repeatability and attainment of results comparable with previous tests, as applicable
- A matrix showing each test objective versus the specification requirement, also the test objective versus runs (at least for those runs satisfying more than one objective, or objectives which are satisfied by more than one type of run)

Limitations/Constraints:

- The limits within which the aircraft will be operated
- Any unusual limitations imposed by weather or aircraft configuration

Instrumentation:

- Description which includes the number and types of systems and recorders, available recording times, locations, sources of data (e.g. which systems are instrumented), how in-flight operation is controlled and monitored (by the pilot, or on the ground)
- Telemetry requirements such as pilot audio, time, status indicators, event indicators, analog and digital data
- Parameter lists
- Checkout and calibration procedures
- Special instrumentation requirements and/or limitations (such as the use of commercial equipment not certified for all flight regimes)
- Requirement that adequate time be made available to thoroughly exercise the instrumentation and data reduction cycle prior to first flight
- Definition of which parameters are go/no-go. The measures and parameters could be categorized as: Category 1 – mandatory for safe conduct, Category 2 – required to meet a test objective, Category 3 – desirable to accomplish the objective and support data analysis, however alternate means of assessment can be substituted
- Required instrumentation system accuracies (as appropriate)
- Any requirements to have a transponder beacon installed for ground based tracking reference systems
- On-board and/or post-flight hand recorded data requirements (pilot/operator comments)
- Weather data requirements

Support Requirements:

- Range support to include a geographic area with specified terrain backgrounds, airspace, and electromagnetic environment
- Equipment
- Manpower/labour
- Test facilities such as Time Space Positioning Information, data sources (tracking radars, cinetheodolites, GPS), mission control rooms, vectoring/flight test control, real time readouts of aircraft closure rates and time correlation capability between airborne and ground based systems
- Other aircraft such as radar targets, instrumented targets, beacon equipped aircraft, etc.
- Target aircraft systems to be instrumented (such and INS, and GPS)
- Training
- Unique technical support requirements
- Key test personnel and their responsibilities

Data Processing Requirements:

- Definition of real time displays for telemetered data

- Quick-look post-flight data requirements
- Detailed post-flight data requirements
- Data distribution plan
- Data processing responsibilities
- Turnaround time requirement for quick-look, detailed data, and range data
- Definition of the data which must be processed before the next flight can be planned or accomplished
- Requirement that sufficient time be allowed between tests for applicable data turnaround and analysis
- Requirements for encrypted data

Data Analysis:

- Data analysis plan which is sufficiently detailed to the point of stating methodologies, equations, types of output and formats
- Analysis responsibilities

Reporting Requirements:

- Periodic status reports
- Service difficulty reporting
- Preliminary report of results
- Final technical report
- Reporting frequency, milestones and responsibilities

Safety:

- Safety planning in accordance with the applicable regulations and requirements
- Requirement that the test program be accomplished under the least hazardous conditions consistent with the test objectives
- Description of any peculiar operating hazards envisioned during the conduct of the tests

Security:

- Operations security requirements
- Communications security requirements
- Requirement that all activities are in accordance with the program security guide
- Any special or unusual problems concerning the safeguarding or transporting of documents or equipment

Appendices:

- Containing detailed explanations and drawings of test conditions and flight profiles

2.2 Proponent Initial System Assessment and Test Plan Review

Each of the proponents presented NRC with a set initial flight test plans that were reviewed by an NRC Test Pilot (Appendix A).

To establish a better understanding of how each system operated the NRC prepared a list of questions that were asked of each proponent:

1. Do you know the specifications of your proposed DAA system:
    a) Field of View (Horizontal and Vertical, angular measurements)
    b) Revisit Rate (of sensor)
    c) Blind Zone(s) if any
    d) Altitude output (if present)
    e) Nominal detection range for a 1m^2 (or other known reference) target. Specify the reference.
    f) Accuracy/resolution?
2. How does your DAA system output its detections? E.g. Does it only display a PPI (or image output), or automatically run a tracker on detections?
3. Does your system present Detections/Tracks in world referenced coordinates (Lon/Lat). If so, how do you calibrate/boresight your system?
4. How does your system know where the RPA is with respect to DAA system detections? (E.g. GCS integration, ADS-B, none, etc…)
    a) Is your DAA system (and display) integrated with the RPA GCS? If so, how?
    b) If your system command the RPA to perform automatic avoidance maneuvers, how does the pilot know it is performing correctly, and not a loss of control?
    c) What will your DAA system do in the event of a lost link?
5. How does your DAA system assess whether a detection (and/or track) is a threat to your RPA operation?
    a) Is this performed automatically, or solely by experienced operator determination (e.g. by viewing a display)?
    b) If automatic, what assumptions are present (e.g. non-maneuvering intruder)?
    c) Is the threat assessment distance based (e.g. 1 km range), or time based (e.g. 30 seconds to a closest approach less than 500 feet), or something else…provide details.
    d) What nominal 'miss distance' are you trying to protect? (e.g. 500 ft lateral, 100 vertical)
    e) How does the system discriminate between real and false alarms? Do you have an estimate of the 'false alarm rate'? Here, a false alarm means that a mitigation maneuver/procedure was performed when it was not necessary.
6. If a detection is considered a threat, what is they system/CONOP response to mitigate collision risk?
    a) What procedure with the system (and crew) perform (maneuvering, communicating etc.)
    b) To what extent is this automated?
    c) What does the RPA pilot need to do?
7. Once the threat mitigation maneuver/procedure is performed, how do you assess that it is safe to resume the mission? (i.e. clear of conflict)
8. What is your proposed CONOP in terms of range, altitude(s), speed(s), terrain, airspace density?
9. How much extra endurance (fuel/battery) will you plan for performing avoidance maneuvers?
10. To what extent does your CONOP rely on visual observers?
11. How do you define your mission in relation to the performance of the DAA system as specified above (e.g. how much bigger of an observation bubble do you need relative to your operations).

The proponent responses to these questions are provided as Appendix B. The quality, and level of detail of proponent responses was quite variable, and it is recommended that an example response form be created should a similar exercise be conducted again.

3.0 PROPOSED DEVELOPMENTAL TEST METHODOLOGY

This section describes the relationship between modelling and simulation of a DAA system and the steps of testing along the course of development. There is a fundamental symbiotic relationship between modelling and simulation and lab/flight tests. One cannot effectively validate the performance of a DAA system without both, as it is too expensive/inefficient to validate via flight test, and too uncertain to validate via pure simulation. The proposed methodology for testing is different for ground based DAA systems versus airborne, however there are many commonalities.

3.1 Ground Based DAA Systems

The following progression is proposed for a ground based DAA system developmental test methodology:

1. Identification of system requirements as well as representative threat environment
2. Identification of RPA flight dynamics for avoidance maneuver via flight test
3. Fundamental modelling of the detect sensor
4. Bench testing of detect sensor
5. Model revision/Prototype refinement
6. Simulation of coupled detector model and avoid maneuver with representative traffic
7. Refinement of system requirements/design following the results of simulation
8. Flight test to demonstrate fundamental performance using a controlled configuration (e.g. aircraft with a reasonably well known RCS, flying with known time/speed/position/orientation information)
9. Refinement of model/system following results of flight test (8)
10. Flight tests to demonstrate system performance with different target characteristics (e.g. radar cross sections, velocity profiles, etc.)
11. Refinement of model/system following results of flight test
12. Integration of flight test data with simulation/synthetic data to estimate performance for cases not-flown
13. System specification refinement, and identification of critical test points
14. Flight test of critical points with RPA flown within VLOS, and RPA position offsets introduced to the DAA system to generate conflict trajectories and requirement to conduct avoidance maneuvers
15. Analysis of end-to-end system effectiveness, and refinement of system models (i.e. Detect, and Avoid)
16. Simulation/modelling to evaluate the coverage/performance of the DAA system for the expected traffic models
17. Identification of critical test conditions required for demonstration via flight test
18. Develop safety protocol and risk assessment/mitigations for conduct of flight test demonstrations
19. Flight test demonstration of critical test conditions
20. System performance assessment
21. Assessment of readiness to proceed to operational testing

There may be several revision cycles required prior to advancing to the next stage. Understanding where along this spectrum of development the system under test is will help in the refinement of the test objectives. For the DAA trials described in this document, the proponents testing ground based systems were at stages 9-12 in the list above. The systems had not yet seen extensive testing and modelling with different target types, and the flight testing did not involve simultaneous operation of an RPA.

3.2 Airborne DAA Systems

The following progression is proposed for a ground based DAA system developmental test methodology:

1. Identification of system requirements as well as representative threat environment
2. Identification of RPA flight dynamics for avoidance maneuver via flight test
3. Fundamental modelling of the detect sensor
4. Bench testing of detect sensor
5. Model revision/Prototype refinement
6. Simulation of coupled detector model and avoid maneuver with representative traffic
7. Refinement of system requirements/design following the results of simulation
8. Flight test to demonstrate fundamental performance in nominal configuration
9. Refinement of model/system following results of flight test
10. Flight tests with radar located on the ground to demonstrate system performance with different target characteristics (e.g. radar cross sections, velocity profiles, etc.)
11. Refinement of model/system following results of flight test
12. Integration of flight test data with simulation/synthetic data to estimate performance for cases not-flown
13. System specification refinement, and identification of critical test points
14. Flight test of critical detection performance points with RPA flown within VLOS, and Intruder maintaining safe separation distances, automatic maneuvering inhibited
15. Analysis of end-to-end system effectiveness, and refinement of system models (i.e. Detect, and Avoid)
16. Simulation/modelling to evaluate the coverage/performance of the DAA system for the expected traffic models, including the effectiveness of the avoidance maneuver
17. Identification of critical test conditions required for demonstration of the coupled detect and avoid system via flight test
18. Develop safety protocol and risk assessment/mitigations for conduct of flight test demonstrations
19. Flight test demonstration of critical test conditions
20. System performance assessment
21. Assessment of readiness to proceed to operational testing

4.0 SYSTEM INSTRUMENTATION REQUIREMENTS TO SUPPORT FLIGHT TEST

This section identifies the minimum set of data to be recorded by proponents taking part in the TC/LookNorth Detect and Avoid Trials scheduled in 2020. While the proponents are each using different sensing modalities, equipment, and CONOPS (air based and ground based), there are common elements to all testing. This section aims to address data requirements for these common elements, and is intended to be used by the proponents in order to ensure that their systems have been adequately configured to record the data necessary to conduct an independent performance assessment.

Each proponent initially proposed to conduct tests using a 'Host' RPA, as well as with an 'Intruder', and with varying degrees of automation in the execution of potential avoidance maneuvers in response to detected collision threats. Over time the proponents using ground based DAA systems indicated that there was insufficient time and system maturity to conduct the trials with a live 'Host' RPA. As a result, the objective of the trials at this stage was focused on assessing the 'detect' performance by comparing reported detections and tracks against Intruder truth data.

4.1 Data Requirements:

Reference 6 is a EUROCONTROL document on radar system performance evaluation for background information on the type of testing required. Section 6 is the one of most interest. Although the reference was intended for the performance evaluation of ATC radars it is worthy reference for the scope of testing being considered in these DAA trials. While it recommends the use of differential GPS for testing, the aircraft (or systems) in these DAA trials do not have D-GPS. Instead, it was proposed to use NRC's in-house developed Inertial Navigation System (INS), which integrates a gyro/accelerometer package with a GPS. This system records positional sigma values, thus the uncertainty of the estimates can be identified. It is recommended that we use 2-Sigma as our threshold, as this would represent 95% confidence. Figure 1 presents the INS alongside a typical credit card sized scale reference. Not shown in the figure are the power source (9-33V DC) and the GPS antenna.

The INS shown in Figure 1 is considered a 'Low-Cost' INS, as it employs a commercial off the shelf MEMS IMU to provide the gyro and accelerometer measurements. NRC's INS software has also been employed using higher quality IMU's [Reference 7] with the primary improvement being reduced heading ambiguity.

Figure 1: NRC Developed Inertial Navigation System

4.1.1 Intruder Inertial Navigation Data – NRC Low-Cost INS:

The data recorded by the NRC INS is:

100 Hz Integrated INS/GPS Data:

1. GPS Time stamp (seconds since Sunday midnight GMT)
2. INS Status (mode, health, etc)
3. Attitudes (Pitch/Roll/True Heading)
4. Rotational Rates (P, Q, R)
5. Accelerations (Ax, Ay, Az)
6. Velocities (Vnorth, Veast, Vup)
7. Position (WGS-84 Latitude, Longitude, MSL Alt)

1 Hz GPS Receiver Data (direct from the GPS solution):

1. GPS Time
2. GPS Position
3. GPS Velocities
4. GPS Position error sigma values
5. Number of satellites in solution
6. Type of solution (NovaTel standard)

1 Hz Kalman Filter Data:

1. Sigma values for state estimates (e.g. Attitude, Pos, Vel uncertainties)
2. Measurement residuals (difference between Kalman filter estimates and GPS position updates)

Since real-time relay of the data is not required for these trials it is possible to record the raw IMU (Inertial Measurement Unit), and raw GPS, and to integrate the data during post-processing. While this is more labour intensive than relying on the real-time calculated output it yields higher accuracy owing to forwards/backwards processing and affords the ability to adjust rotations in the event the unit was installed in a different orientation on a flight. GPS accuracy measurements will be used to make the assessment regarding whether post processing is required.

4.1.2 DAA System Data – Ground Based Radar:

To be able to correlate the Intruder data set with the data collected by the radar based GBDAA system, the system needs to supply the following:

Radar sensor status:

a. Antenna tilt
b. Location (WGS84 Lat/Lon,MSL Altitude)
c. 0 Azimuth angle (True heading)
d. RPM
e. PRF
f. Instrumented Range and MTI Range (if applicable)
g. Transmit Power
h. If available, indications of Noise figure and receiver sensitivity are highly desirable.

Radar track data:

a. GPS Time (preferably), or UTC at time of report (NRC will need to know what the time-base is). This time should have a resolution of at least 1/10th second.
b. Track ID/Name/Number
c. Track status (updated, propagated, stale, etc…)
d. Track position (WGS-84 Lat, Lon), and altitude if available
e. Track velocity (either Groundspeed and track angle, or North/East velocities)
f. Track uncertainty (if available)
g. Track threat level (if available). If there is threat detection enabled in the system, we should conduct flight test assessment of it. To do this we will need to know:
    i. The size of the ‘bubble’ being protected around the RPA (e.g. NMAC volume of 500 ft radius)
    ii. The intended de-confliction maneuver, and associated RPA performance
h. Track azimuth (optional), specify reference frame
i. Track range (optional), specify reference frame

If track azimuth and range are available (or inferable), an analysis can be conducted to remove bias errors (e.g. boresight error), and better understand the performance of the sensor itself. This sort of analysis can prove very instructive for developing calibration and boresighting routines

In addition to the Radar track data is beneficial to see radar detection data; it is highly recommended that the proponent record this data (as well as raw imagery), however its inclusion/submission to NRC/TC is optional:

Radar raw detection data:

a. GPS Time (or other time stamp)
b. Range, azimuth

4.1.3 DAA System – Onboard/Airborne Radar

To be able to correlate the Intruder data set with the data collected by the airborne radar based DAA system, the system would need to supply the following:

Ownship Position at a minimum of 5Hz (more is preferable):

a. GPS Time
b. GPS Position
c. GPS Velocity
d. GPS Uncertainty
e. RPAS attitude (pitch, roll, heading)

Radar Configuration Data:

a. FOV and Elevation (if adjustable)
b. Location of 0 Azimuth/Elevation relative to RPAS inertial measurement axis
c. Lever arm between Radar and IMU (or CG…whichever position the RPAS references)

Radar track data:

a. GPS Time (preferably), or UTC at time of report (NRC will need to know what the time-base is). This time should have a resolution of at least $1/10^{th}$ second.
b. Track ID/Name/Number
c. Track status (updated, propagated, stale, etc…)
d. Track position (WGS-84 Lat, Lon), and altitude if available
e. Track velocity (either Groundspeed and track angle, or North/East velocities)
f. Track uncertainty (if available)
g. Track threat level (if available). If there is threat detection enabled in the system, we should conduct flight test assessment of it. To do this we will need to know:
    i. The size of the 'bubble' being protected around the RPA (e.g. NMAC volume of 500 ft radius)
    ii. The intended de-confliction maneuver, and associated RPA performance
h. Track azimuth (optional), specify reference frame
i. Track elevation (optional), specify reference frame
j. Track range (optional) , specify reference frame

In addition to the Radar track data it would be of interest (and benefit) to see radar detection data; it is highly recommended that the proponent record this data (as well as raw imagery), however its inclusion/submission to NRC/TC is optional:

Radar raw detection data:

a. GPS Time (or other time stamp)
b. Range, azimuth

4.1.4 DAA System – Electro Optical

During the early stages of the DAA Trials there was an additional proponent that proposed to use an airborne electro optical sensor based DAA system. During Spring 2020 the proponent identified that they would no longer be continuing in the trials, however the data requirements identified for the EO system have been included in this document for completeness and future consideration.

To be able to correlate the Intruder data set with the data collected by the airborne electro-optical based DAA system, the system would need to supply the following:

1. Ownship Position at a minimum of 5Hz (more is preferable):
    a. GPS Time
    b. GPS Position
    c. GPS Velocity
    d. GPS Uncertainty
    e. RPAS attitude (pitch, roll, heading)
    f. Location of 0 Azimuth/Elevation relative to RPAS inertial measurement axis

2. EO system data:
    a. GPS Time (preferably), or UTC at time of report (NRC will need to know what the time-base is). This time should have a resolution of at least 1/10th second.
    b. Track ID/Name/Number
    c. Track status (updated, propagated, stale, etc…)
    d. Track position (WGS-84 Lat, Lon, altitude) as available (may be range + azimuth + elevation)
    e. Track velocity (either Groundspeed and track angle, North/East velocities, or closing rate) as available
    f. Track uncertainty (if available)
    g. Track threat level (if available). If there is threat detection enabled in the system, we should conduct flight test assessment of it. To do this we will need to know:
        i. The size of the ‘bubble’ being protected around the RPA (e.g. NMAC volume of 500 ft radius)
        ii. The intended de-confliction maneuver, and associated RPA performance
    h. Track azimuth (optional)
    i. Track elevation (optional)
    j. Track range (optional)

4.1.5 Additional Data – Flight Test Notes

In addition to the data recorded by the various systems, it will be necessary to have copies of the flight test notes. These notes should detail information such as:

1. The date/time of testing
2. Weather/environmental conditions
3. Flight test objective (link to flight test plan)
4. Maneuvers performed (link to flight test plan)
5. System readiness (note any malfunctioning equipment)
6. File names associated with the test

4.2 Data Delivery Format(s)

The data from the NRC developed INS was collected in a binary format that compatible with existing processing routines at NRC’s Flight Research Laboratory.

The system data collected by the proponents had to be delivered in a well described, and easily imported format to facilitate data analysis. The analysis was conducted in MATLAB, thus *.mat files were preferred. NRC was open to considering alternative formats provided they were reasonably common and could ultimately serve to increase the consistency/accuracy of the subsequent analysis.

4.3 Required INS Modifications to Support the Transport Canada/LookNorth DAA Trials

The NRC Low Cost INS was developed to support flight test activities involving small RPA's, however it was not conceived with 3rd party operation in mind. For the Transport Canada/LookNorth DAA trials it is necessary for each proponent to be able to configure, initialize, monitor, and extract the data from the INS. To support this ability the following modifications to the INS software and documentation were required:

1. Mark the case with the reference point for the IMU, as well as the desired direction of installation
2. Label the status LEDs
3. Read GPS date, and embed date in the output filename (or output directory)
4. Monitor file recording progress, and remaining disk space
5. Display output filename, size, and remaining space on webserver
6. Heading initialization via webserver
7. In-flight reset via webserver
8. Filename prefix read from configuration file (i.e. so the output filename can describe the aircraft the INS was installed in, simplifying the data analysis from multiple proponents)
9. Record GPS measurements to support offline post processing to achieve greater accuracies
10. Redundant recording to the internal flash drive
11. Installation, operation, and data download instruction manual

These modifications/improvements were accomplished over the summer of 2020, and two new INS systems were constructed and tested to support these trials.

5.0 RADAR FUNDAMENTALS

Since the proponents involved in these trials are using radar systems as the primary sensor in their DAA systems it was felt that a primer on radar fundamentals would be of benefit to the reader. This primer is located in Appendix D. A coverage of search volumes as applied to DAA systems is provided in the below.

5.1 Search Volumes

DAA systems can be airborne or ground-based. Airborne DAA systems place the sensing and processing components onboard the RPA, which places increased requirements for payload size, weight and power; however this approach has the advantage of the ability to function in the presence of a lost communications link between the operator station and the RPA as well as performance requirements that do not vary with range from the base station. Conversely, a ground-based Dense and Avoid (GBDAA) system relies on fixed ground-based technology to protect a volume of space around the site of operations. In the event of a potential threat, a warning is issued to the pilot-in-command (PIC), so that action may be taken to reduce the likelihood of a collision between the RPAS and another aircraft.

The performance of the GBDAA system defines three levels of search volume, in decreasing order of size:

1) Surveillance Volume
2) Operational Volume
3) Threat Volume

These volumes are depicted graphically in Figure 2. The surveillance volume is the largest volume in which the ground radars, can detect intruders, and represents the maximum scan volume based on the current configured parameters (e.g. power, pulse width, field of regard, and elevation). The surveillance volume should be defined based on a documented % confidence of detection threshold for a nominal target (e.g. 90% confidence for a Cessna 172). The threat volume is a subset of the surveillance volume that is nominally centered on the RPA (assuming a slow moving RPA), in which detected intruders are treated as collision threats. If an intruder is detected in the threat volume, the RPA must proceed to a “safe state”. The operational volume is the space within which the RPA may conduct its operations, and its maximum size is defined by the difference between the surveillance volume and the threat volume at the maximum extents of the operation. The operational volume is smaller than the surveillance volume by a factor related to the maximum possible closing rate between an intruder entering the surveillance volume coupled with the length of time it takes to perform an effective deconfliction maneuver.

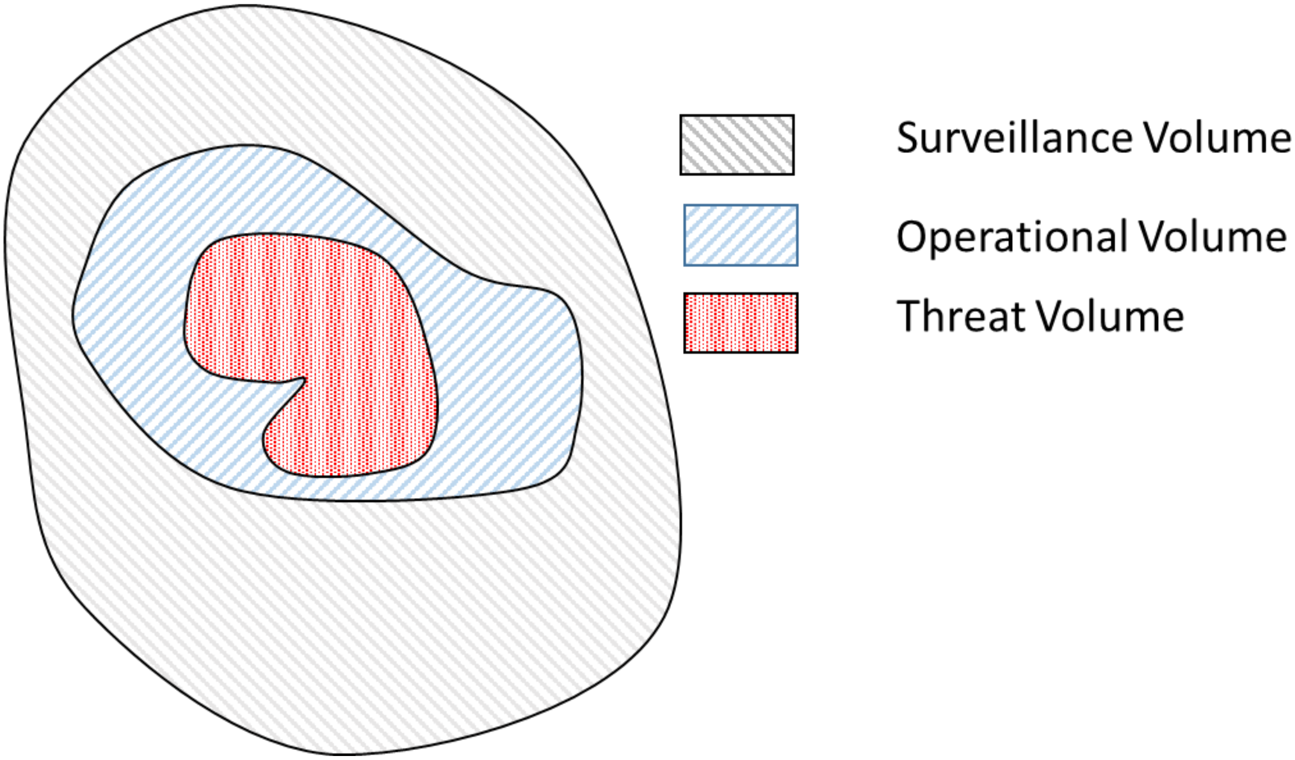

Figure 2: Depiction of the Surveillance Volume, Operational Volume, and Threat Volume

These volumes can also be envisioned in terms of the range inequality established by Reference 11, and repeated here:

$$R_0 \geq R_{det} \geq R_{warn} \geq R_{min}$$

The terms are defined as follows:

R_0: Defined as the range at first detection, this represents the theoretical maximum range that a target may be detected by the sensor system. Each sensing modality may have its own model for determining R_0.

R_{det}: The target detection range, R_{det}, is the maximum range at which a target is established as a collision course intruder by the processing algorithms. R_{det} is a useful predictor of the processing algorithms performance/utility. In particular, $R_{det} = R_0 * v_{close} * t_{proc}$, where v_{close} is the closing rate between ownship and intruder, while t_{proc} is the processing time. A longer t_{proc} value allows for robust tracking and high target confidence, to the limit where R_{det} remains greater than R_{warn}. Inversely, a processing algorithm with a high R_{det} may reach a conclusion quickly, but be prone to higher false-positives.

R_{warn} and R_{min}: The values for R_{warn} and R_{min} are derived directly from the proposed regulatory recommendations. $R_{min} = v_{close} * t_{CA}$ is defined as the range at which the avoidance maneuver must be initiated to ensure that the near-miss volume will not be penetrated if the avoidance maneuver is initiated. By extension, R_{warn}, denotes the time offset at which the pilot-in-command should be warned, and can be modeled as Rwarn = vclose * t_{warn} = vclose * ($2t_{CA}$ + 15) . This example provides a safety factor of 2 on the time taken to perform the avoid maneuver and incorporates a 15 second factor of safety to account for human factors delays. These two range parameters can be directly determined from the host performance characteristics, the collision geometry, and typical intruder speeds and bearings.

6.0 CANADIAN UAVS – FLIGHT TEST AND DATA ANALYSIS

This section describes the aircraft instrumentation set-up, the conduct of the flight test, and the preliminary analysis of the data.

6.1 Intruder Aircraft and INS Installation

Canadian UAVs' contracted flights from a local pilot who operates a Vans RV-10 aircraft. The Vans RV-10 is a four person airplane with a wing span of approximately 32 feet, and a cruise speed of 170 knots. A three view drawing of the Vans RV-10 is shown in Figure 3, and a photo is provided as Figure 4.

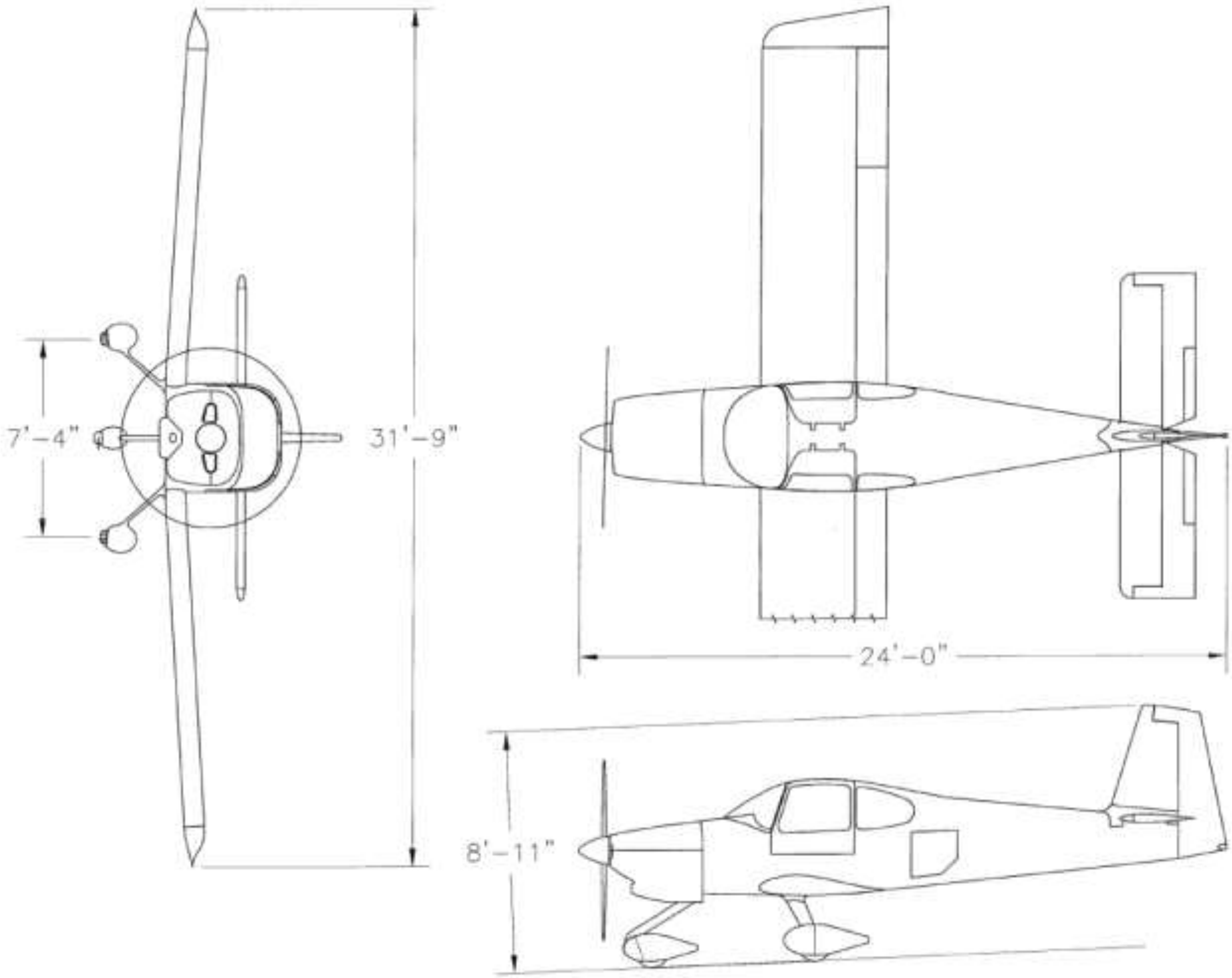

Figure 3: Three view dimensioned drawing of a Vans RV-10 aircraft

Figure 4: Vans RV-10 as used in the flight test

The INS and GPS antenna were installed in the center pedestal and on the instrument glare shield respectively as shown in Figure 5.

Based on the orientation of the INS, and lever arm to the GPS, the following rotation, and lever configuration files were employed on the INS:

Rotation.cfg

```
# Misalignment correction for static values of IMU roll, pitch, and
yaw in degrees
# Angles represent the orientation of the IMU axes relative to the
aircraft axes
0               0       -90       CUAVS Intruder
```

Lever.cfg

```
# Lever arm is position of GPS antenna relative to IMU in metres
# Note the change in sign convention compared to legacy code!
# Values are in IMU XYZ body axes after misalignment rotation has been
applied
#  0          0           0          Default
1.0           0          -0.81      CUAVS Intruder
```

Figure 5: Interier view of the Canadian UAVs' RV-10 intruder aircraft

6.2 Flight Test

The NRC INS was shipped to Canadian UAVs in early November 2020, and was configured remotely with the rotation and lever settings described in section 5.1.

Flight testing took place on November 26, 2020 in a single flight that was divided into three distinct maneuvers, which CUAVs called 'Missions'. The original plan called for an overall flight pattern as shown in Figure 6.

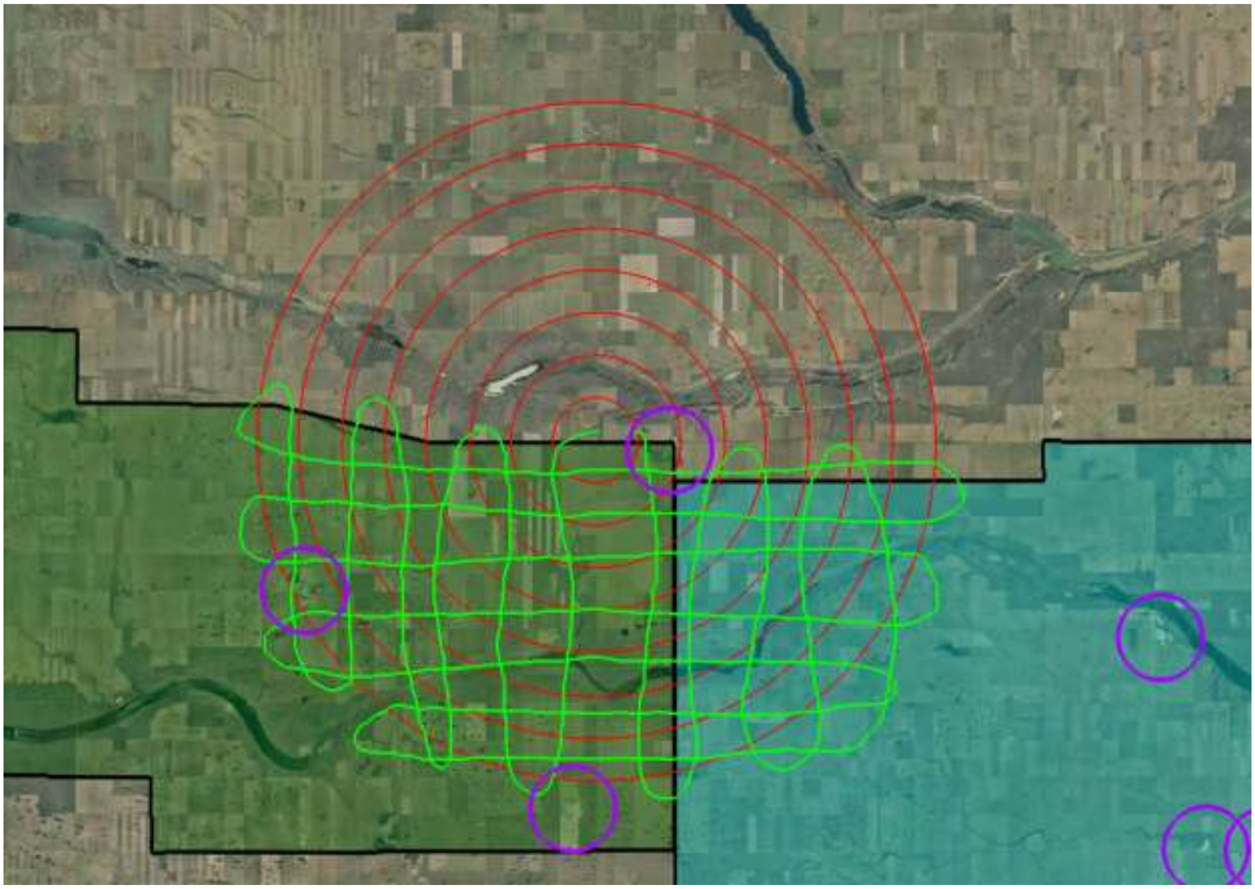

Figure 6: Canadian UAVs proposed flight profile (each red ring is 1 NM)

Figure 7 shows the three missions as flown on November 26, 2020, with the mission plans in green, and the flight tracks in yellow. As can be seen from comparing Figure 6 with Figure 7, the North/South lines were dropped from the missions in favour of a series of 'Figure 8' maneuvers. The East/West lines were flown at two different altitudes (500 ft AGL, and 1,500 ft AGL).

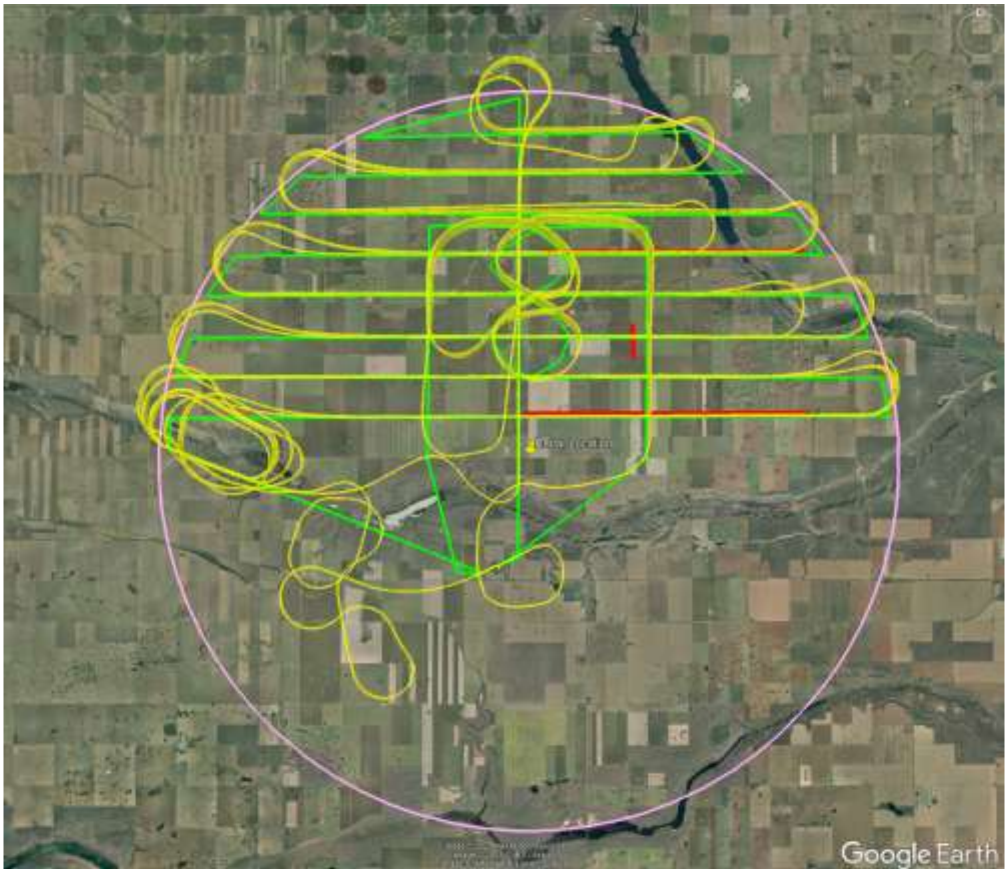

Figure 7: Missions 1-3 as flown November 26, 2020

6.3 Relevant System Specifications

This section presents the relevant specifications of the Canadian UAVs' proposed DAA system.

- CONOP – Long range quad copter (5-7 km) to collect EO or IR imagery, flying linear or grid missions, at altitudes of 200 ft AGL, at speeds of 8 m/s to 12 m/s
- Typical Intruder dynamics: Small fixed wing aircraft (Cessna-172) flying at 110 knots linearly
- RPA Type: SUAS VTOL, <5kgs
- Candidate avoidance maneuver: Descend to hover at 60 ft AGL, can also initiate automatic return home at minimum altitude (60ft AGL)
- Performance characteristics of RPA while conducting avoid maneuver: Vehicle communications latency is 3s, and descent rate is 600ft/min
- Sensor FOV (horizontal and vertical): 360 Degrees horizontal, 20 Deg vertical, 1 degree beam width
- Estimated sensor max horizontal position error/vertical position error: Unknown
- Maximum wind under which the RPA can operate: 25 knots
- Detect sensor revisit period: 2.4 seconds
- Sensor resolution: 1 degree beam width (Ideally we would want angular, and range resolution)
- Pulse width: 0.22 microseconds

- Antenna gain: -31.5 dB
- Transmit power: 25 kW
- Pulse repetition time: 0.00067s (PRF: 1500 Hz)

Figure 8: Canadian UAVs' Sparrowhawk Radar System

Canadian UAVs performed system modelling of their radar system using a commercial off the shelf modelling software package called CARPET (Computer Aided Radar Performance Evaluation Tool). Using this package an estimate of the probability of detection for a $1m^2$ target was established as shown in Figure 9. The modelling data suggests that a maximum surveillance range of approximately 6.5 nautical miles can be achieved for a 90% probability of detection.

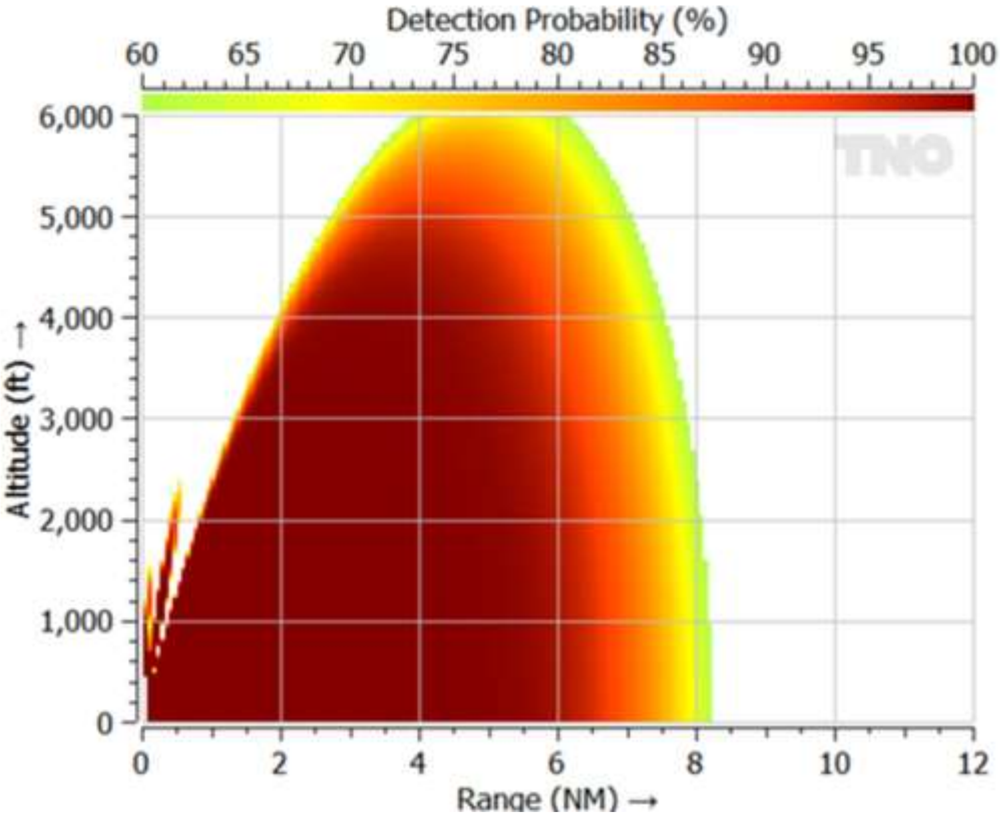

Figure 9: Probability of Detection for a 1m2 Target Modelled for the Sparrowhawk radar

Canadian UAVs also performed ground clutter analysis for their chosen location, however they did not provide details regarding how the ground clutter was processed by the system. For the purposes of this report, NRC assumes that the system does not accept new detections arising from known areas of clutter. The clutter analysis plot provided by Canadian UAVs' is shown in Figure 10, with the radar location being at the center of the figure. Most of the clutter was located south of the radar location, whereas the flight testing was planned to the north of the radar location. The only significant clutter in the planned test area was located at close range (less than 0.5 nautical mile), and between 6-8 nautical miles north east of the radar location.

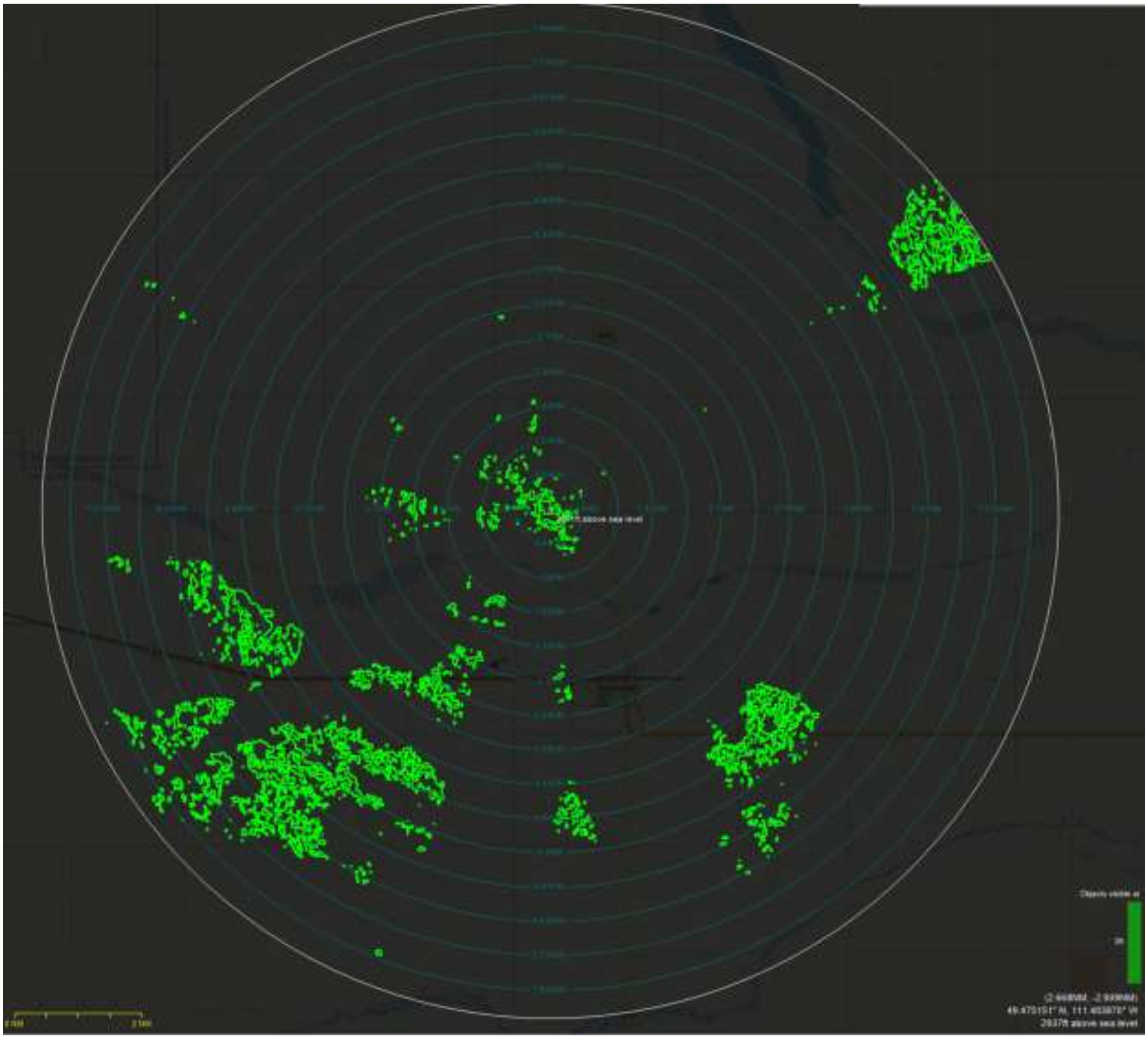

Figure 10: Ground Clutter at Radar Location

6.3.1 Principle of Operation

The Canadian UAVs' Sparrowhawk radar detects aircraft through a combination of radar detection, and proprietary Computer Vision (CV) based analysis of the radar's Plan Position Indication (PPI). The CV analysis performs tracking, and a classification to establish if a detection is to be considered as a likely aircraft, or "flier". Canadian UAVs has indicated that these algorithms have been tuned to increase probability of detection at the expense of higher likelihood of false positives, and that they are conducting continual improvements to the detection and tracking routines.

The tracker that Canadian UAVs developed propagates its tracks for up to 30 seconds allowing the system to miss detections while still presenting an estimate of the intruder aircraft position based on last known location, speed, and bearing.

Detected ‘fliers’ are presented to the RPA crew at the GCS, and proximity to the RPA is then used to trigger alerts to the PIC. Canadian UAVs provided Figure 11 as a sample of the display to the PIC.

NOTE: At the time of writing NRC has not been given any details regarding this display, thus no discussion of display human factors/design has been conducted.

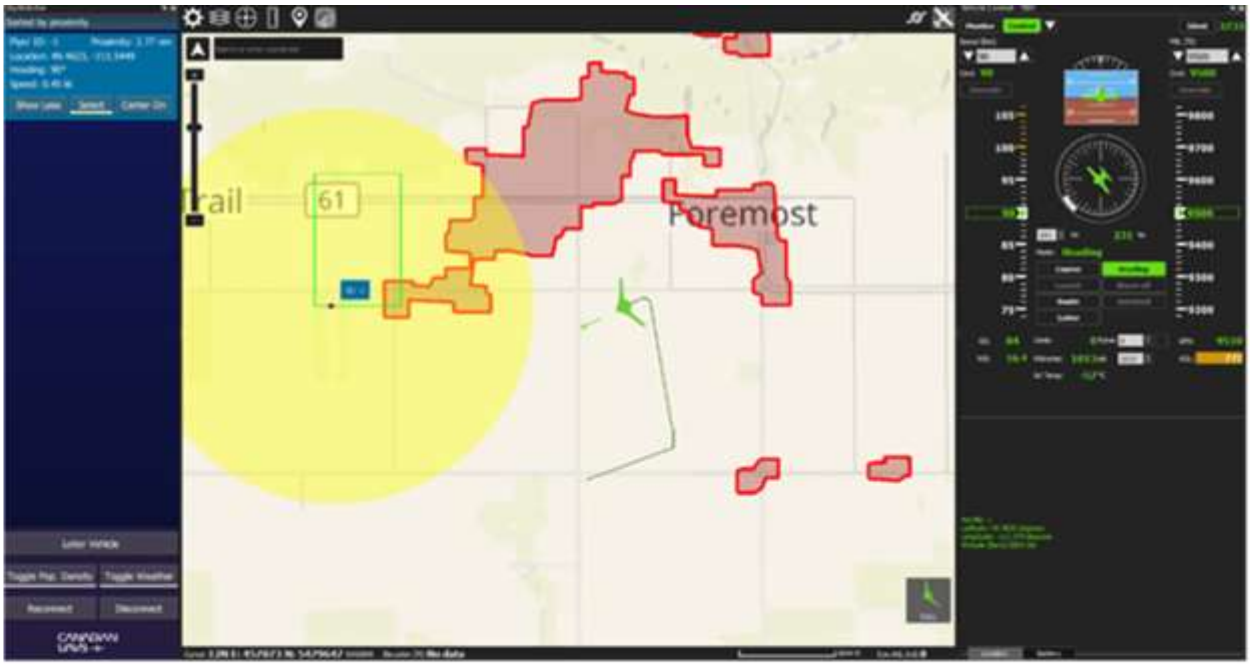

Figure 11: CUAVs’ GCS Display

6.4 Detection Range Requirements Analysis

This section presents an analysis conducted by the NRC to establish the desired detection range, and ultimately the operational volume for the Canadian UAVs’ DAA system.

The nominal intruder for Canadian UAV’ operation is General Aviation (GA) traffic, and we assume a typical cruise speed of 120 knots (60 m/s). The RPA operated by Canadian UAVs has a maximum speed of 12 m/s resulting in a maximum possible closing speed of 72 m/s (v_{close}) for the nominal GA intruder.

The scan rate of the Sparrowhawk is 2.4 seconds, and up to 5 detections may be required in order to initiate a track, resulting in a total time to declare a detection a track of 12 seconds, i.e. T_{det} = 12s.

In the event that a deconfliction maneuver is required it will descend from 300 ft AGL to 100 ft AGL at a descent rate of 600 ft/m (3 m/s). Given the rate of descent it will take 20.33 seconds to complete the maneuver, i.e. T_{ca} = 20.33s.

A human factors delay time of 5 seconds accounts for the time taken for the radar operator to assess the threat situation, a further 5 seconds is required for the PIC to issue the deconfliction maneuver, and a communications latency of 3 seconds elapses before the RPA can start the maneuver, resulting in a warning time of 13 seconds, i.e. T_{warn} = 13s.

These time values can be converted to ranges and related to the range inequality which was introduced in section 4.

R_0 = 12038 m = 6.5 nautical miles
$R_{min} = v_{close} * T_{CA}$ = 72 m/s *20.33s = 1463 m = 0.79 nautical miles
$R_{warn} = R_{min} + v_{close} * T_{warn}$ = 1463m + 72 m/s * 13s = 2400 m = 1.3 nautical miles
$R_{det} = R_0 - v_{close} * T_{det}$ = 12038 – 72 m/s * 12s = 1174 m = 6.03 nautical miles

The calculations above do not include factors for the accuracy of the DAA system, however it is possible to account for such effects by adding positional uncertainty directly to the R_{min} range value. A comprehensive model would account for the fact that uncertainty is greater at longer ranges, however at early stages of development an average approximation of range error is appropriate and useful.

For a ground based DAA system one can determine the operational volume as a radius of R_{det} - R_{warn} centered on the DAA sensor. For the CUAVs application this results in an operational radius of 8774 m, or 4.74 nautical miles.

Note that the operational volume has been determined here based on a R_0 established with a modelled probability of detection of 90% for a 1 m^2 target. One of the objectives of the flight testing is to evaluate the probability of detection.

6.5 Data Analysis

In addition to the Intruder data recorded by the NRC INS, Canadian UAVs provided three comma separated value (CSV) files containing the track output from their radar system. The raw detection output was not provided, therefore it is not possible to assess the raw sensor probability of detection. The provided CSV files contained the following columns, and are described below

1) EPOCH_TIME
2) SYSTEM_AGENT_ID
3) SYSTEM_AGENT_LAT
4) SYSTEM_AGENT_LON
5) SYSTEM_AGENT_SPEED
6) SYSTEM_AGENT_HEADING
7) SYSTEM_DISTANCE_FROM_RADAR

EPOCH_TIME: is the Unix time standard which counts milliseconds elapsed since 00:00:00 UTC January 1, 1970.

SYSTEM_AGENT_ID: Is the track ID number associated with the row of data. A new system agent ID number is generated for each new track that is propagated to “flyer” status. This provides a means to count ‘split tracks’.

SYSTEM_AGENT_LON, SYSTEM_AGENT_LAT: are the estimated location of the track in decimal degree WGS-84 latitude and longitude coordinates.

SYSTEM_AGENT_SPEED: is the estimated speed of the track in knots.

SYSTEM_AGENT_HEADING: is the estimated velocity track angle of the track in degrees.

SYSTEM_DISTANCE_FROM_RADAR: The estimated distance to the radar in nautical miles.

In order to analyze the data it was necessary to convert the timestamps from Unix time to the same GPS time standard employed in the NRC INS, which measured seconds since Sunday midnight GMT of the current GPS week. This was accomplished by converting the Epoch time from milliseconds to seconds, and subtracting 1,606,003,200 from it. Here, 1,606,003,200 is the Epoch time in seconds associated with Sunday November 22, 2020.

The data provided by Canadian UAVs was pre-processed to remove false positives, allowing the analysis to focus on the tracking accuracy. This, however, prevented an analysis of false alarm rate from taking place.

The data from each the three missions was analyzed separately for:

1) Position error
2) Range error
3) Bearing error
4) Speed error
5) Heading/Track error
6) Number of split tracks
7) Probability of track

To establish each of the error measurements it was necessary to linearly interpolate the INS data (which was recorded at 100 Hz) to the reported time of each of the radar tracks. Given the 100 Hz operating rate of the INS, very little error will result from this interpolation.

To determine the position error the latitude and longitude measurements and estimates were converted from WGS-84 to UTM coordinates, which have the benefit being Cartesian, and with units of meters. The position error differs from the range error in that the position error includes the effect of both range and bearing errors, whereas the range and bearing error analysis separate these components into the two primary measurements provided by the radar.

The speed and track error analysis demonstrate the accuracy of the system's ability to estimate the magnitude and direction of the intruder aircraft's velocity vector. This will affect system accuracy in determining if an intruding aircraft is a collision threat, as the system will need to project estimate the distance of closest approach between the controlled RPA and the detected intruder by extrapolating from the detected position along the estimated velocity vector.

The number of split tracks was determined by counting the number of tracks reported with the same time stamp, and a unique track ID. A split track is a new track that begins near the capture/association volume of an existing active track, and may be the result of a detection that is just outside the association volume of an extrapolated track. The end result is that two tracks appear where there was previously only one. Split tracks were averaged for the determination of the error performance characteristics.

The probability of track was assessed by determining the total amount of INS data collected over each mission where the intruder aircraft was known to be in the field of view and range of the radar (8 nautical miles). Each INS sample in this range represented 1/100th of a second, and the sum of the samples determined the total time for a 100% track confidence.

6.5.1 Time Histories and Track Plots

Figures 12-20 present time histories and track plots for the three missions flown on November 26, 2020. The time histories show the data recorded by the NRC INS as a blue trace, and the track output provided by Canadian UAVs as red X's. The time histories show latitude, longitude, altitude, speed, range, and intruder track angle. Individual X's were used to present the radar track outputs as this allows for gaps in tracking to be readily seen.

The track plots are presented as distance north and east from the radar position, again with the data recorded by the NRC INS as a blue line, and the radar tracks as red X's. For the track plots a cyan O has been used to denote the start of a new track ID, and the track # is shown beside the start of each new track. Note that the track ID's do not increment linearly. It is understood that this results from Canadian UAVs' system incrementing track ID for each detection that is promoted to a new track (i.e. the detection is not associated with an existing track), however it takes at least 3 associated detections for a track to be displayed to the operator and promoted to 'flier' status.

As can be seen from the time history plots there is generally good agreement between the position information from the INS and the radar system, however there are notable gaps where the radar is unable to track the intruder aircraft. By looking at the track plots one can see that the radar consistently does not detect the intruder on the right hand turns to conduct the west to east legs of Missions 1 and 2. The reason for this is that these turns were performed just outside of the radar's stated 8 nautical mile range.

The time histories show that there is significant variability in the speed estimate of the intruder aircraft. This may be a result of the detection system angular resolution, but it is impossible to be certain as CUAVs did not provide raw detection data. The reason for suspecting angular resolution is that for Missions 1 and 2 the flights traversed the radar's FOV in an east/west manner that would require the radar to determine velocity of the track based more on the change in bearing from the radar, than the range. This characteristic could have been better investigated by planning a series of circular orbits centered on the radar position (i.e. constant range), as well as test points that involved no azimuthal variation (i.e. constant bearing).

The track plots also reveal that the CUAVs' DAA system is more likely to lose tracks while the intruder aircraft is performing a turn. The left hand turns to establish the east to west legs of missions 1 and 2 were within the radar's range, and the track plots reveal that the track is often dropped during the turn, and that the tracker continues to propagate the track with a linear velocity. It is recommended that CUAVs investigate the use of an Interacting Multiple Model (IMM) tracker which would allow for the blending between models using constant velocity assumptions (i.e. non-maneuvering), and constant acceleration assumptions (i.e. coordinated turns, Reference 12).

Mission 3 involved conducting 'figure-8' maneuvers to test the DAA system's ability to track a maneuvering target. This test was conducted at a higher altitude, and it is believed that at least part of the test was conducted above the radar's vertical field of view. CUAVs indicated that their radar field of view was 20 degrees vertically, but that the radar was not necessarily leveled with the horizon during the flight test. For the purposes of the subsequent analysis in section 5.5.2 a vertical field of view of 15 degrees has been assumed.

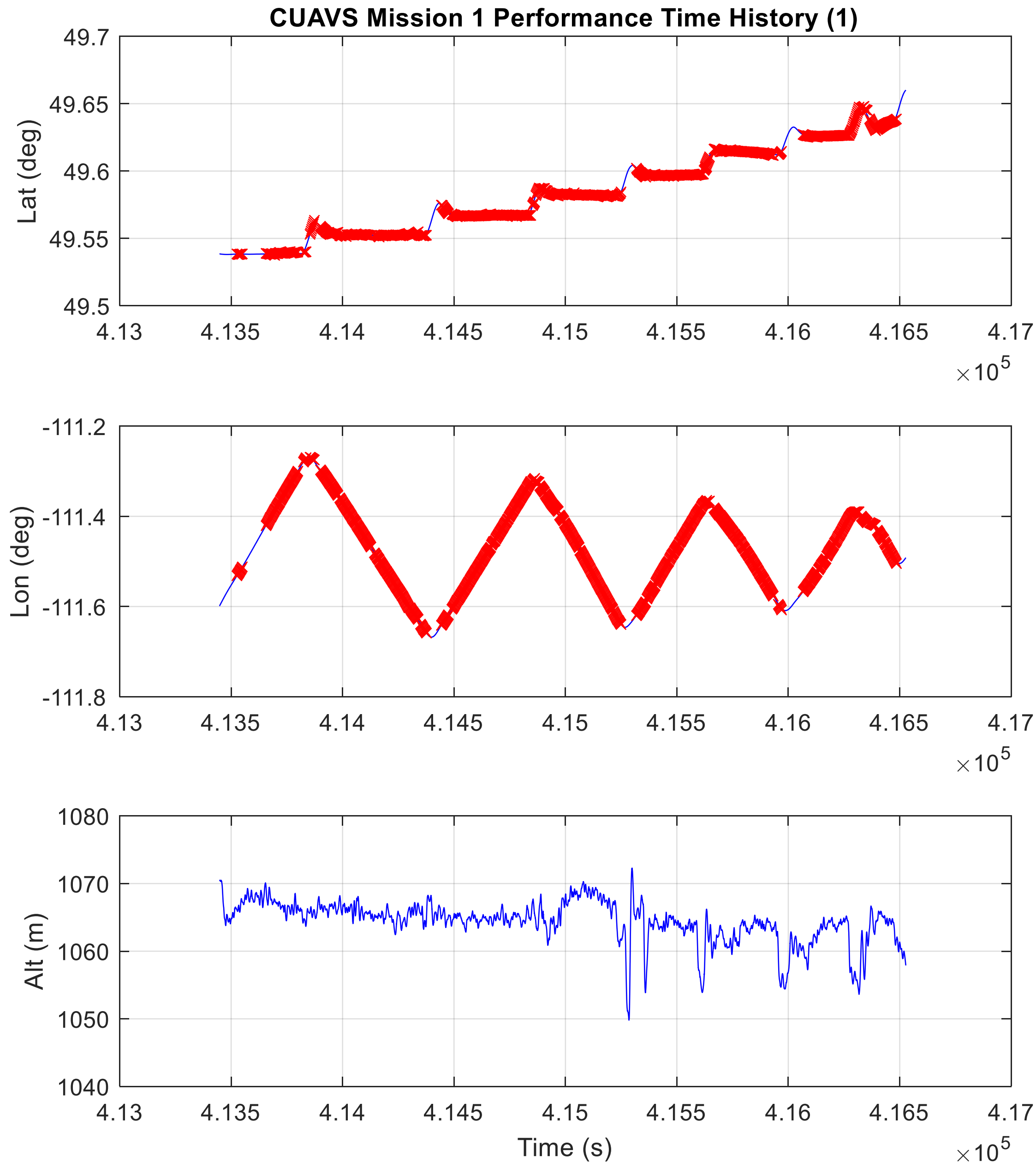

Figure 12: Mission 1 time history (1)

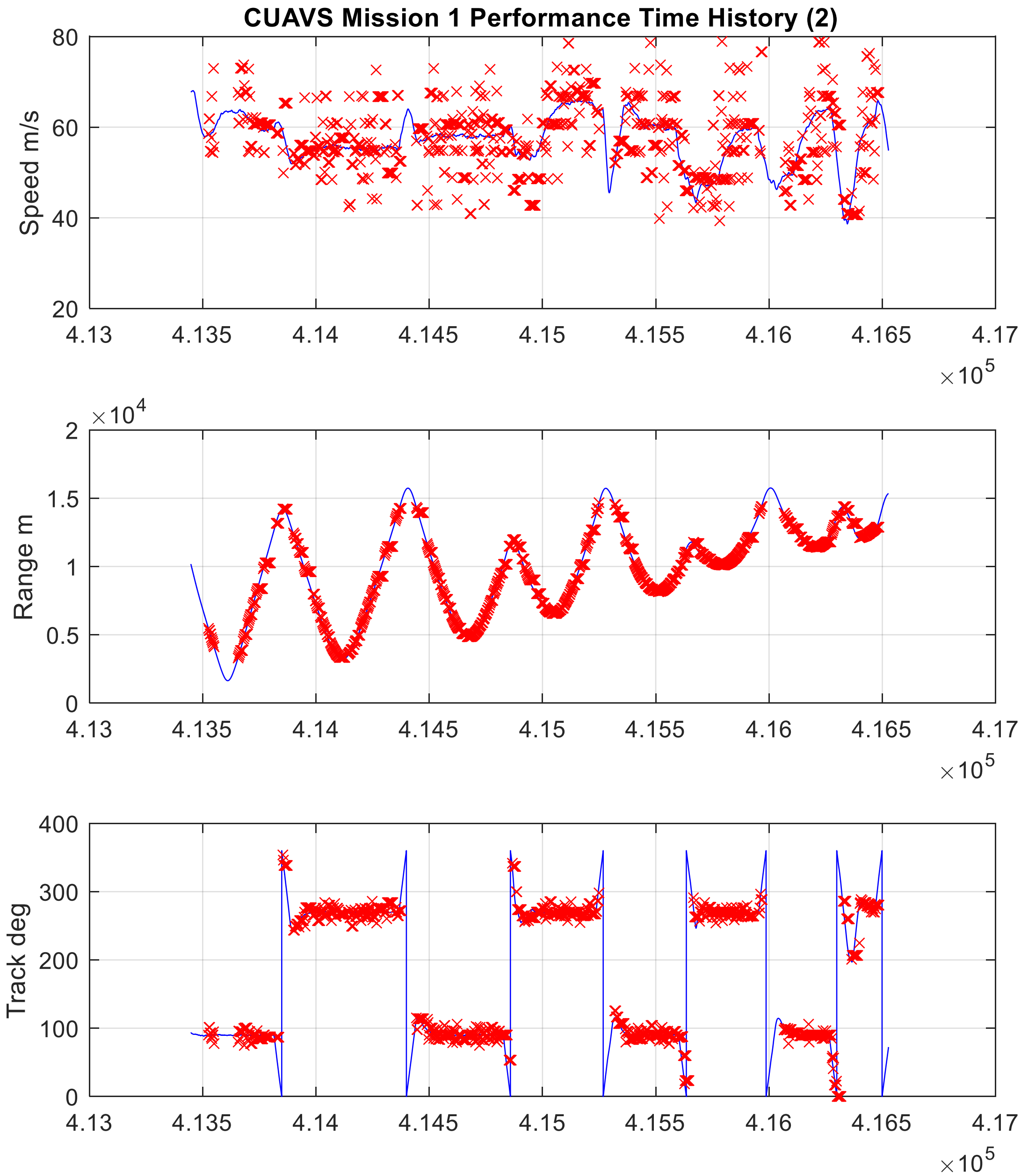

Figure 13: Mission 1 time history (2)

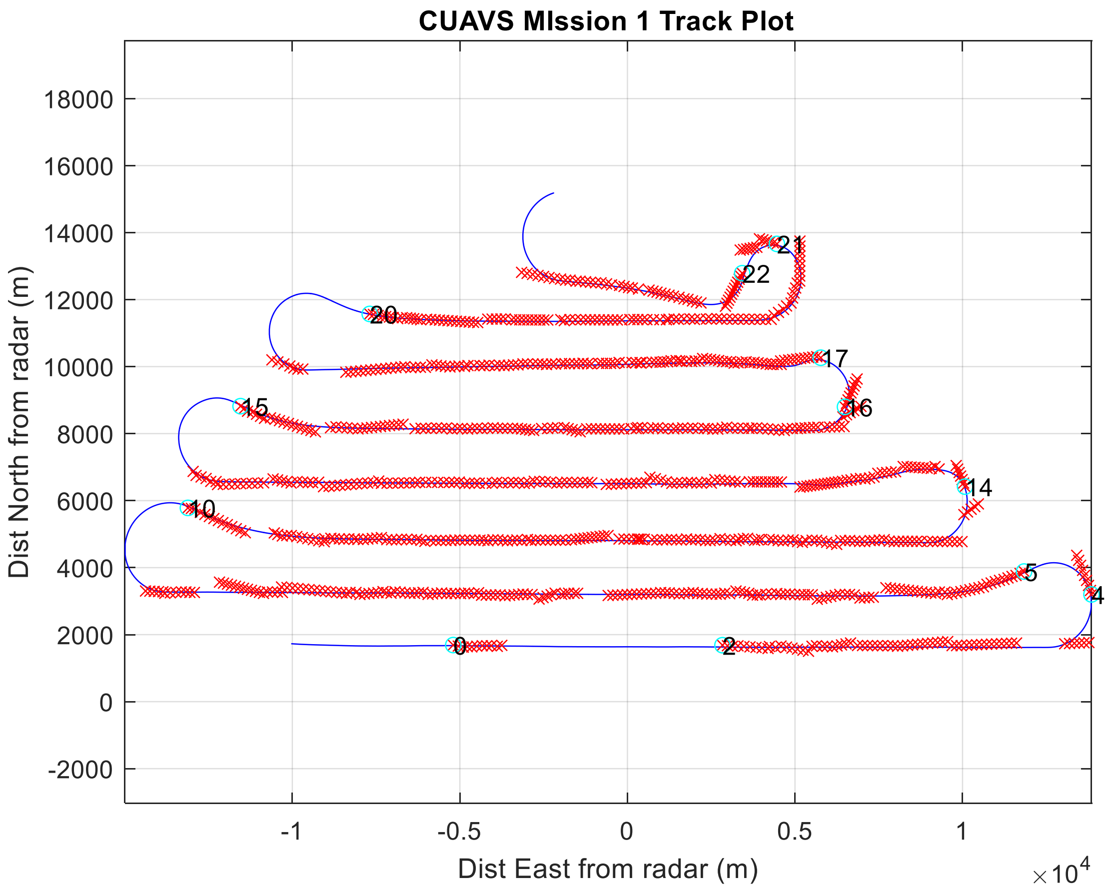

Figure 14: Mission 1 Track Plot

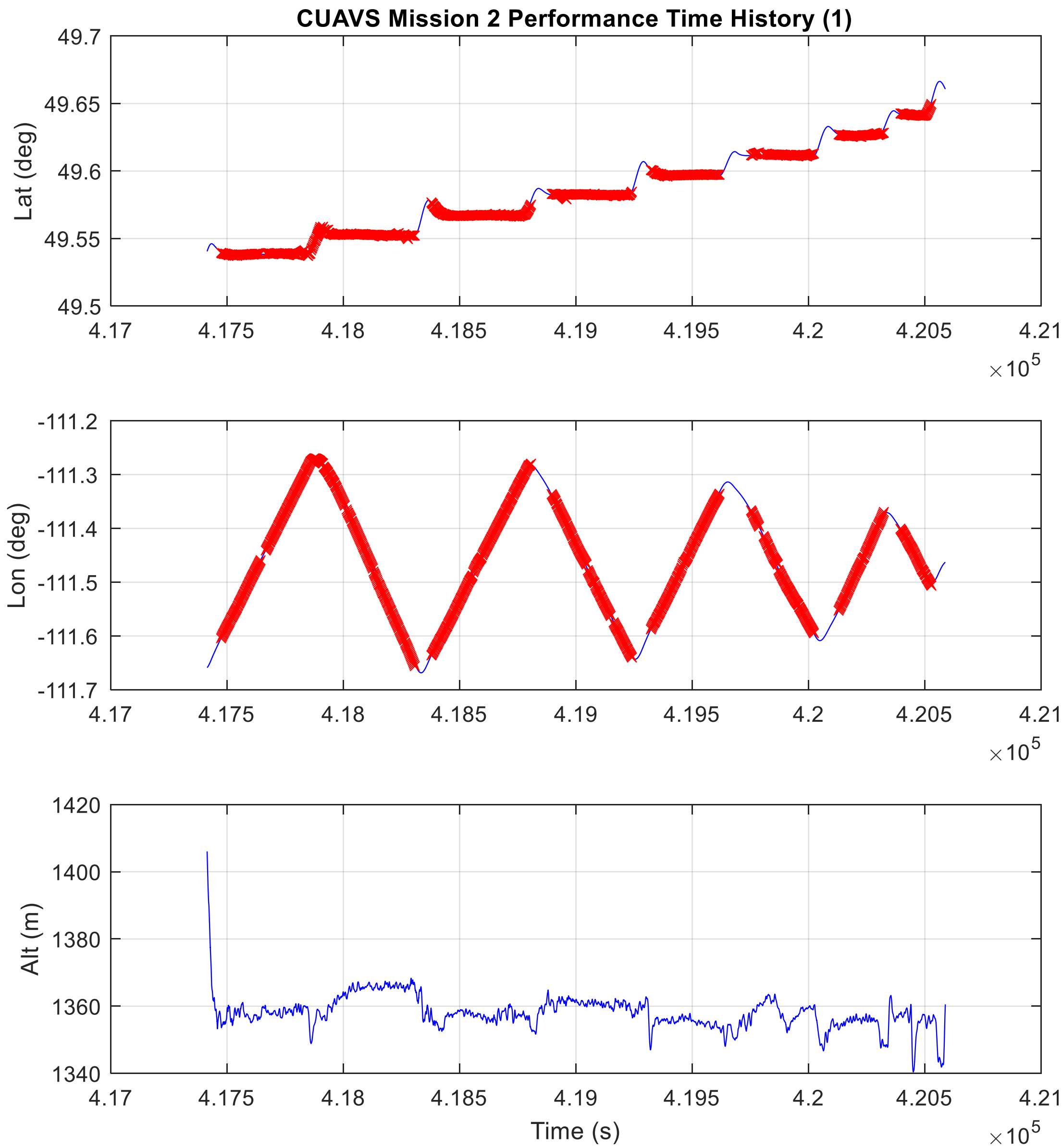

Figure 15: Mission 2 Time History (1)

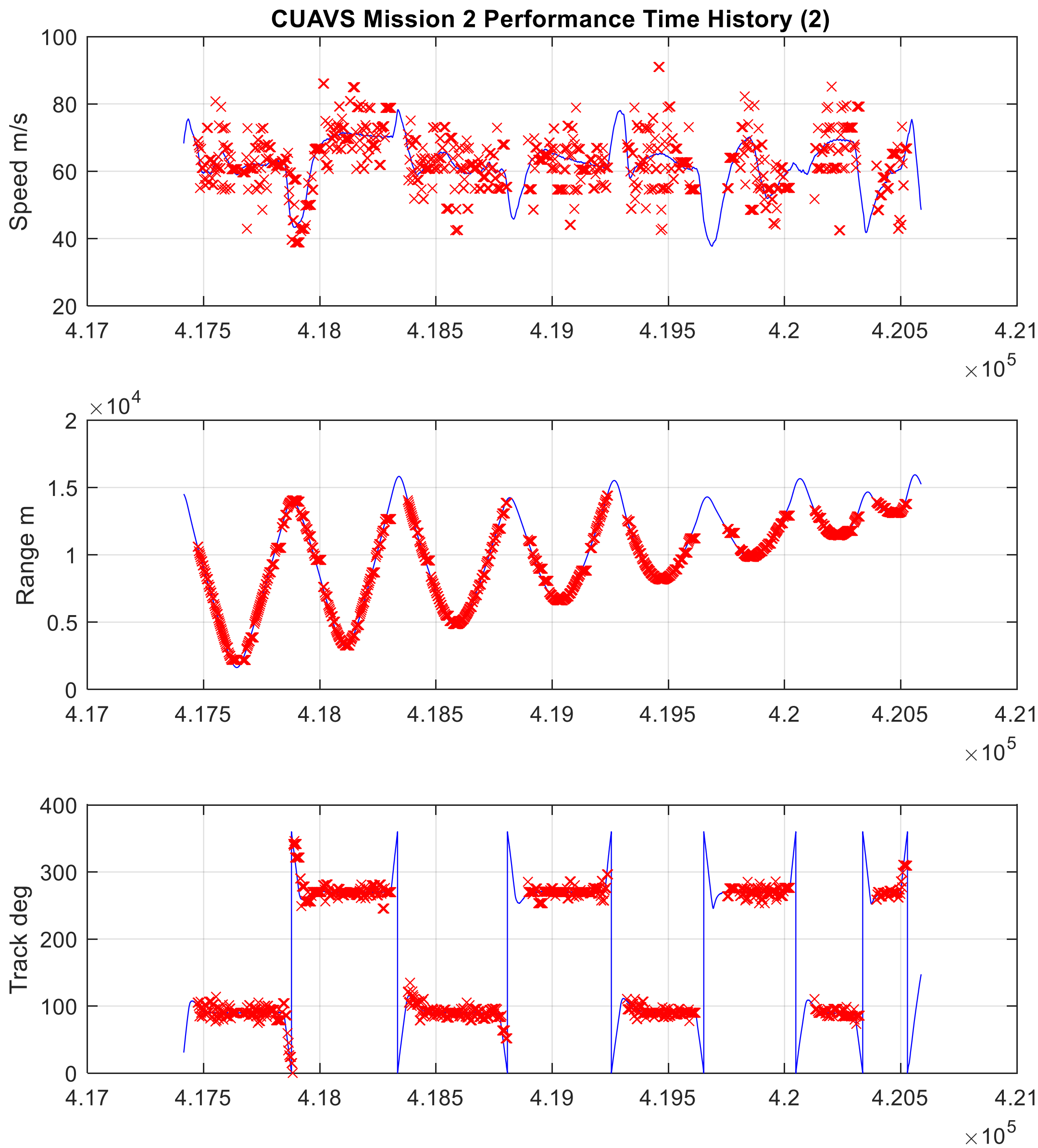

Figure 16: Mission 2 Time History (2)

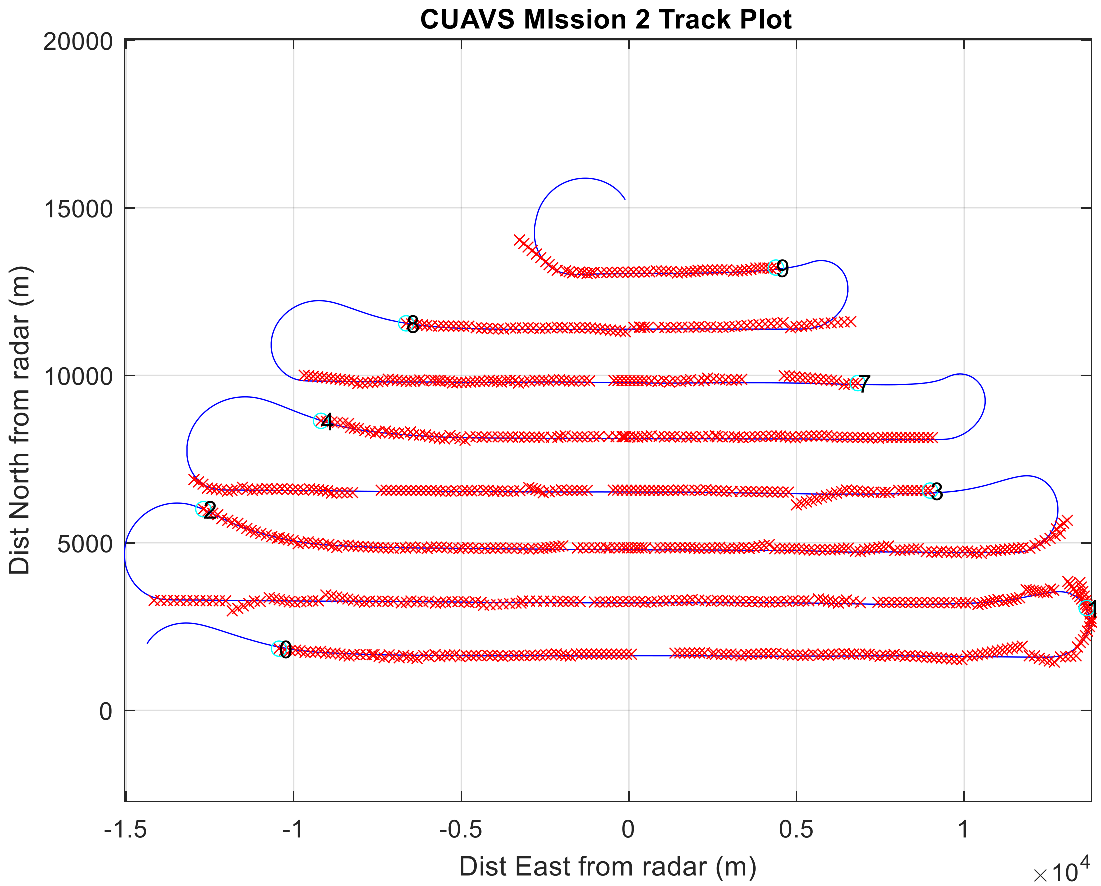

Figure 17: Mission 2 Track Plot

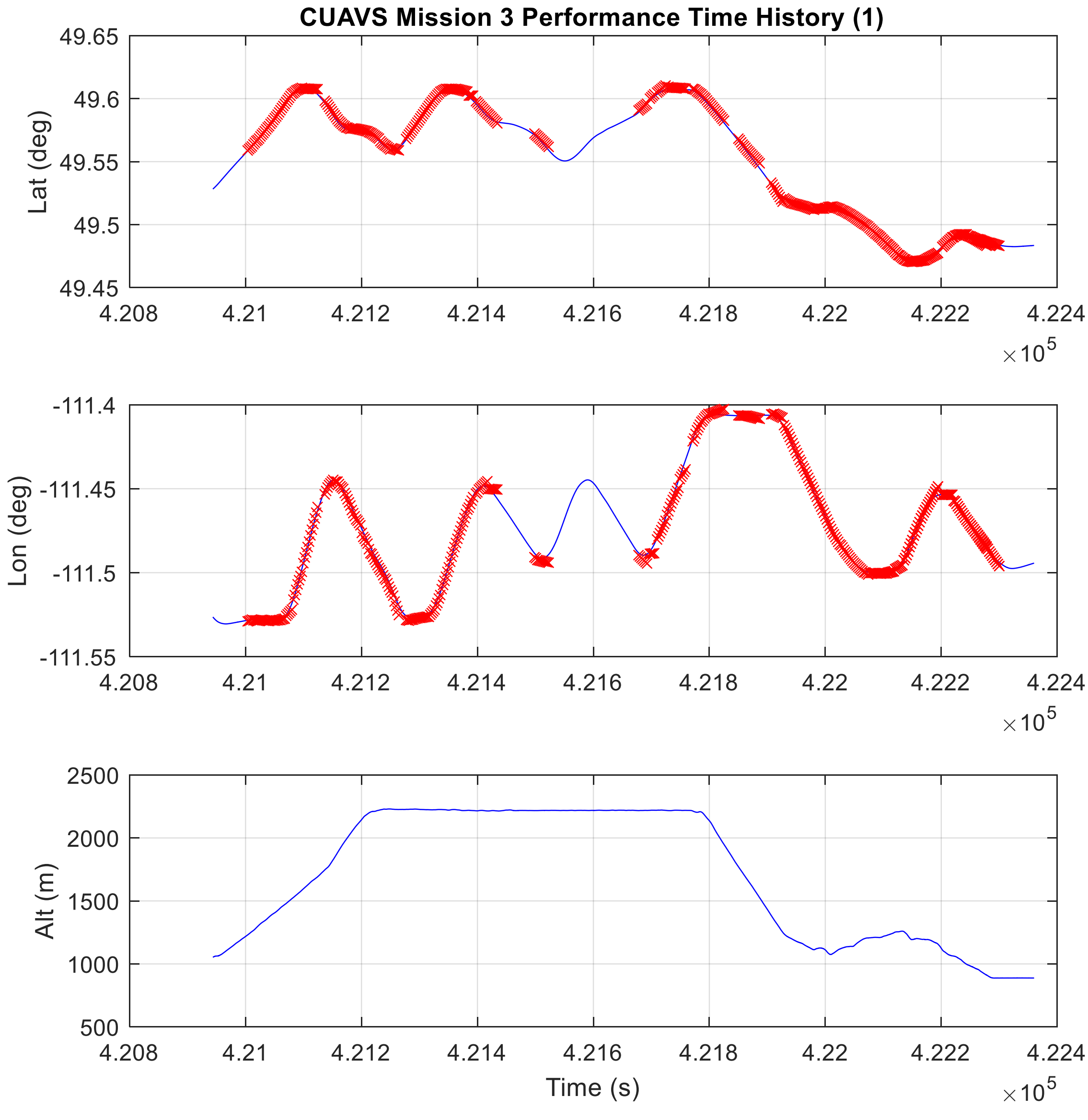

Figure 18: Mission 3 Time History (1)

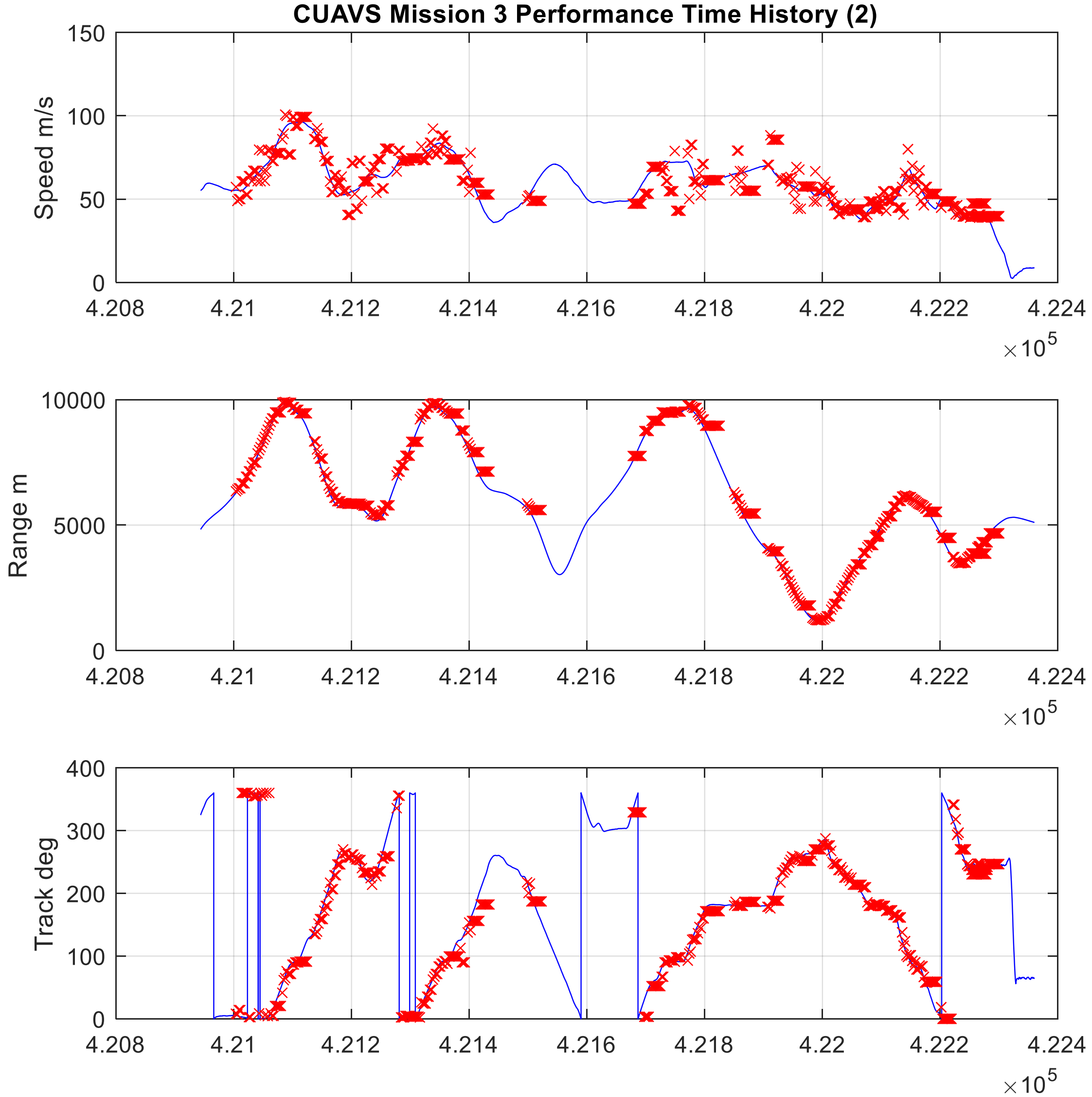

Figure 19: Mission 3 Time History (2)

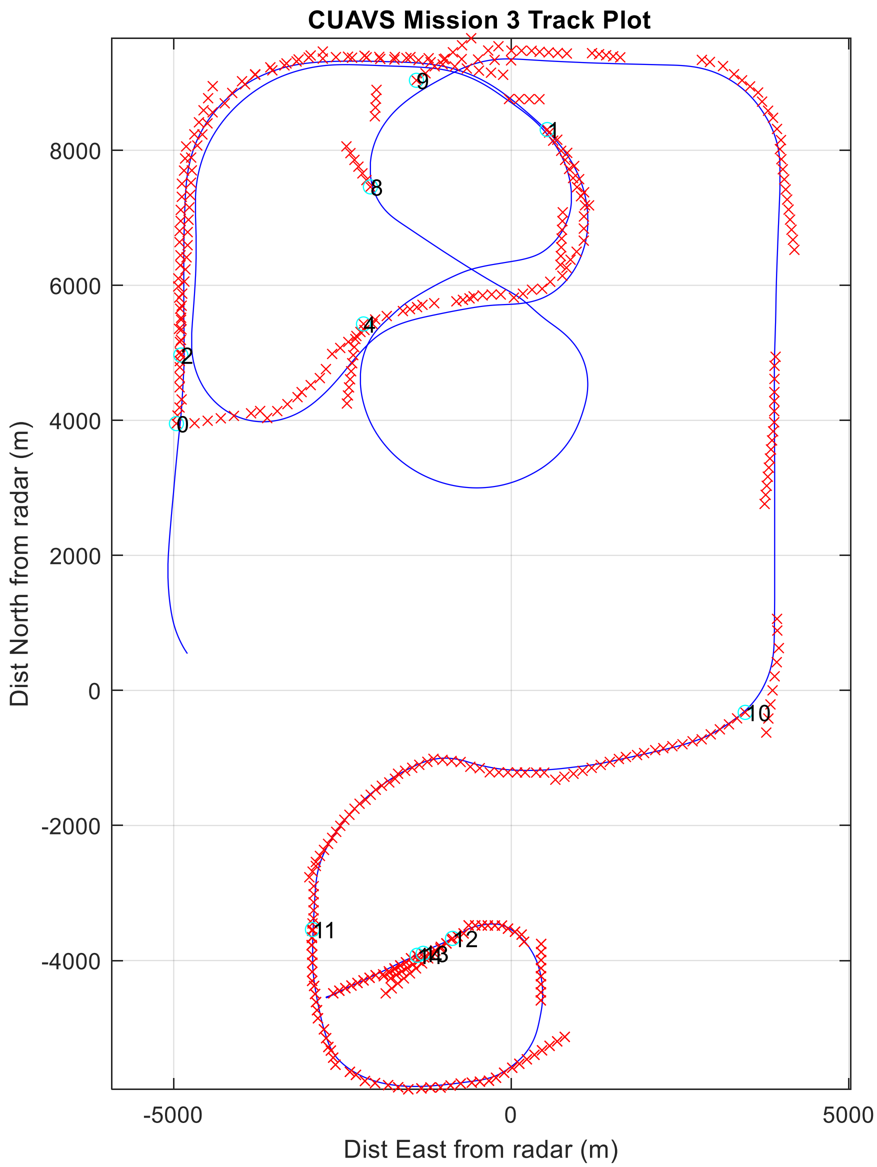

Figure 20: Mission 3 Track Plot

6.5.2 Performance histograms and statistics

Figures 21-26 present histograms and mean and variance statistics for the following performance measures:

1) Position error
2) Range error
3) Bearing error
4) Speed error
5) Heading/Track error

Histograms are presented for each of these performance measures, allowing the distribution of errors to be investigated for any trends. In all cases the distribution of errors appeared to be Gaussian (normal), however in many cases there were non-zero means, implying that system bias may be present. This was particularly true with range, which tended to over predict. To some extent this may be a result of the radar reporting slant range and lacking an altitude output. The standard deviation data is of particular importance as it demonstrates the variability of performance that can be expected. Given the normal distribution of errors once can expect 95% confidence in the radar's performance within two standard deviations.

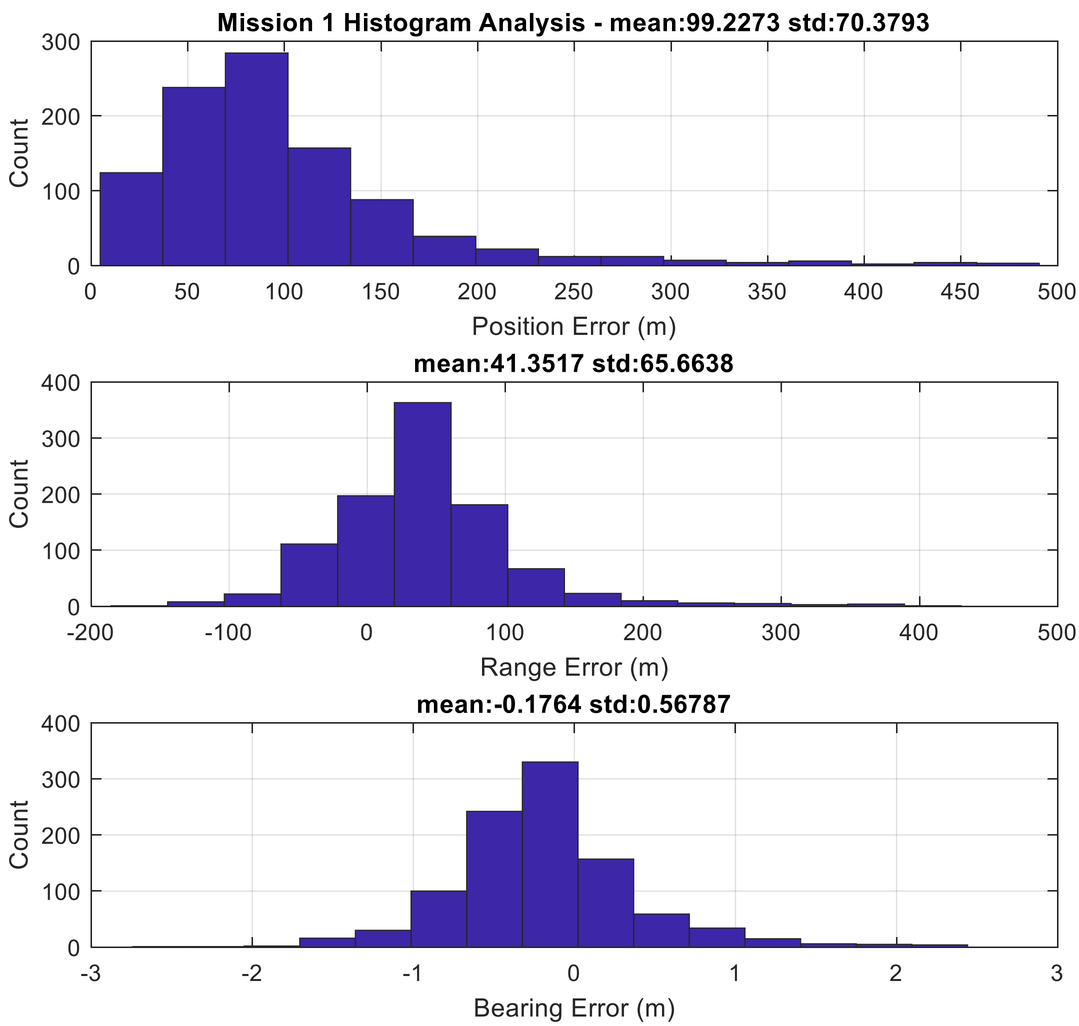

Figure 21: Mission 1 Histograms (1)

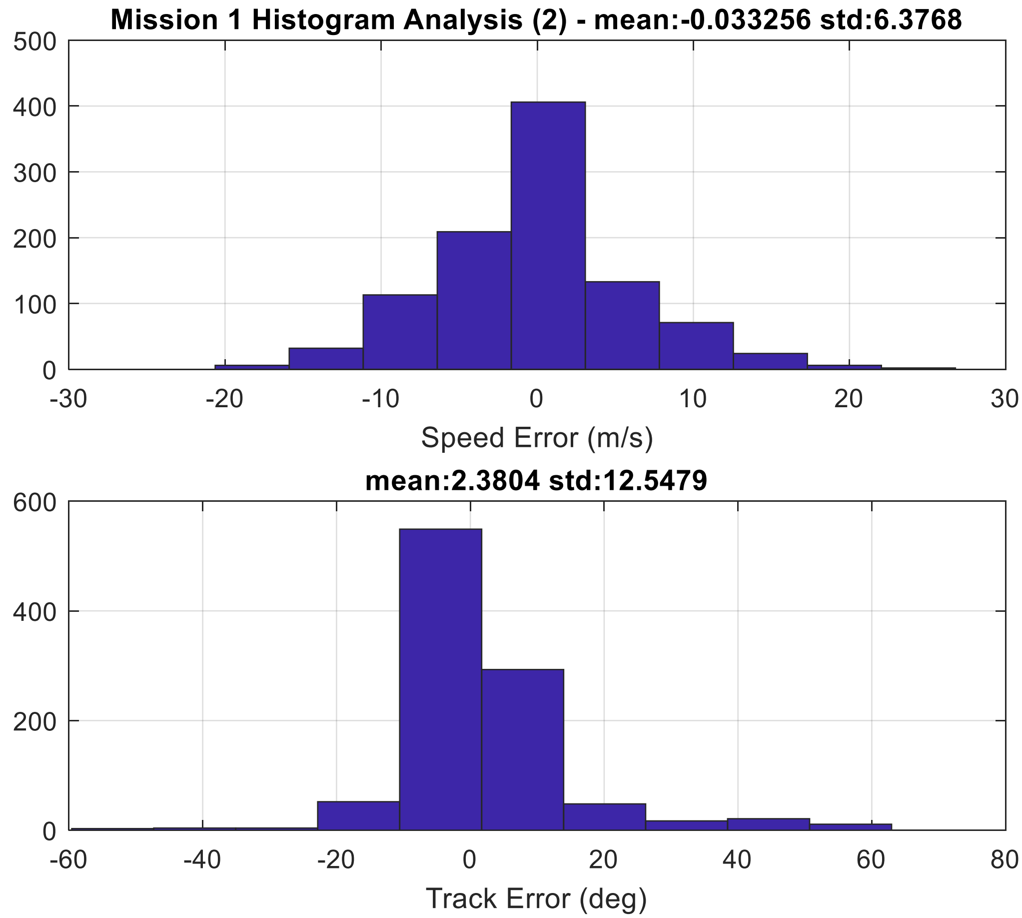

Figure 22: Mission 1 Histograms (2)

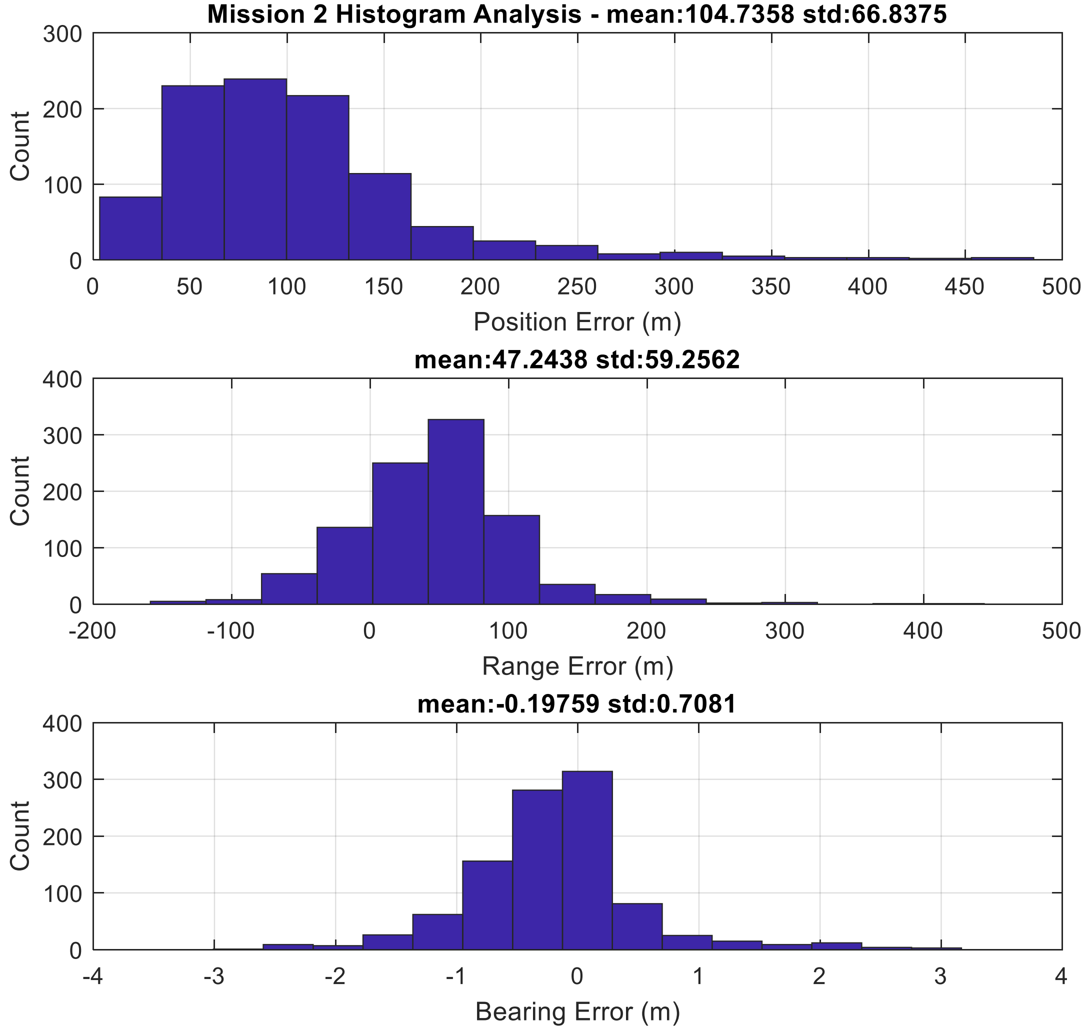

Figure 23: Mission 2 Histograms (1)

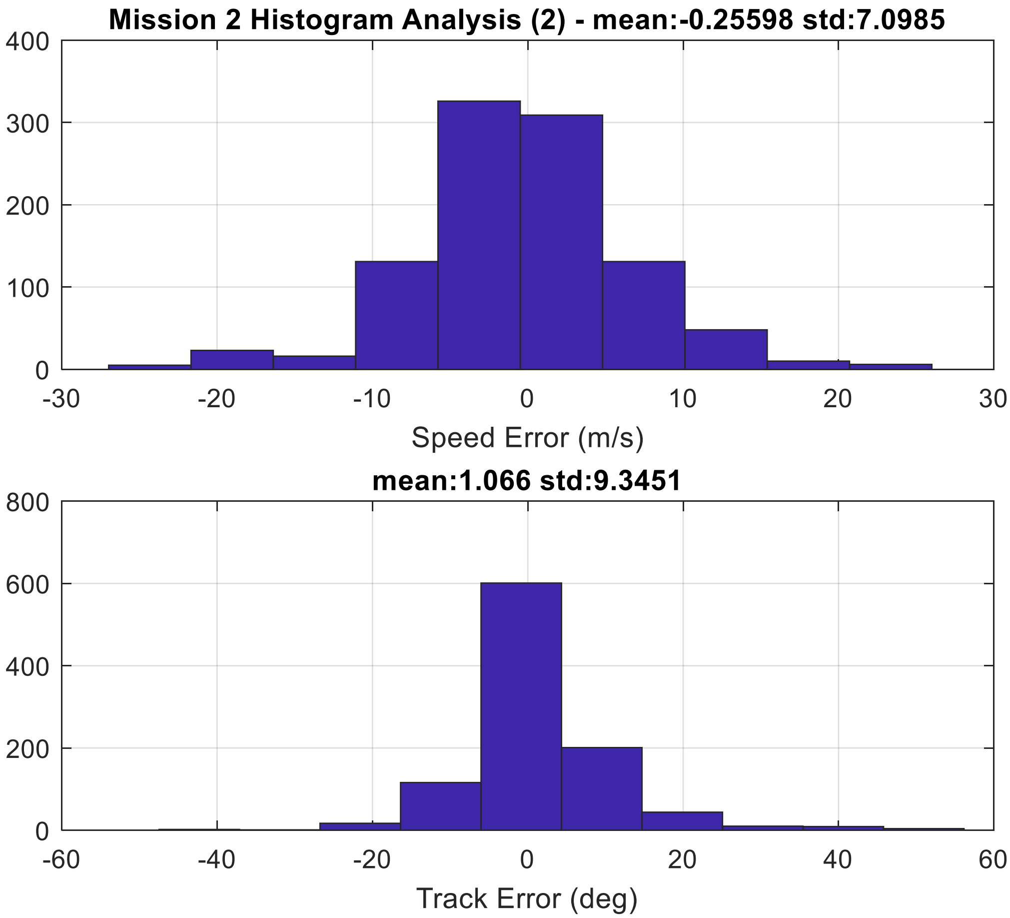

Figure 24: Mission 2 Histograms (2)

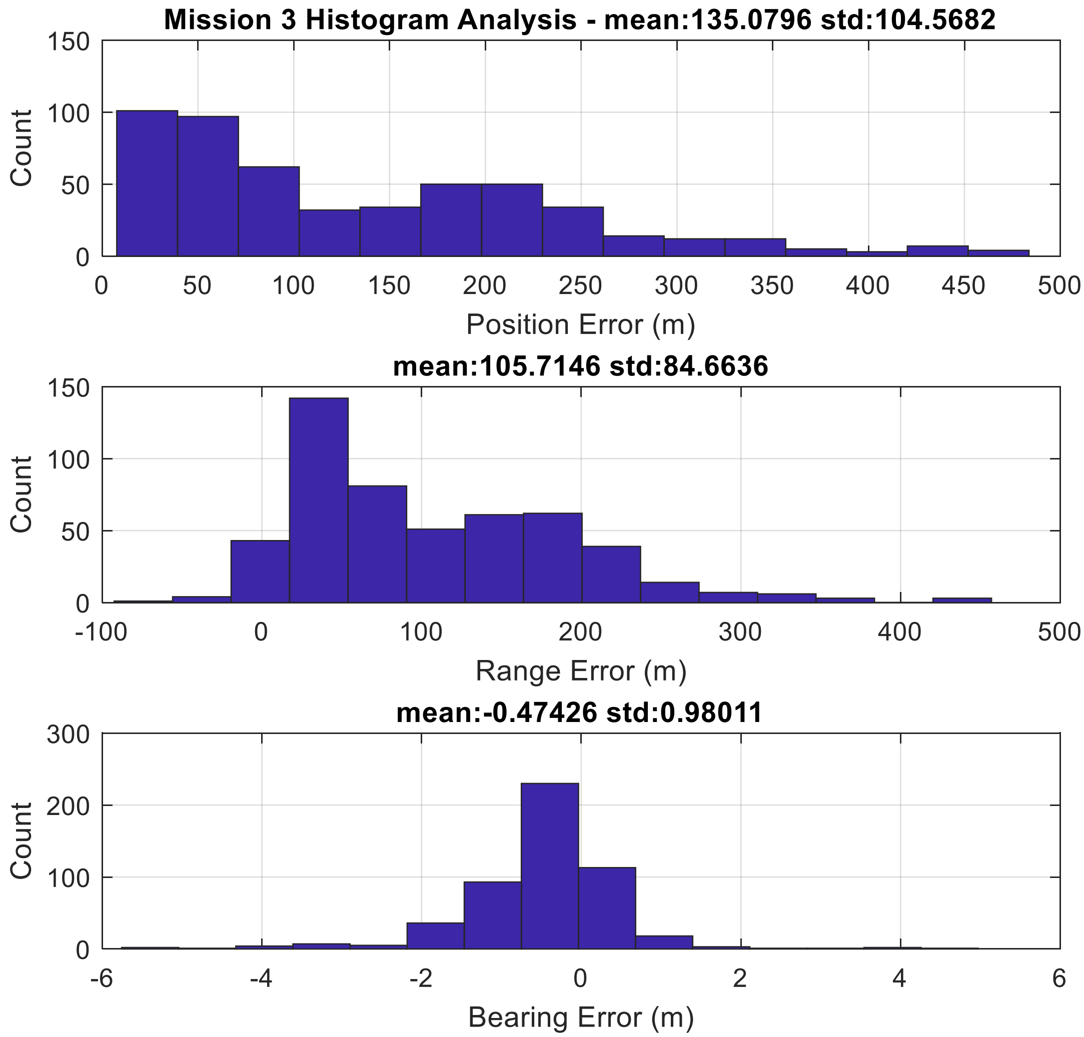

Figure 25: Mission 3 Histograms (1)

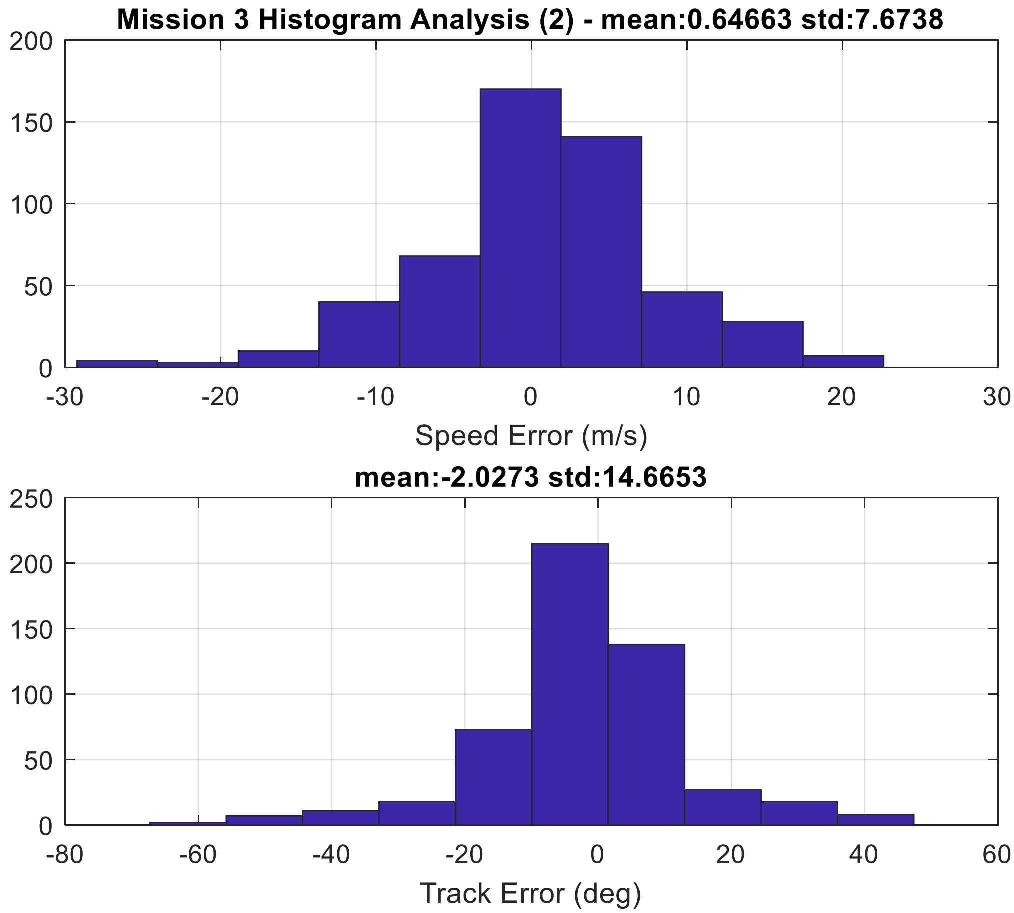

Figure 26: Mission 3 Histograms (2)

6.5.3 Maneuvering vs. Non-Maneuvering

On observation of the track plots it was noted that the CUAVs' DAA system appeared to have lower performance while the intruder aircraft was turning. To further investigate this a metric for determining if the intruder aircraft was maneuvering or was in steady flight was established. Yaw rate as measured by the NRC INS was used as a discriminator. Here, if the INS sample corresponding with a radar track had a yaw rate above 1.5 degrees per second the track was declared as 'maneuvering', whereas all other tracks were declared to be 'non maneuvering'.

Based upon this yaw rate discriminator the three missions were broken down as follows:

Mission 1: 13% Maneuvering, 87% Non-Maneuvering
Mission 2: 11% Maneuvering, 89% Non-Maneuvering
Mission 3: 46% Maneuvering, 54% Non-Maneuvering

6.5.4 Split Tracks

The number of split tracks was determined by establishing the total number of radar tracker output samples that had a non-unique time (i.e. two tracks were output at the same time). These number of repeated samples were then further broken down by maneuvering and non-maneuvering segments. The results show that there is a significantly higher likelihood of encountering a split track during a maneuver, however Mission 3 did exhibit a higher propensity for split tracks even in the non-maneuvering segments.

Total:

Mission 1: 4 of 1002 samples
Mission 2: 6 of 1006 samples
Mission 3: 109 of 517 samples

Non-Maneuvering:

Mission 1: 0 of 872 samples
Mission 2: 0 of 896 samples
Mission 3: 65 of 277 samples

Maneuvering:

Mission 1: 4 of 130 samples
Mission 2: 6 of 110 samples
Mission 3: 44 of 240 samples

6.5.5 Track Confidence:

Track confidence was assessed by determining the total amount of INS data collected over each mission where the intruder aircraft was known to be in the field of view and range of the radar (8 nautical miles). Each INS sample in this range represented 1/100th of a second, and the sum of the samples determined the total time for a 100% track confidence.

Total:

Mission 1: 86.7%
Mission 2: 84.0%
Mission 3: 76.5%
Average Track Confidence: 82.4%

Non-Maneuvering:

Mission 1: 88.9%
Mission 2: 90.9%
Mission 3: 68.4%
Average Track Confidence: 82.7%

Maneuvering:

Mission 1: 12.8%
Mission 2: 10.5%
Mission 3: 63.2%
Average Track Confidence: 28.8%

The results show that the CUAVs' DAA system has good ability to present tracks for non-maneuvering targets, however the track confidence decreases when the targets are maneuvering. It should be noted that since the raw detection data was not provided the figures presented here do not reflect 'probability of detection', and instead reflect the likelihood that an intruder within range and FOV is present within a track. The CUAVs' tracker propagates tracks for up to 30 seconds thus a track may be present for an extended period of time while there is no detection. Considering this, one can conclude that the probability of detection is no higher than the track confidence levels presented here.

6.5.6 Performance Tables

This section presents the mean and variance for the various performance metrics in a tabular form. For most of the metrics the mean simply indicates whether there is bias in the measurement, and the variance is the filed that is of more interest. A column has been added that shows the 95% confidence interval spanning two standard deviations on either side of the mean. It is NRC's opinion that this interval should be used as the nominal measure of performance of the radar system.

Table 1: Position Error Performance

	Total			Non Maneuvering		Maneuvering	
Mission	**Mean (m)**	**Std (m)**	**95% Conf (m)**	**Mean (m)**	**Std (m)**	**Mean (m)**	**Std (m)**
1	99.2	70.3	-41 to 240	90.1	55.7	160.4	114.7
2	104.7	66.8	-30 to 238	101.0	60.2	135.3	102.3
3	135.1	104.6	-74 to 344	119.8	99.8	152.7	107.4
Average	113.0	80.6	-48 to 274	103.6	71.9	149.5	108.1

Table 2: Range Error Performance

	Total			Non Maneuvering		Maneuvering	
Mission	**Mean (m)**	**Std (m)**	**95% Conf (m)**	**Mean (m)**	**Std (m)**	**Mean (m)**	**Std (m)**
1	41.3	65.7	-90 to 173 m	40.5	56.5	47.2	109.0
2	47.2	59.3	-71 to 166 m	47.7	54.1	43.4	91.5
3	105.7	84.7	-64 to 275 m	91.6	73.7	121.9	93.3
Average	64.7	69.9	-75 to 205 m	59.9	61.4	70.8	97.9

Table 3: Bearing Error Performance

	Total			Non Maneuvering		Maneuvering	
Mission	**Mean (deg)**	**Std (deg)**	**95% Confidence**	**Mean (deg)**	**Std (deg)**	**Mean (deg)**	**Std (deg)**
1	-0.18	0.57	-1.3 to 1.0	-.22	0.52	-0.12	0.74
2	-0.19	0.71	-1.6 to 1.2	-0.21	0.71	-0.11	0.65
3	-0.47	0.98	-2.4 to 1.5	-0.56	0.97	-0.37	0.99
Average	-0.28	0.75	-1.8 to 1.2	-0.33	0.73	-0.2	0.79

Table 4: Speed Error Performance

	Total			Non Maneuvering		Maneuvering	
Mission	**Mean (m/s)**	**Std (m/s)**	**95% Conf (m/s)**	**Mean (m/s)**	**Std (m/s)**	**Mean (m/s)**	**Std (m/s)**
1	-0.03	6.38	-12.8 to 12.7	-0.2	6.3	1.1	6.8
2	-0.26	7.10	-14.5 to 13.9	-0.52	6.9	1.9	7.9
3	0.64	7.67	-14.7 to 16.0	0.33	7.3	1.0	8.1
Average	0.12	7.05	-14.0 to 14.2	-0.13	6.8	1.3	7.6

Table 5: Track Error Performance

	Total			Non Maneuvering		Maneuvering	
Mission	**Mean (deg)**	**Std (deg)**	**95% Confidence**	**Mean (deg)**	**Std (deg)**	**Mean (deg)**	**Std (deg)**
1	2.38	6.38	-10.4 to 15.1	0.5	7.1	15.0	26.3
2	1.07	9.34	-17.6 to 19.8	0.2	6.9	8.1	18.2
3	-2.03	14.66	-31.3 to 27.3	-0.9	8.9	-3.3	19.2
Average	0.47	10.12	-19.8 to 20.7	-0.1	7.6	6.6	21.2

Table 6: Max Range Performance

Mission	Max Range (m)
1	14,754
2	14,689
3	9,983
Average	13,142 m

The performance tables demonstrate that the Sparrowhawk system can operate at up to 14 km range with 95% position confidence established within 274 meters of the actual target location, to a speed within 14 m/s (30 knots), and to a velocity track within 20 degrees. The low velocity and track accuracy of the system will inhibit the utility of any routines that attempt to calculate the estimated closest point of approach between the RPA and the intruder. CUAVs did not provide any threat classification/warning output generated by their system. It is possible that none was available since the flight testing was conducted without an RPA being present. The Sparrowhawk system exhibited reduced accuracy while the Intruder aircraft was maneuvering, and may suggest that improvements to the tracking algorithm are warranted. NRC recommend the investigation of ‘Interacting Mixture Model’ trackers to allow for track smoothing using linear methods for straight and level flight and coordinated turn models for maneuvering flight.

The data provided to NRC for analysis appeared to be pre-filtered to remove any false positives, precluding an assessment of false positive rate. Further, it should be noted that that since tracks were maintained for 30 seconds since last data association it is possible that false positives may be present on the display system for an extended period of time. The specific details used for initiating and terminating tracks were not provided, however.

7.0 DRONE DELIVERY CANADA – FLIGHT TEST AND DATA ANALYSIS

Drone Delivery Canada's DAA system flight test campaign did not advance beyond the planning stage owing to changes in operational/corporate interests, and responses to the Covid-19 pandemic. As such, no flight testing was performed, and there was no data to assess.

8.0 PEGASUS – FLIGHT TEST AND DATA ANALYSIS

Pegasus of Sturgeon County Alberta design and manufacture the Eos RPAS pictured in Figure 27. The Eos is a VTOL system designed to be runway independent with a 10 hour endurance and a cruising speed of 65 knots. The Eos can be equipped with the A3S Autonomous Airspace Awareness System which fuses airborne radar and other sensors to detect and track airborne threats.

The A3S system, as tested, employed a Commercial Off-The-Shelf 24GHz radar (Figure 28) as the primary detection sensor. The radar had a horizontal FOV of up to 120 degrees, and a vertical FOV of up to 80 degrees. The radar's transmit power was 4 watts resulting in a specified nominal detection range of 2.5 km for a 0 dBm^2 target and 90% probability of detection. The radar included a search and track function that can maintain tracking data on up to 20 simultaneous targets of interest. The radar unit did not perform threat assessment and de-confliction, thus it was the responsibility of the system integrator (e.g. Pegasus) to perform these functions using their connected support systems.

Figure 27: Pegasus Eos RPAS (Credit Pegasus Website)

Figure 28: Example Electronically Scanned Radar

8.1 Intruder Aircraft and INS Installation

The intruder aircraft was a civilian contracted Cessna 172 as shown in Figure 29. Pegasus staff installed the NRC INS, configured the orientation and lever files, and monitored the system status throughout the flight.

Figure 29: Cessna 172 aircraft

8.2 Flight Test

Flight testing was conducted with the radar mounted at a fixed location on the ground, specifically 53.64585 deg latitude, and -113.80258 deg longitude. The radar outputs tracks relative to its own position using X/YZ, or Range/Azimuth/Elevation coordinates in its own reference frame. Conversion to world referenced Lat/Lon/Alt coordinates requires transformations by the customer integration software. This was performed by Pegasus' A3S system. To test the accuracy and efficacy of these transformations two types of tests were conducted:

1. The radar bore-sight location and orientation was manually determined and directly entered into the system, and
2. The radar's location and orientation was provided automatically via an integrated Pixhawk PX4 COTS Autopilot unit

The tests with the manually entered coordinates allowed for assessment of the radar's performance in isolation, whereas the tests with the boresighting performed by the autopilot allowed for an assessment of the expected performance (and potential problems) in an in-flight application.

The following maneuvers were performed for each of the two configurations listed above:

1. Serpentines – The Cessna conducted North/South transits at various distances from the radar
2. Straight – The Cessna flew an East/West trajectory nominally towards the radar location

A total of 12 maneuvers were performed.

8.3 Overall Comments Regarding Flight Test Data

When the INS and radar track data was sent to NRC for processing it became apparent that the Pegasus crew member on-board the Intruder Cessna had adopted a practice of power cycling the INS prior to each flight test maneuver. This was done to ensure that there was a separate file recorded for each maneuver, and to prevent files from containing large amounts of data that was not relevant to the actual test maneuver, however, due to the power cycling the NRC INS was unable to establish long term estimates of bias and scale errors, and thus did not perform at its highest level of accuracy. For some maneuvers, the INS solution diverged, and required an in-flight re-alignment. For analysis purposes, any data from a 'non-aligned' state was rejected.

Pegasus provided NRC the unfiltered track data from the A3S system for comparison against the truth data collected using the NRC INS. The track data was delivered in MS-Excel spreadsheet form, and post-processing was performed to align the track data with the INS data. Once the timestamps were converted to seconds since Sunday midnight it was noticed that there was an apparent offset in the data. This was found to be a result of GPS Leap Seconds not being accounted for. The column labeled as GPS time was actually UTC time. This offset was corrected by adding 18 seconds to the time. A sample timehistory of original and corrected data is shown below in Figure 30.

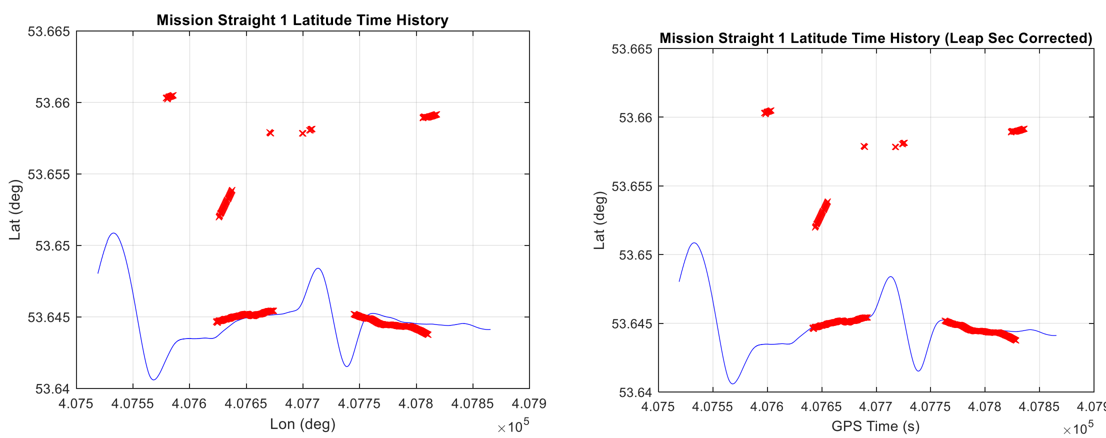

Figure 30: Sample Timehistory Data, Uncorrected (left), and Leap Second Corrected (right)

Since the radar track data was un-filtered it was necessary to perform manual association of the radar tracks in order to assess the detection and tracking accuracy. To assist in the manual determination of the tracks associated with the Cessna intruder aircraft a custom plotting routine was developed. This routine overplotted the Lat/Lon data from the INS as a blue line along with the world referenced radar tracks as red X's. At any time a new track ID was encountered the plotting routine indicated the ID number as text at the Lat/Lon coordinates of the corresponding track. A sample is shown in Figure 31. As can be seen from the figure, track ID's 999, and 261 correspond to the Cessna, whereas the remaining tracks appear to be from ground vehicles on a nearby road.

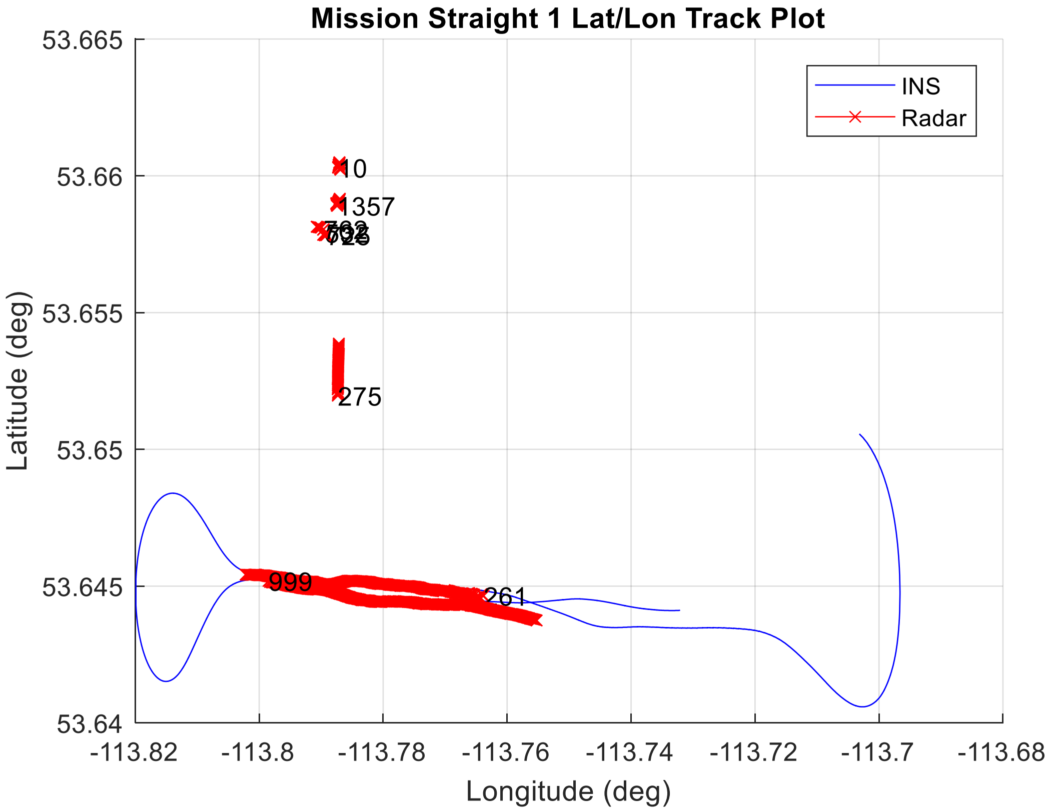

Figure 31: Sample Lat/Lon Scatter Plot

The COTS radar did not provide output in world reference coordinates, thus the Pegasus A3S system was responsible for converting the radar range/azimuth/elevation measurements to the world reference (e.g. WGS-84 Lat/Lon) coordinate system. Figure 32 provides a depiction of how the radar's X/Y/Z local coordinate system relates to the Range/Az/El coordinate system. Conversion to world coordinates is accomplished by rotating the local coordinates through the heading, pitch, and then roll Euler angles of the radar's orientation.

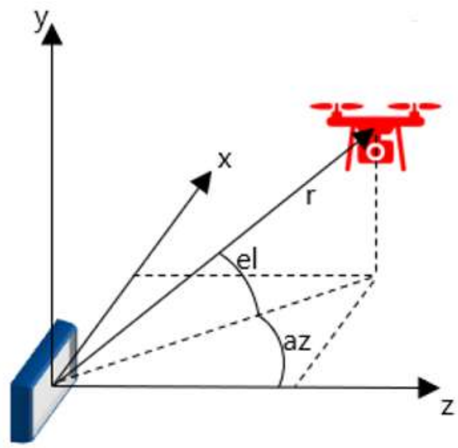

Figure 32:Radar coordinate conventions

The data from each of the missions was analyzed separately for:

1) Position error
2) Range error
3) Bearing error
4) Probability of track

To establish each of the error measurements it was necessary to linearly interpolate the INS data (which was recorded at 100 Hz) to the reported time of each of the radar tracks. Given the 100 Hz operating rate of the INS very little error will result from this interpolation.

To determine the position error the latitude and longitude measurements and estimates were converted from WGS-84 to UTM coordinates, which have the benefit being Cartesian, and with units of meters. The position error differs from the range error in that the position error includes the effect of both range and bearing errors, whereas the range and bearing error analysis separate these components into the primary measurements provided by the radar.

Figure 33 below provides a sample of the analysis of the comparison of available radar bearing/azimuth measurements against the truth data from the INS installed on-board the Cessna. The three traces shown in the figure represent the raw bearing measurement as reported by the radar as red X's, and the bearing as determined from world referenced coordinated determined by the Pegasus A3S as blue X's. The bearing as determined from the INS is shown as a cyan solid line. To determine the bearing from the world referenced coordinates it was necessary to convert to UTM coordinates, subtract the radar position, and rotate through the radar's heading (i.e. so a bearing along the radar's heading yields zero degrees). The figure presents a surprising result that the radar tracks in world referenced coordinates match the INS data with greater accuracy than the raw bearing measurements from the radar itself. Upon further analysis it was found that adjusting the nominal radar heading eliminated the error, as can be seen by Figure 34.

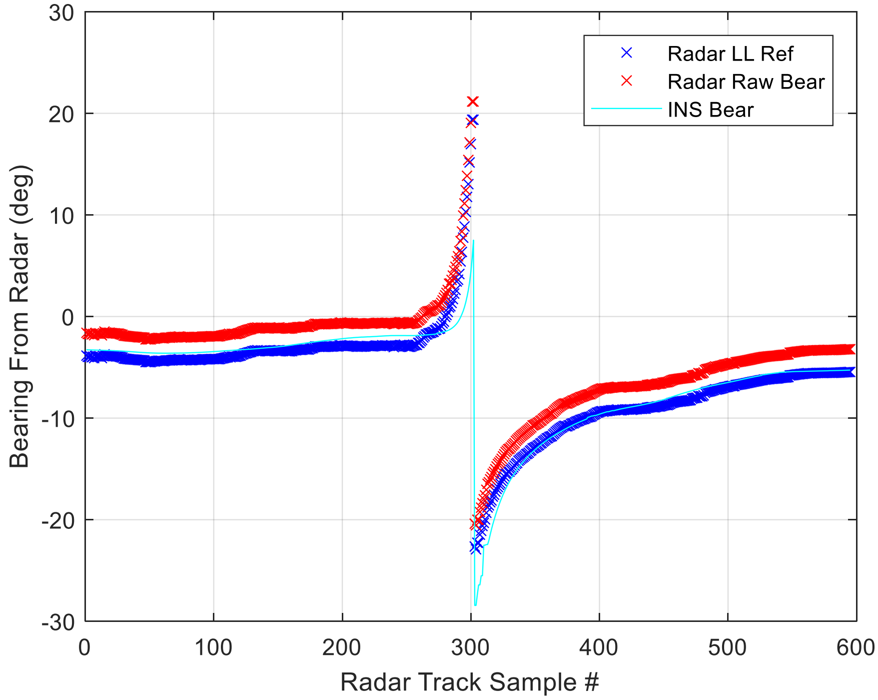

Figure 33: Sample of Echoflight bearing analysis

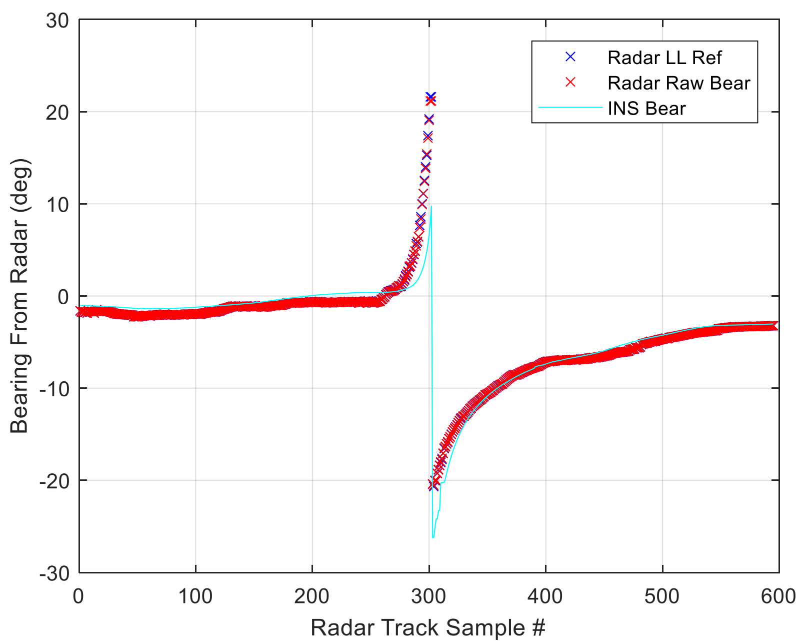

Figure 34: Sample of heading corrected bearing analysis

8.4 Mission Data

8.4.1 Time Histories and Track plots

Figures 35-53 present time histories and track plots for the seven missions flown with manual entry of the radar's location. The time histories show the data recorded by the NRC INS as a blue trace, and the track output provided by Pegasus's A3S system as red X's. The time histories show latitude, longitude, and altitude. Individual X's were used to present the radar track outputs as this allows for gaps in tracking to be readily seen.

The track plots are presented as distance north and east from the radar position, again with the data recorded by the NRC INS as a blue line, and the radar tracks as red X's. As can be seen from the time history plots there is generally good agreement between the position information from the INS and the radar system out to 3km range, however variable performance was noted during the serpentine run. Unfortunately, only one of the serpentine runs had valid data, owing to an apparent loss of GPS on the first serpentine mission (Figure 50). This prevented an analysis of maneuvering vs non-maneuvering performance from being conducted.

Upon closer examination of the timehistory data it was observed that there was an apparent variable time bias present on each file. The source of this time bias is unknown, although since the INS data uses GPS time directly for its clock data it is believed that the bias resulted from within the Pegasus system. To minimize the impact of this time bias, the time-histories were manually adjusted for best apparent match. The offset adjustment is indicated in the figure caption for the time-histories.

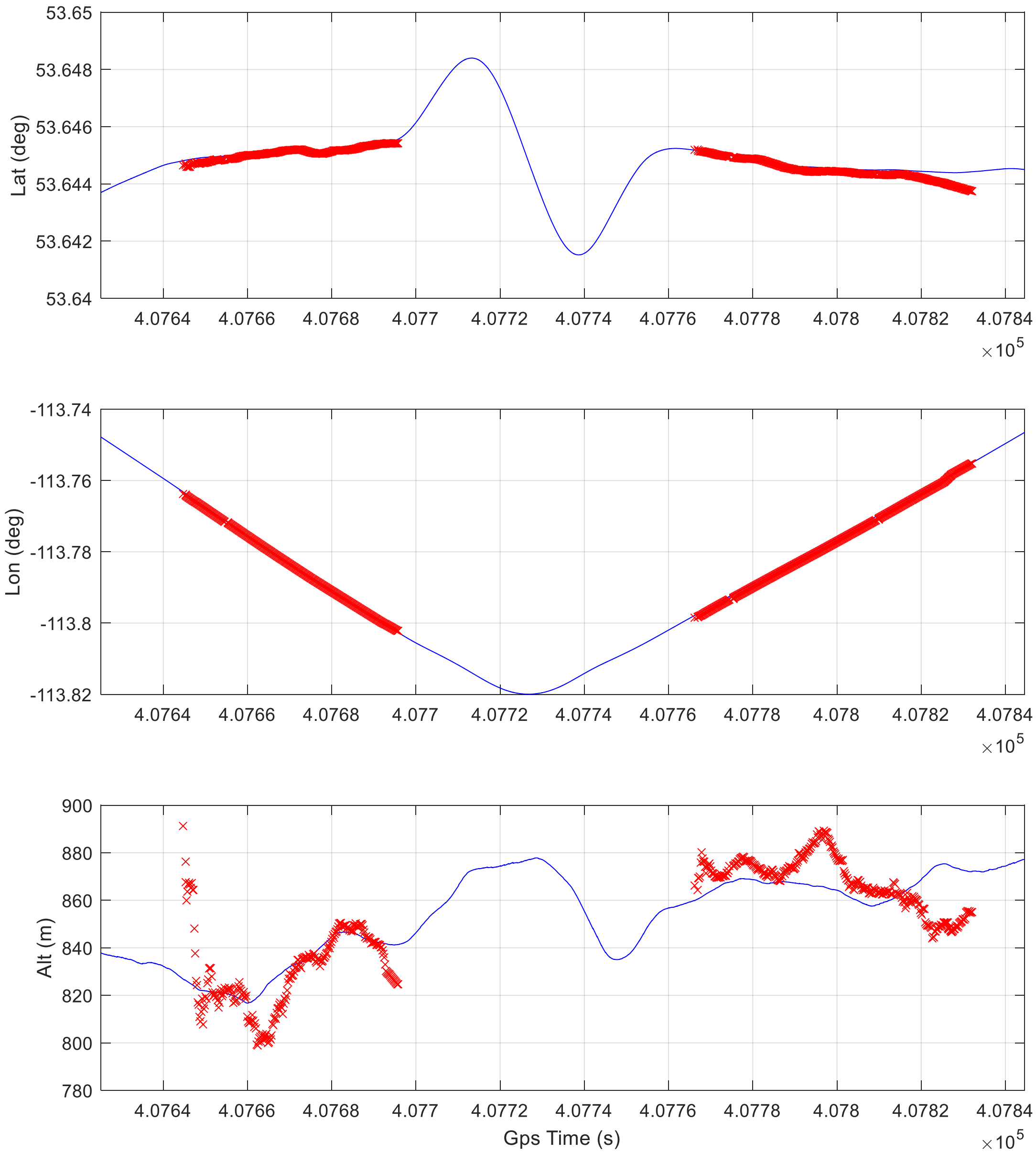

Figure 35: Mission 1 Timehistory (Offset: 3.5 s)

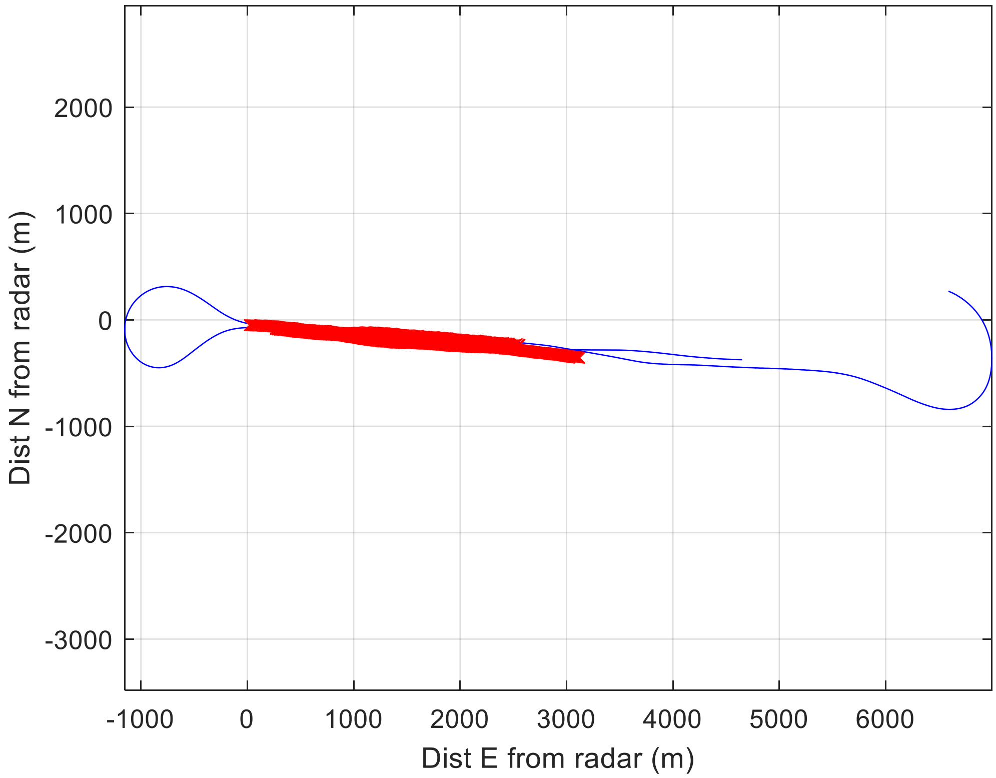

Figure 36: Mission 1 Trackplot

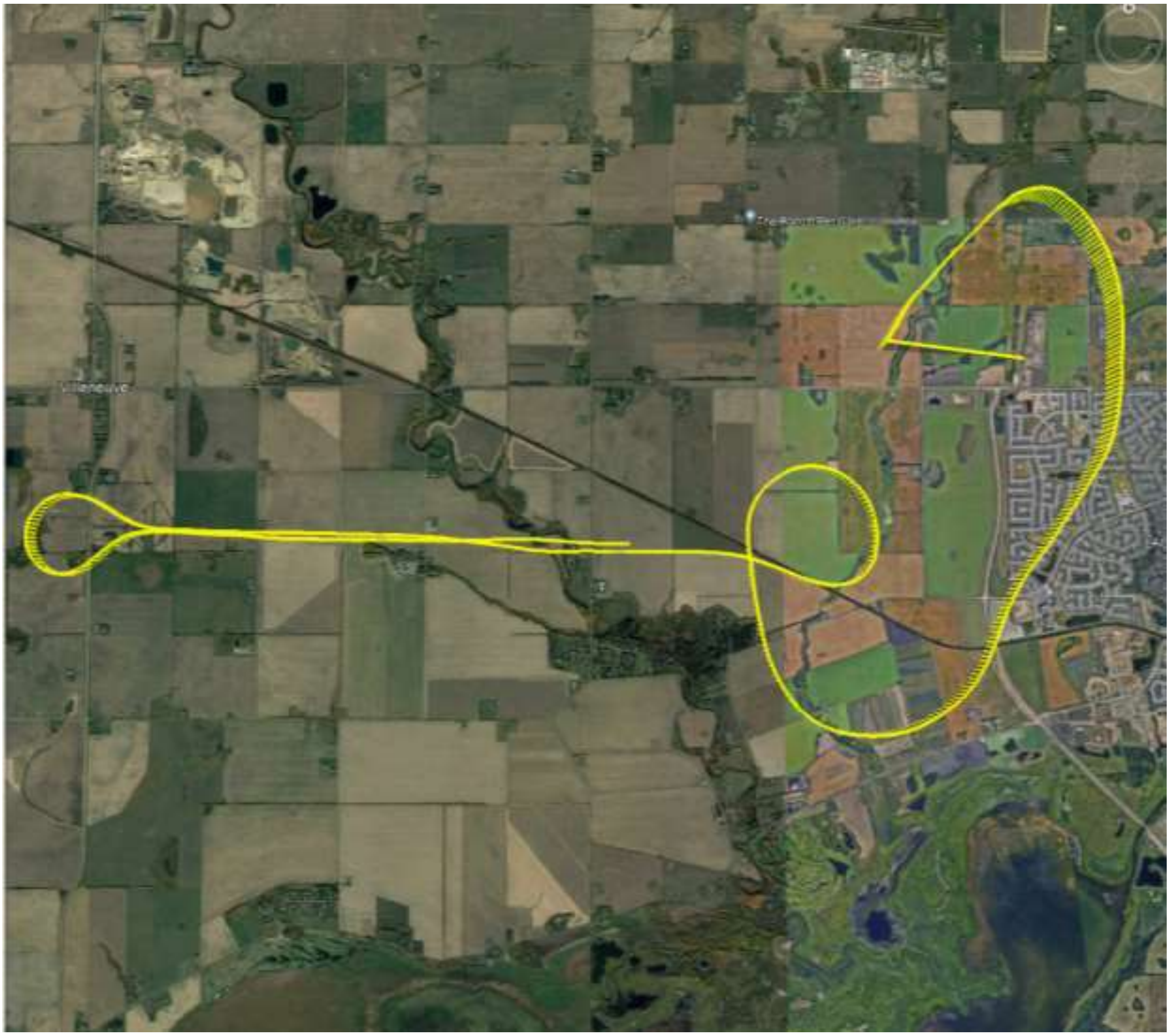

Figure 37: Mission 1 Satellite View

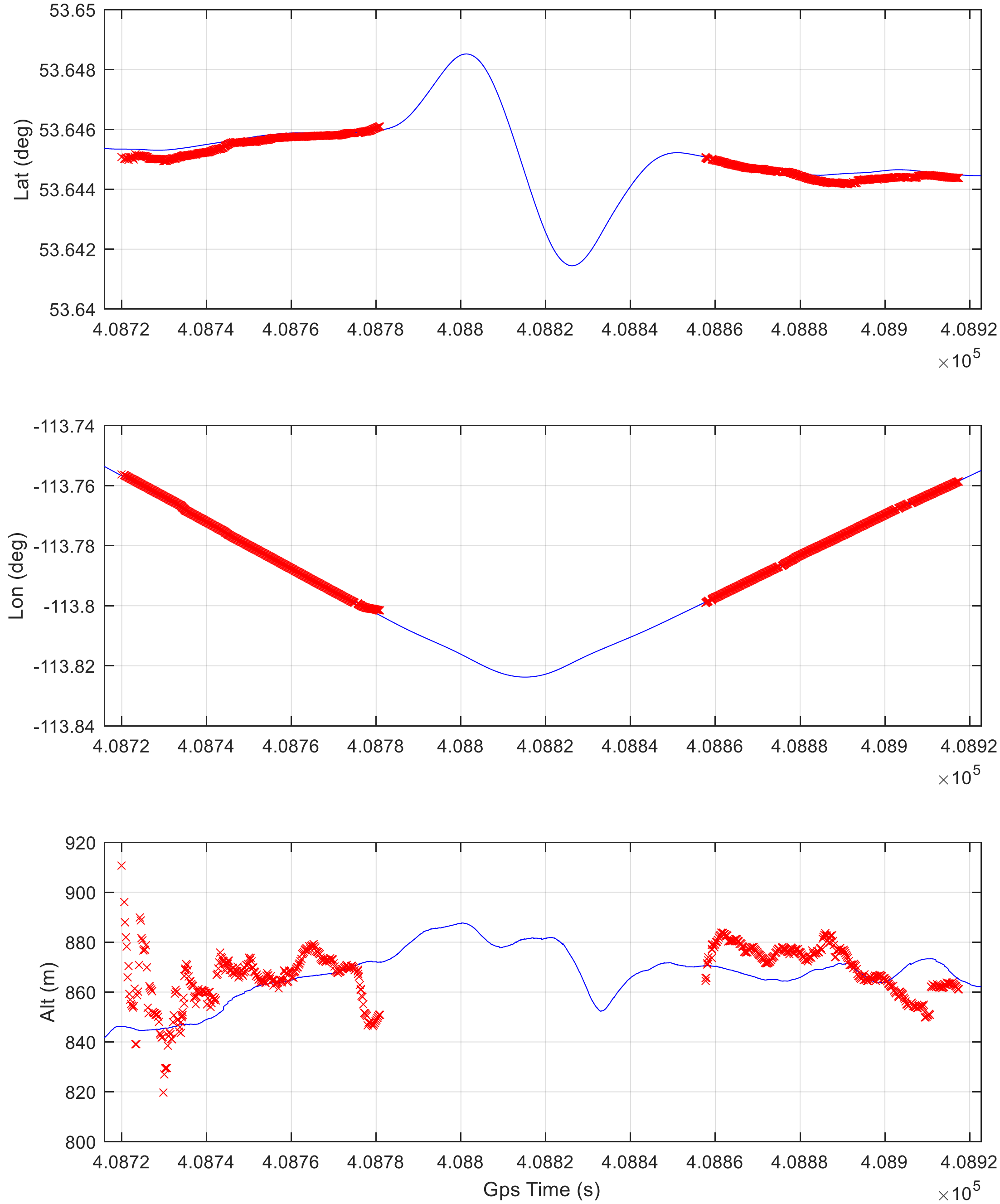

Figure 38: Mission 2 Timehistory (Offset: 2s)

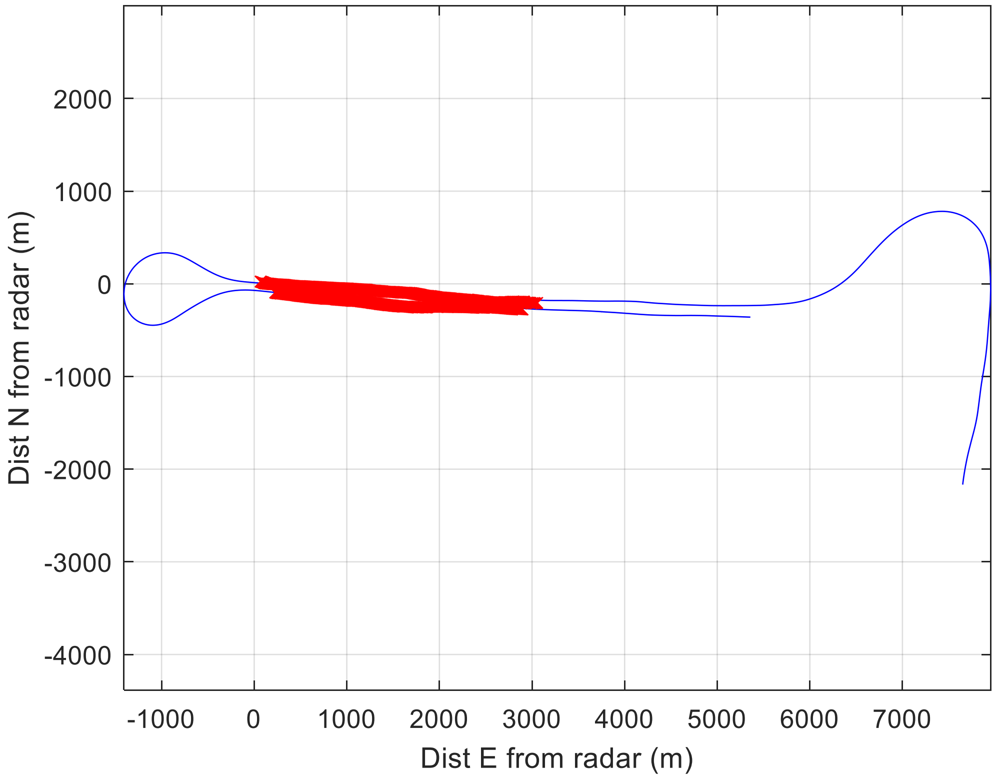

Figure 39: Mission 2 Trackplot

Figure 40: Mission 2 Satellite View

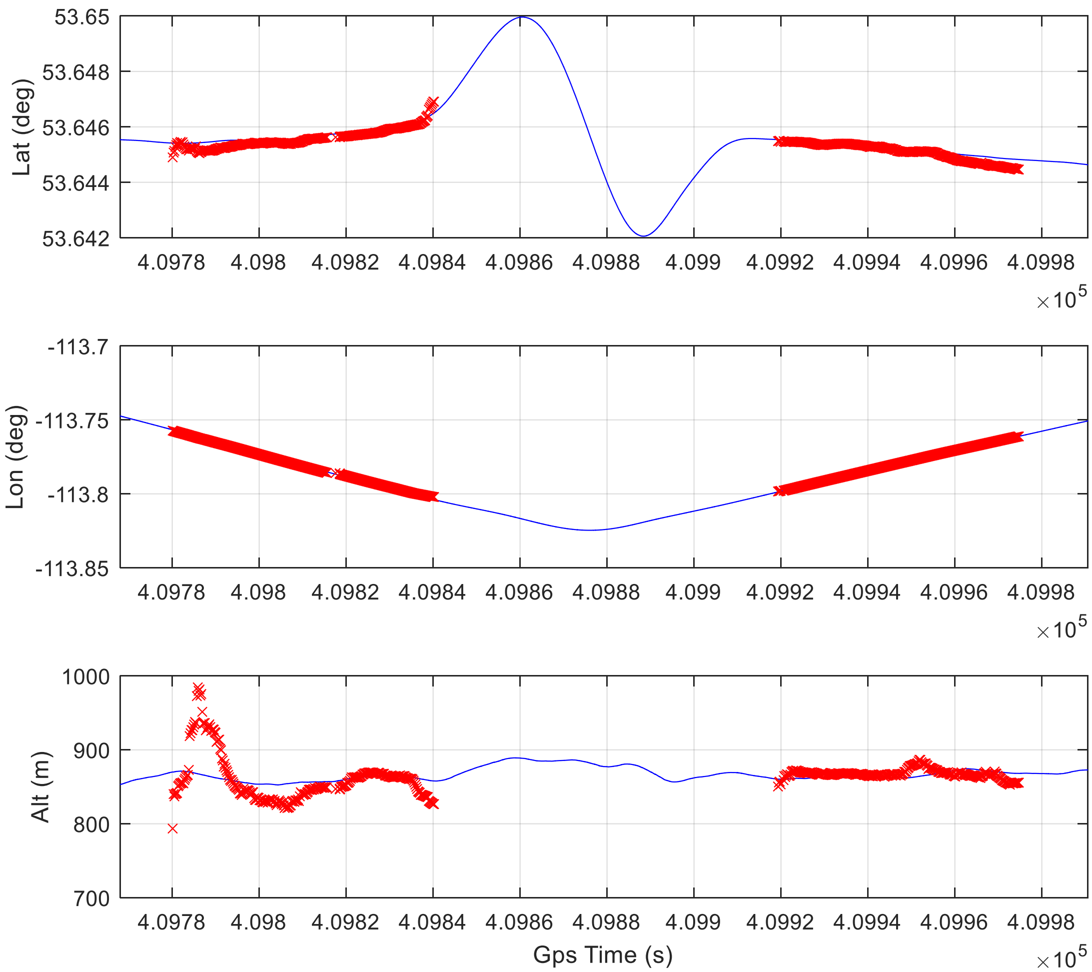

Figure 41: Mission 3 Timehistory (Offset: 3.3 s)

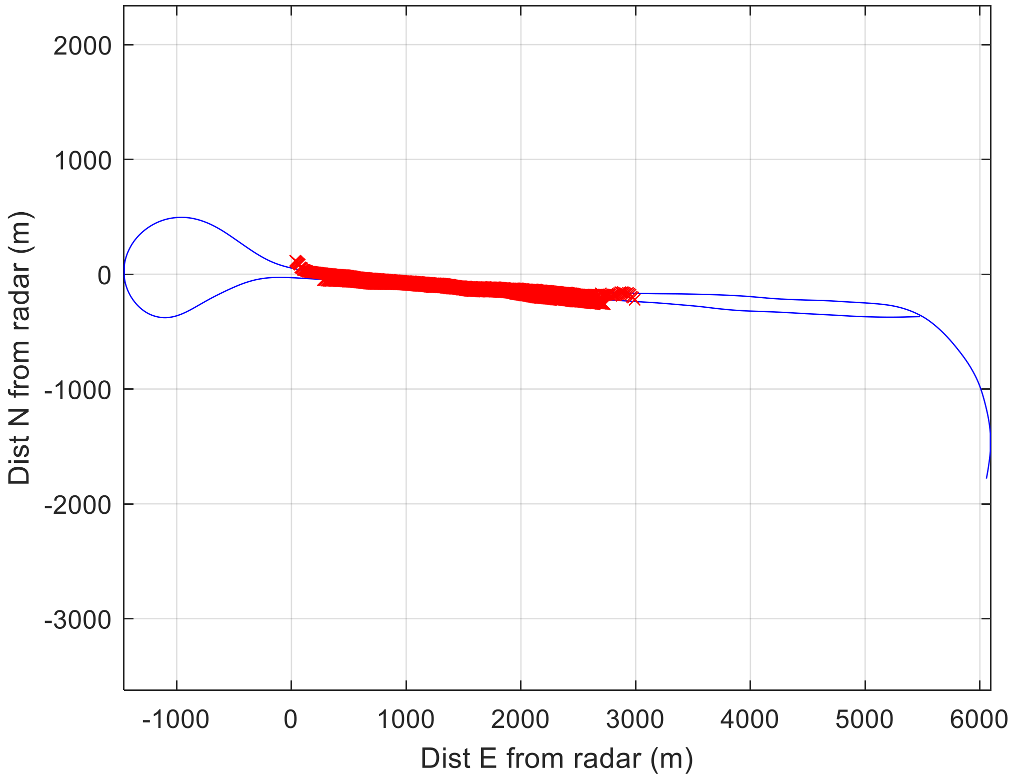

Figure 42: Mission 3 Trackplot

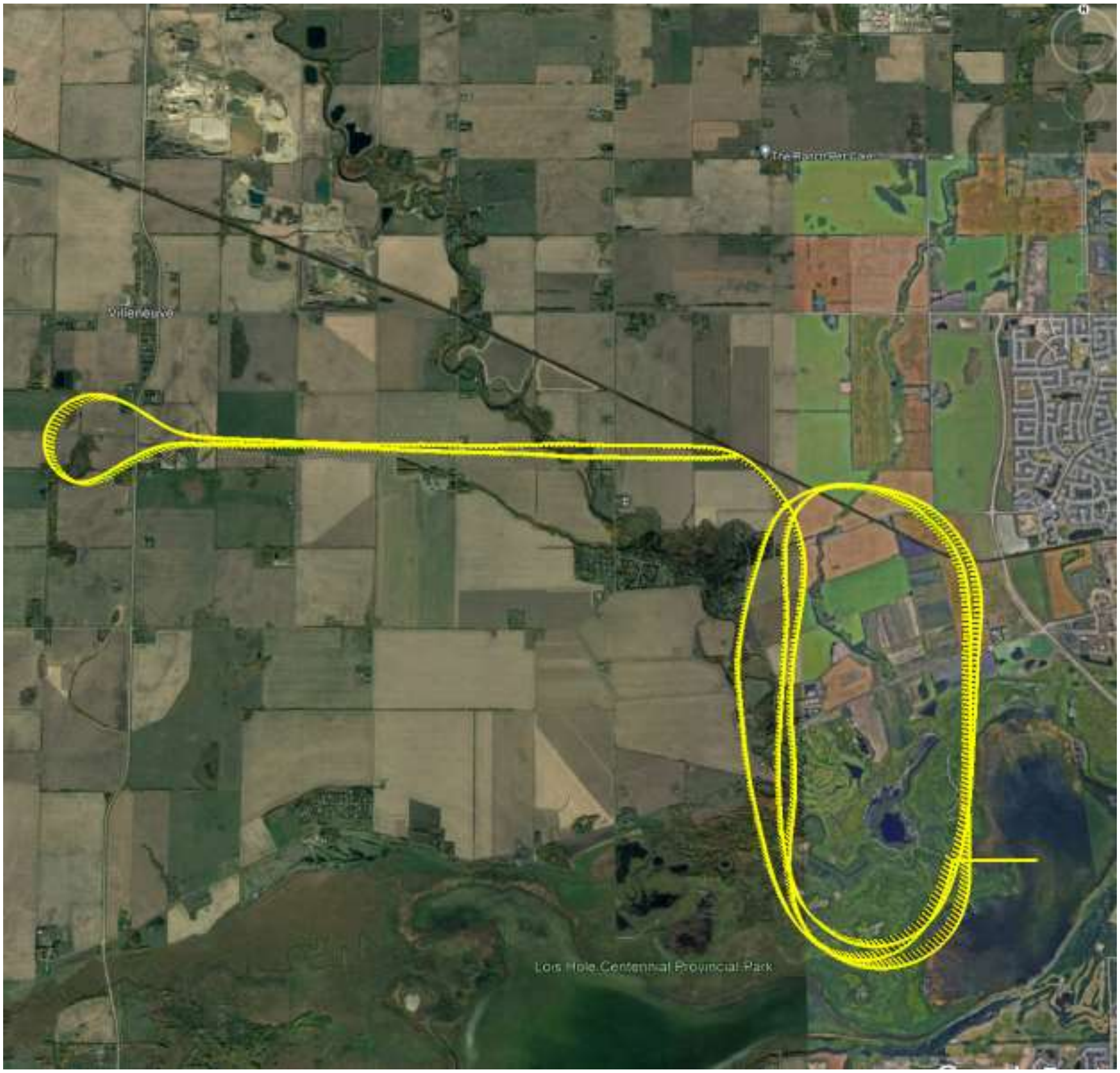

Figure 43: Mission 3 Satellite View

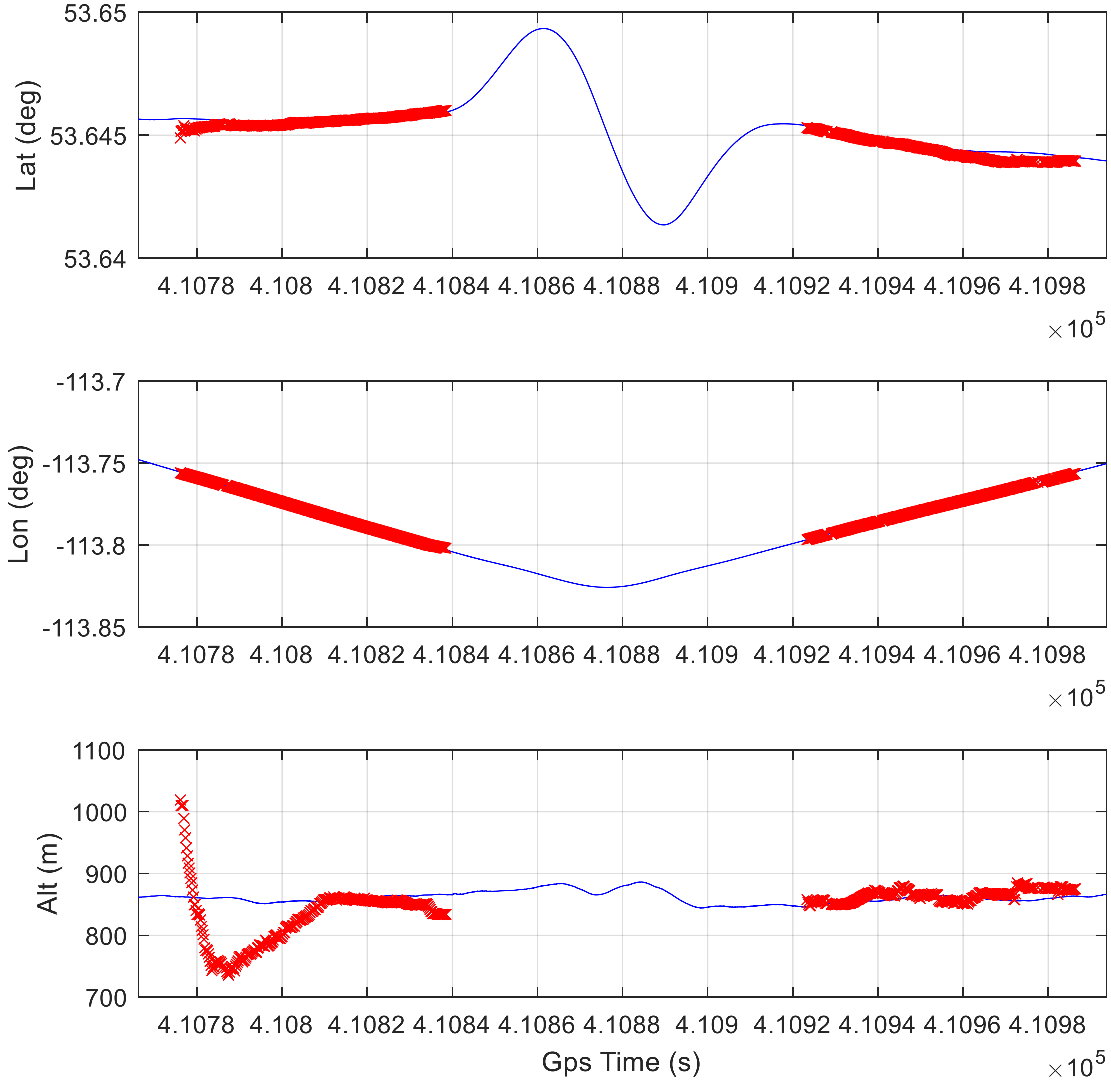

Figure 44: Mission 4 Timehistory (Offset: 4s)

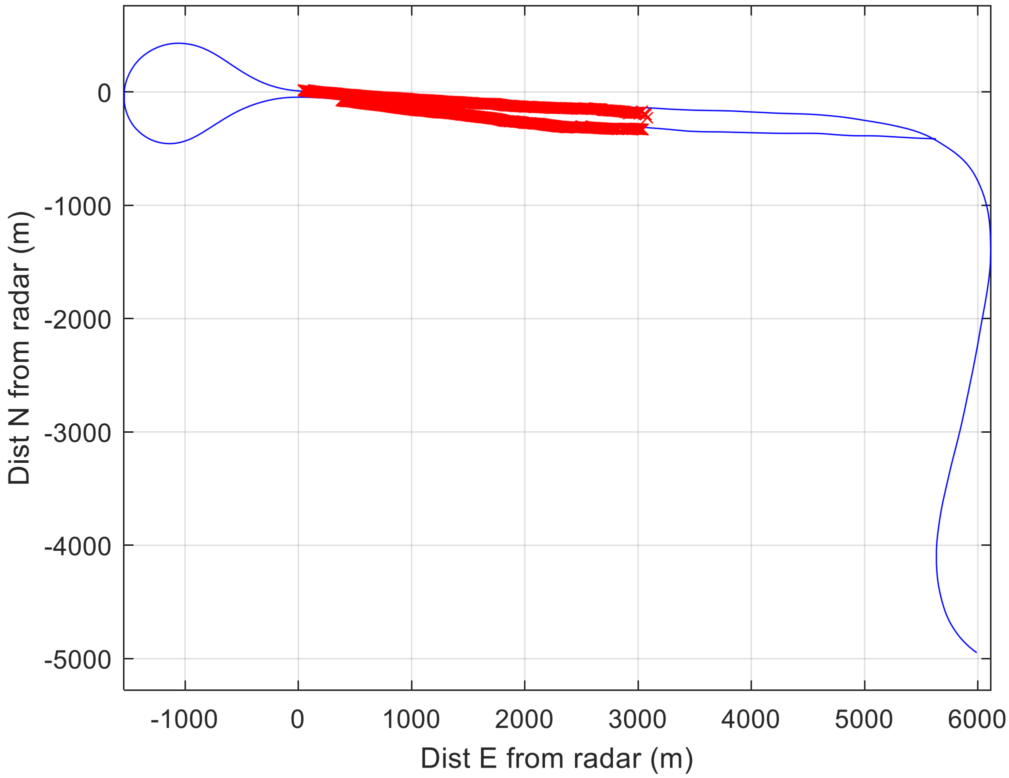

Figure 45: Mission 4 Trackplot

Figure 46: Mission 4 Satellite View

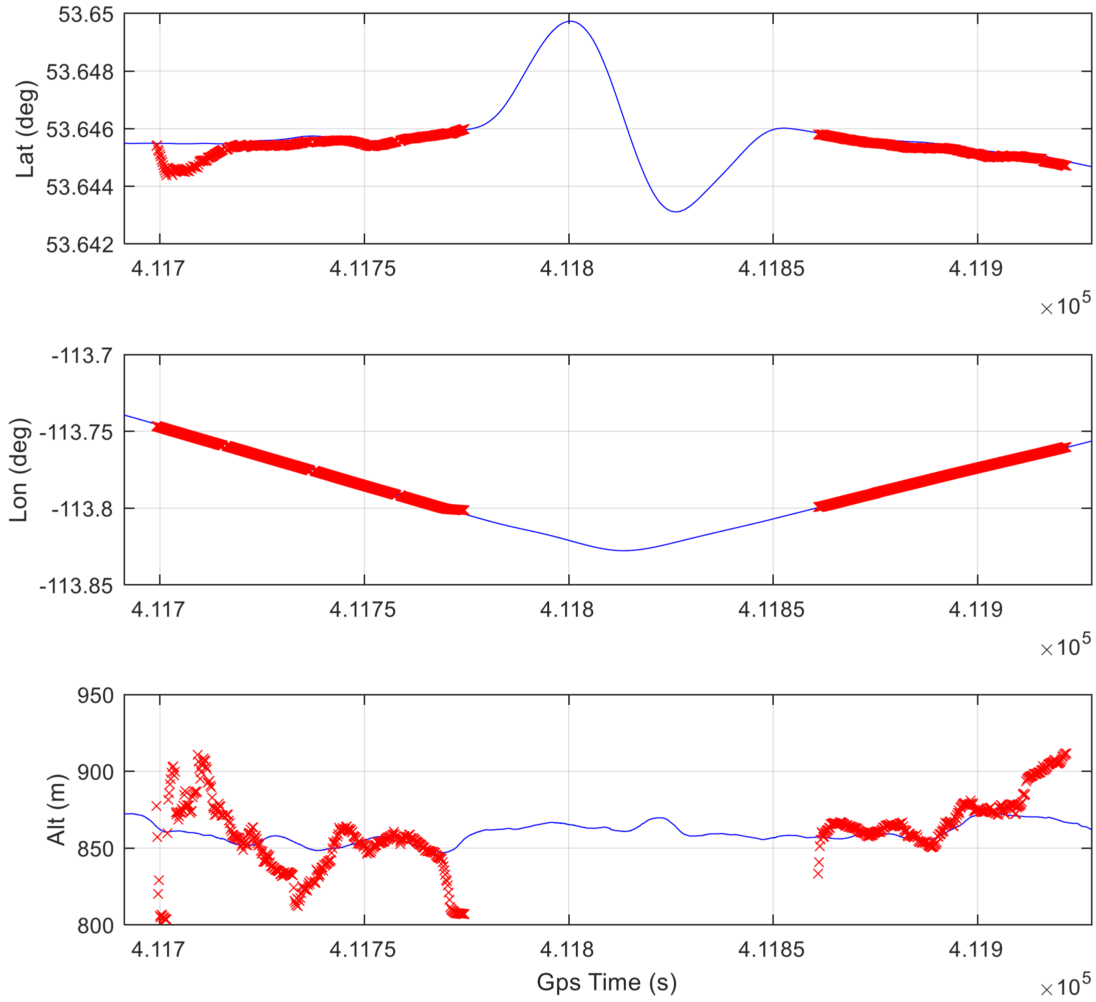

Figure 47: Mission 5 Timehistory (Offset: 1s)

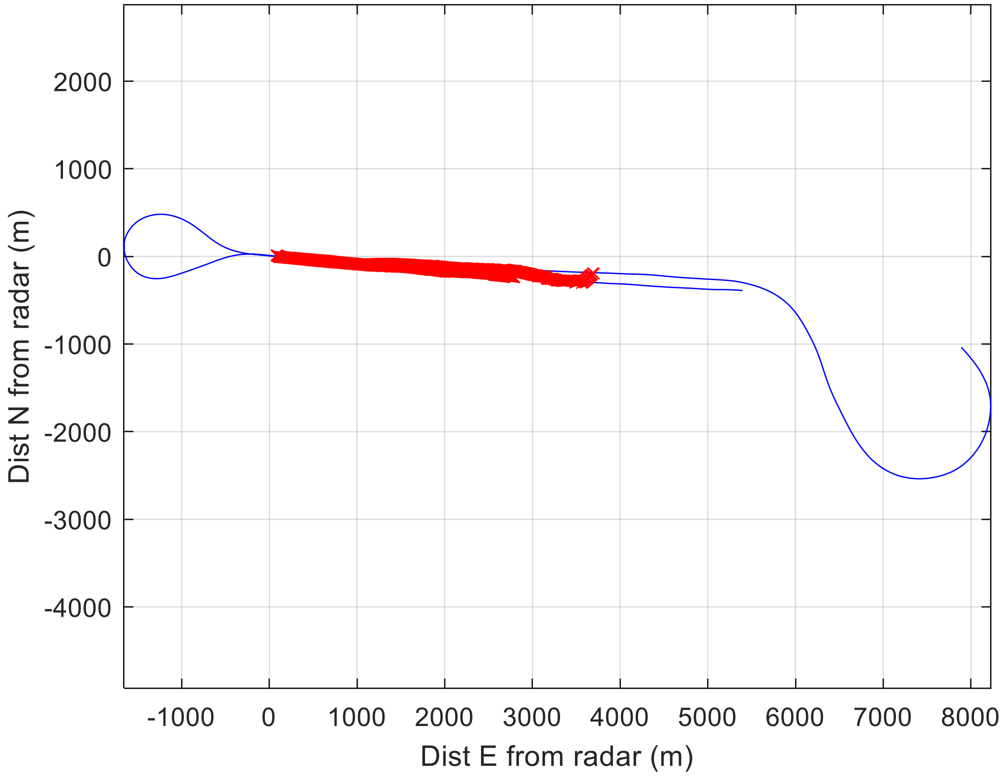

Figure 48: Mission 5 Trackplot

Figure 49: Mission 5 Satellite View

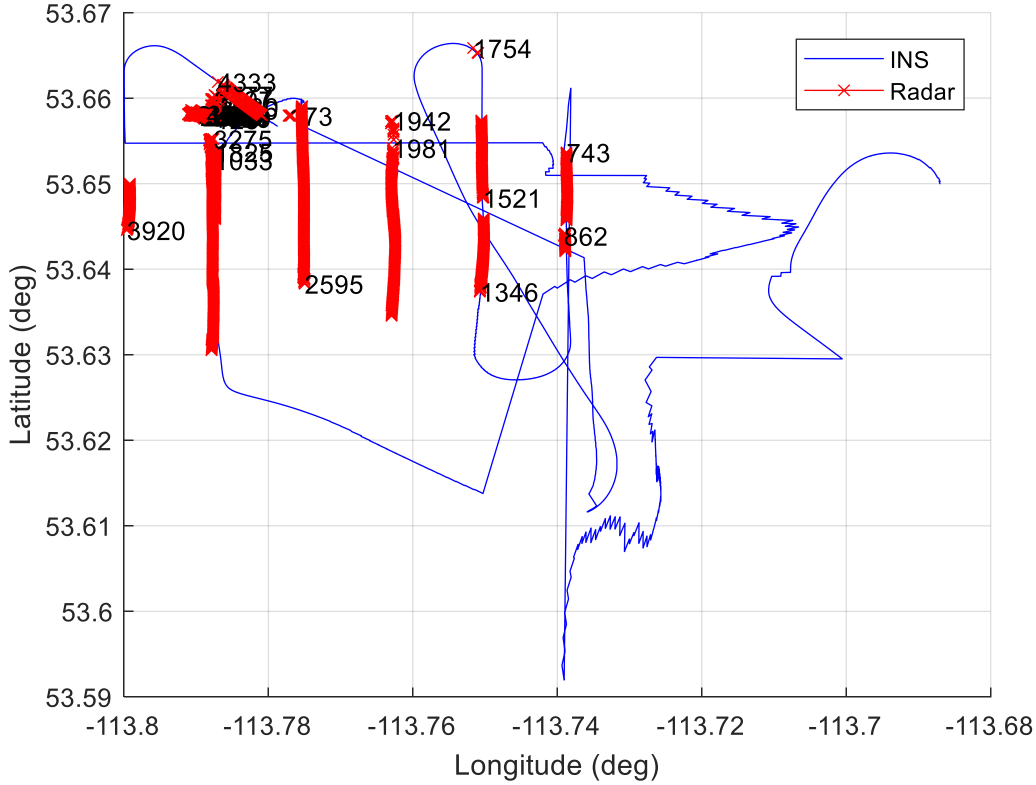

Figure 50: Sample Trackplot from Mission 6 (Serpentine 1)

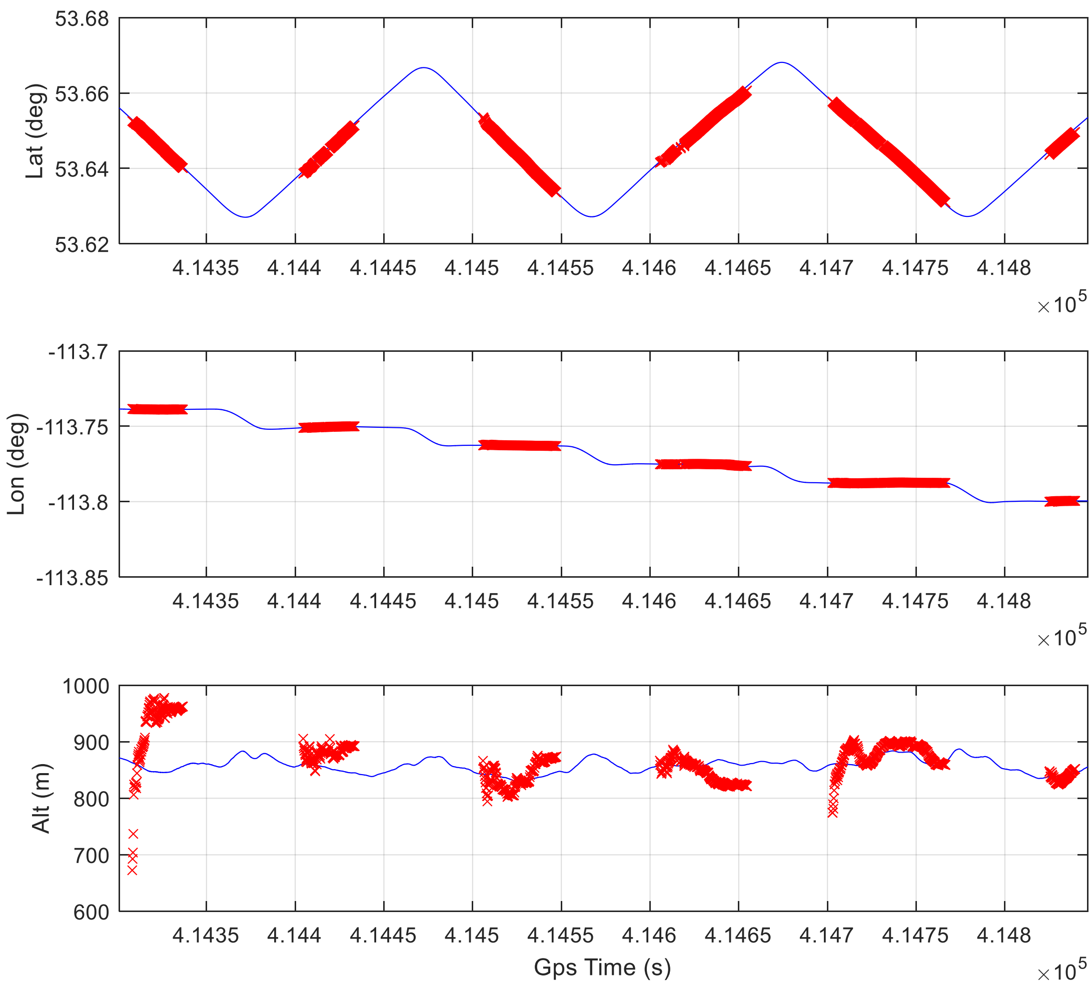

Figure 51: Mission 7 Timehistory (Offset: 4.5 s)

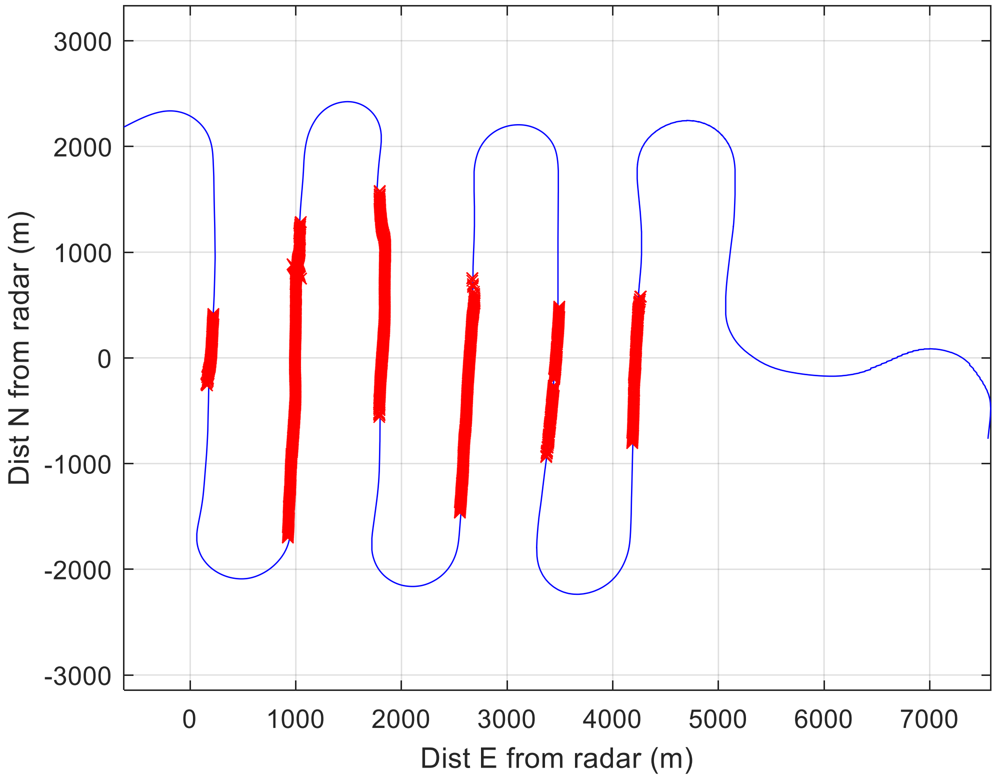

Figure 52: Mission 7 Trackplot

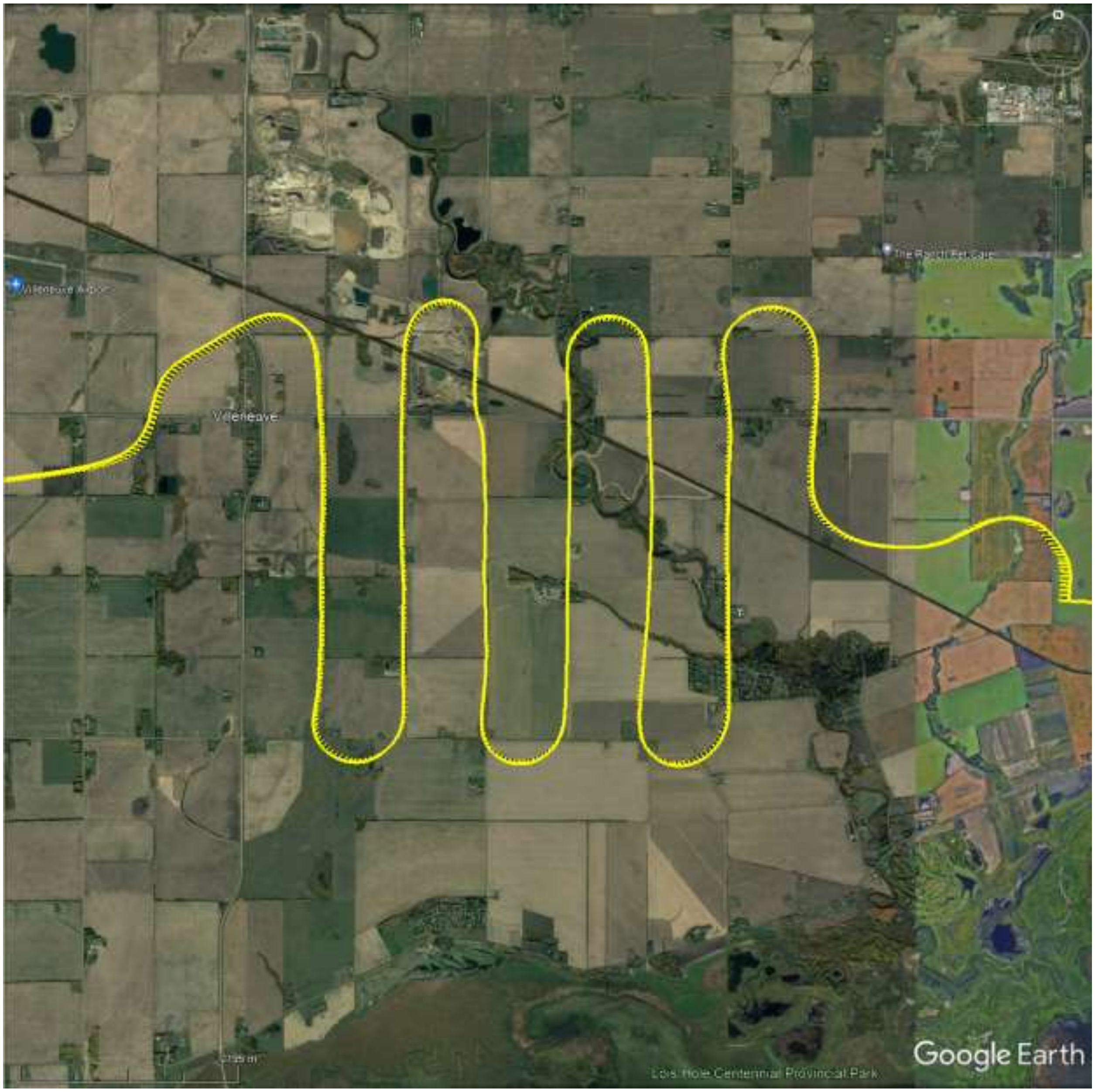

Figure 53: Mission 7 Satellite View

8.4.2 Detection and tracking performance histograms and statistics

Figures 54-59 present histograms and mean and variance statistics for the following performance measures:

1) Position error
2) Range error
3) Bearing error

Histograms are presented for each of these performance measures, allowing the distribution of errors to be investigated for any trends. The distribution of errors appeared to be bi-modal in many cases. This may have been due to timing, or bore-sighting errors with the track data. The standard deviation data is of particular importance as it demonstrates the variability of performance that can be expected. Given the normal distribution of errors once can expect 95% confidence in the radar's performance within two standard deviations.

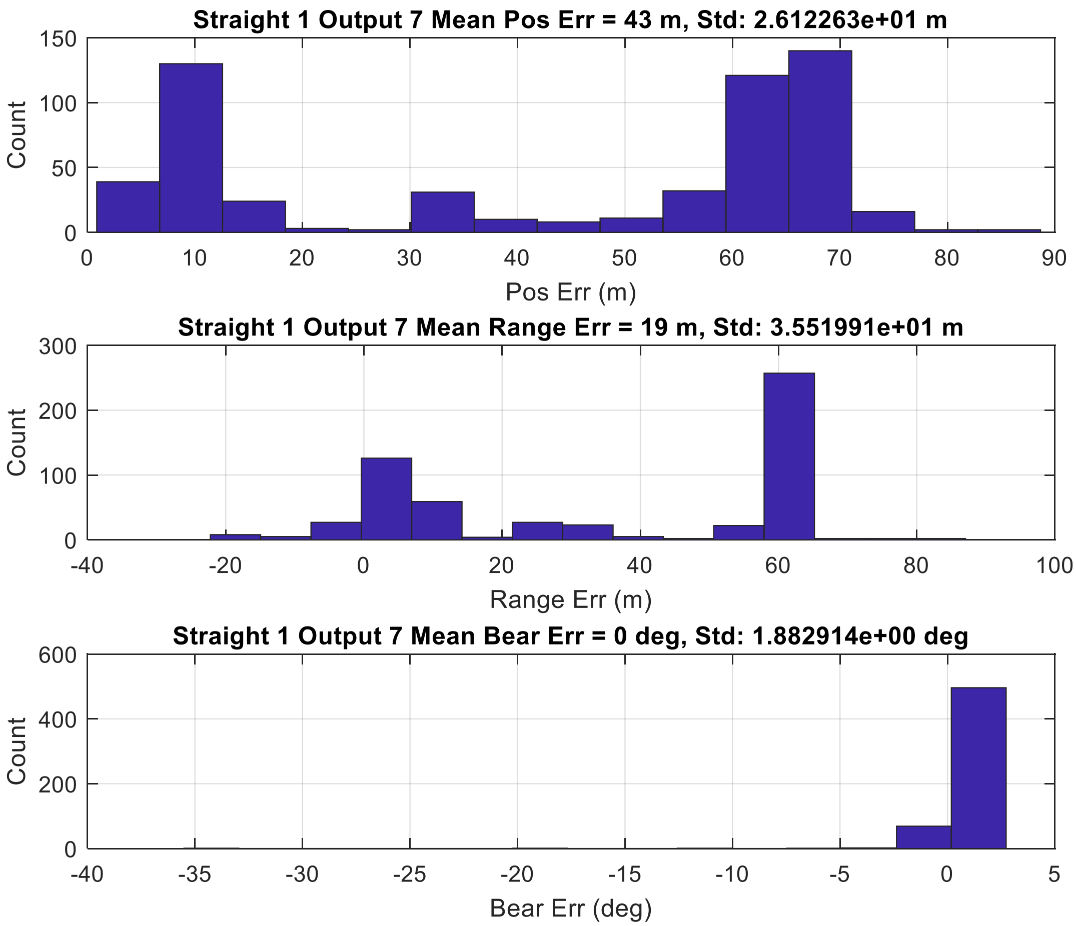

Figure 54: Mission 1 Performance Histogram

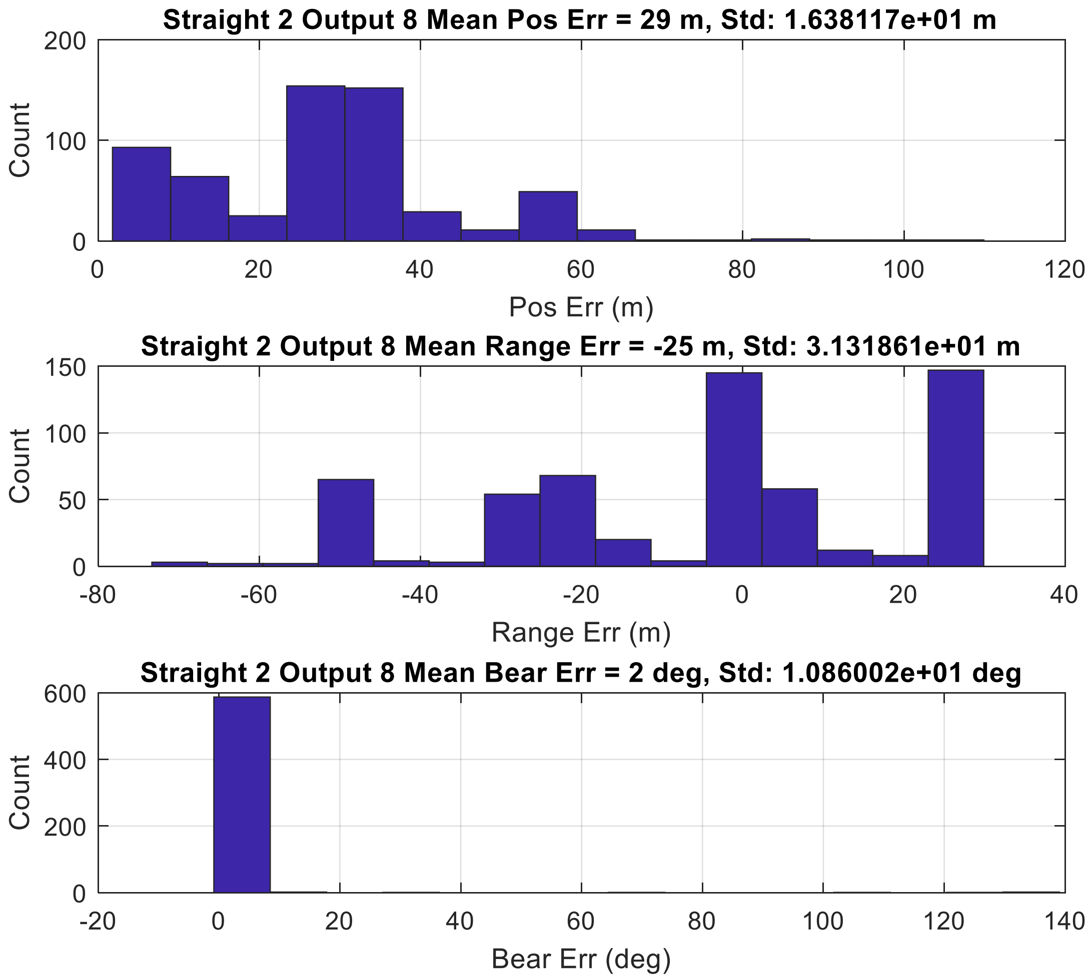

Figure 55: Mission 2 Performance Histogram

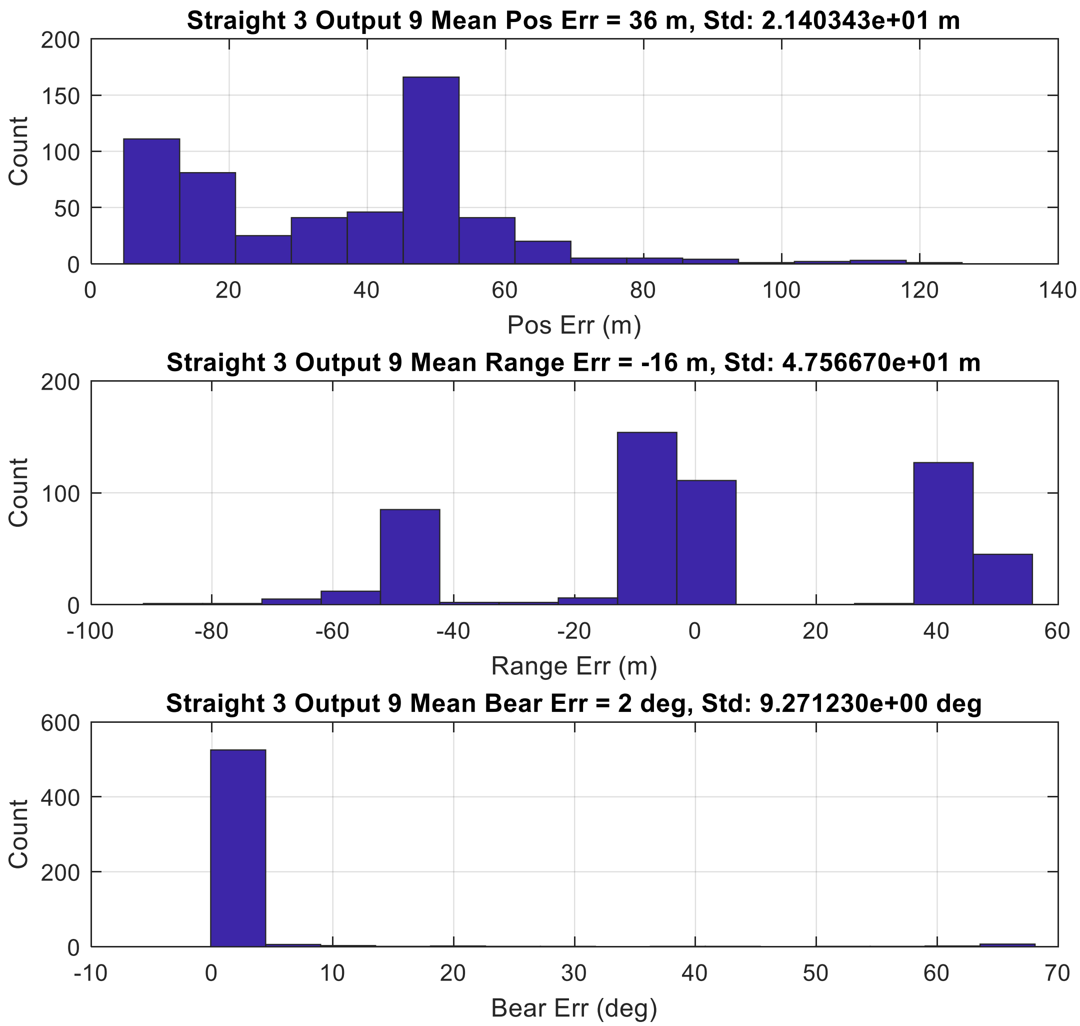

Figure 56: Mission 3 Performance Timehistory

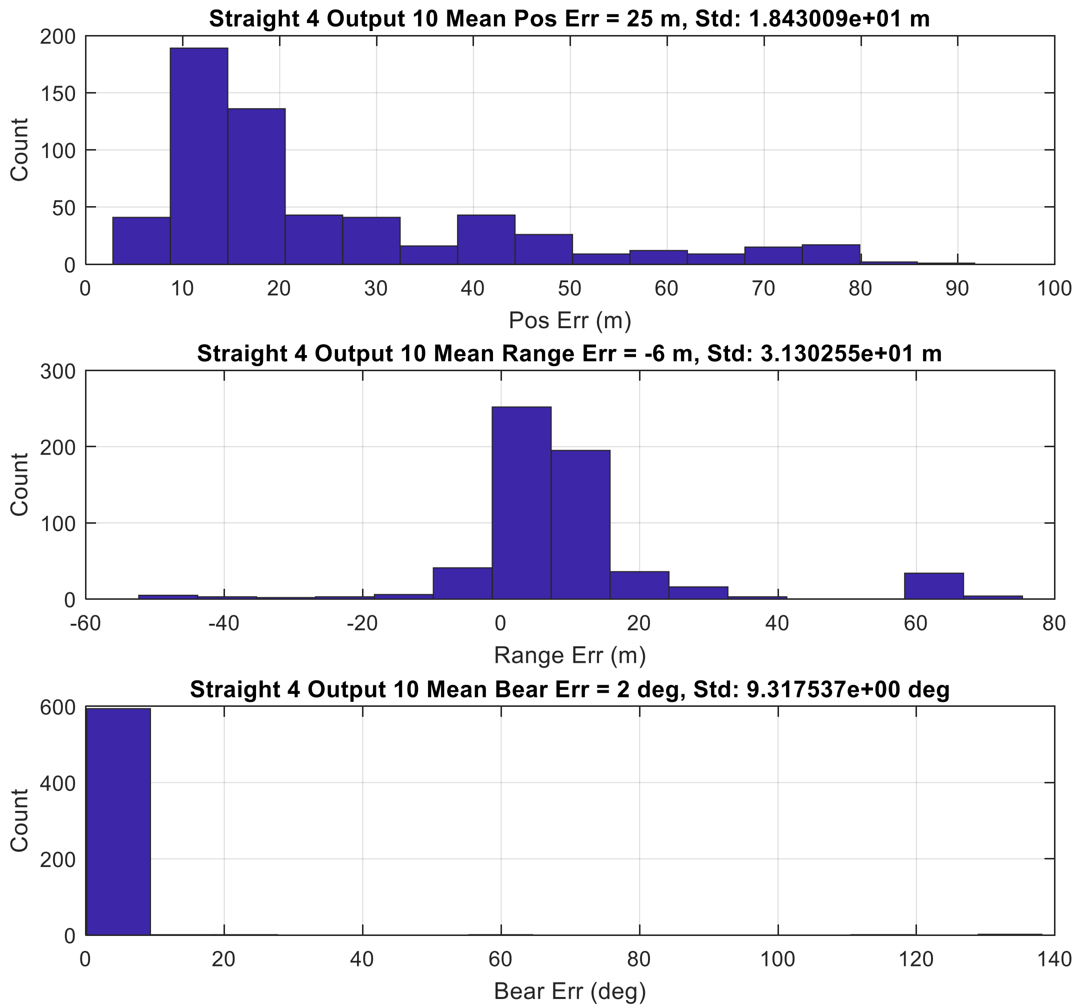

Figure 57: Mission 4 Performance Historgram

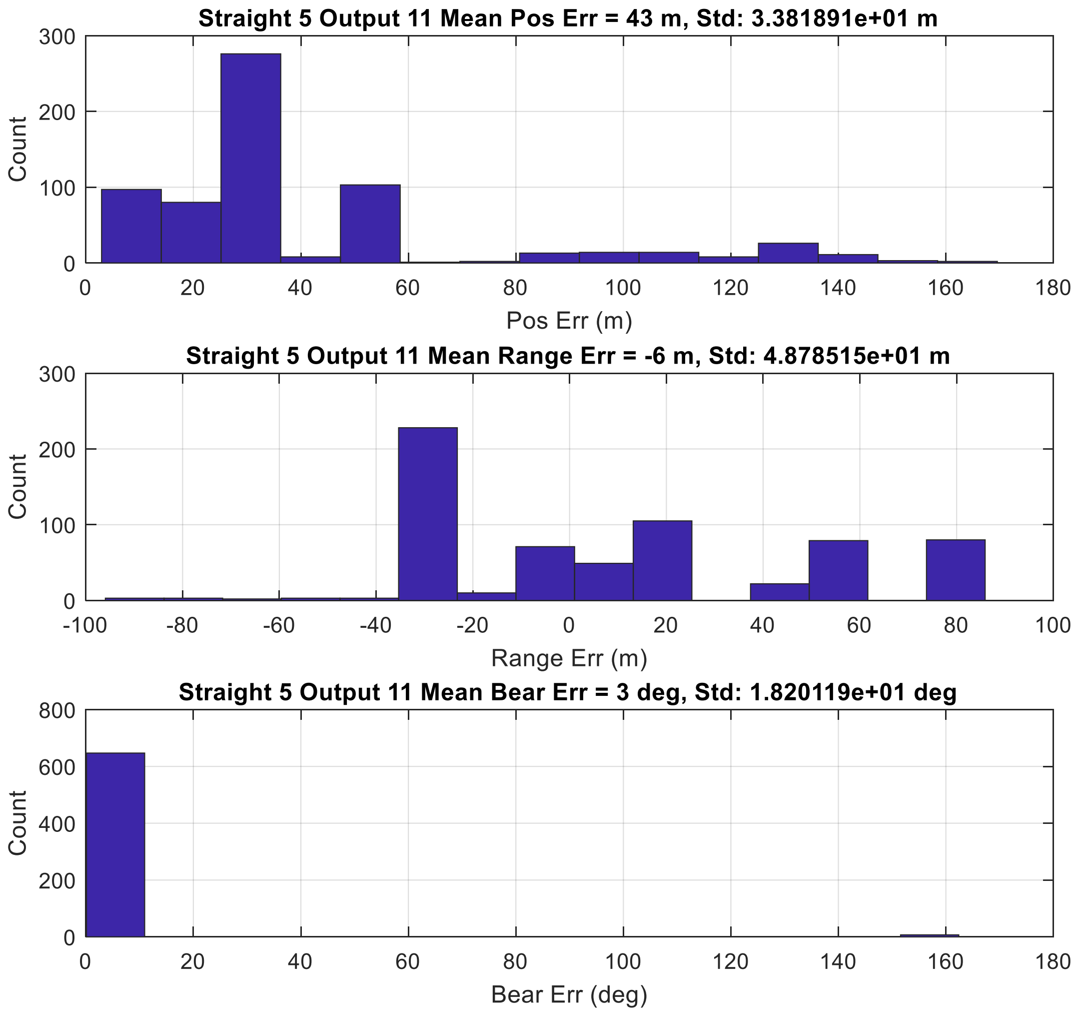

Figure 58: Mission 5 Performance Historgram

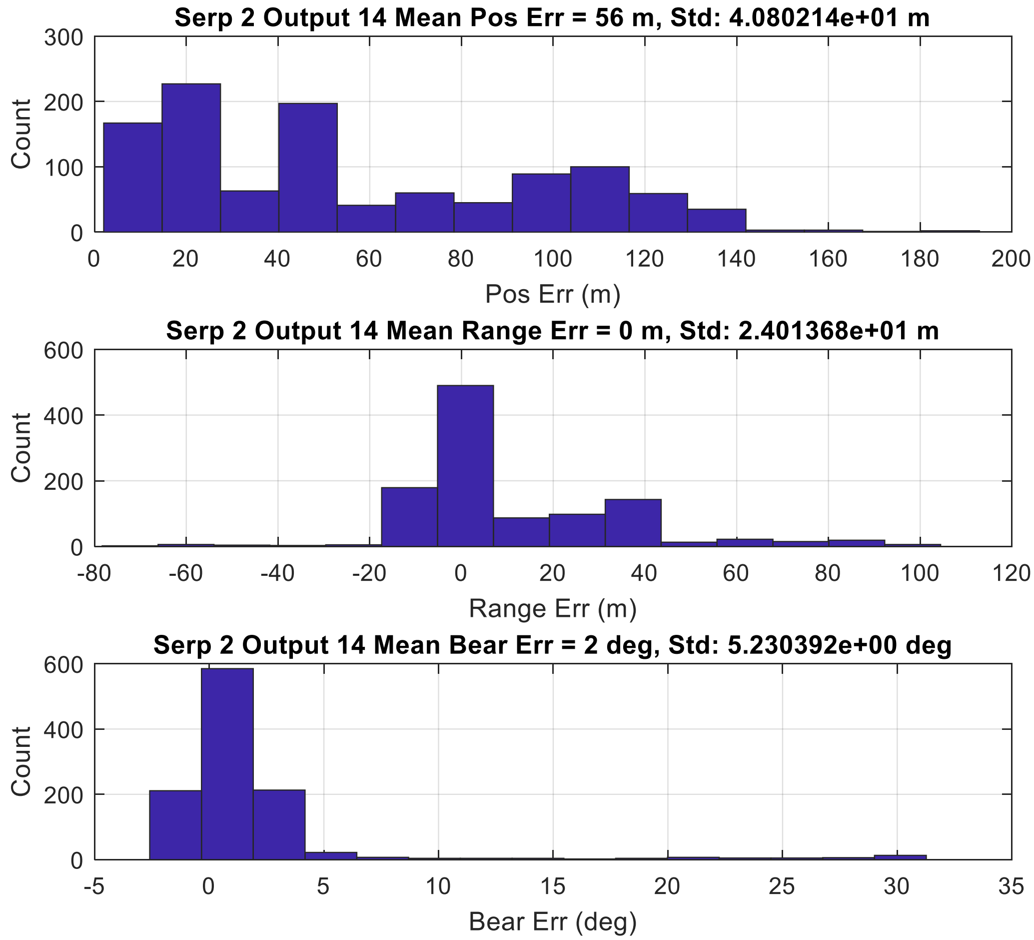

Figure 59: Mission 7 Performance Histogram

8.4.3 Position Performance Table:

Table 7 presents a summary of the position error performance as collected from the histograms presented earlier. The A3S system has a nominal accuracy of 39 meters, and a 95% confidence accuracy of 90 meters.

Table 7: Position performance

Mission	Mean (m)	Std (m)	95% Conf (m)
1 Straight	43	26	94
2 Straight	29	16	60
3 Straight	36	21	77
4 Straight	25	18	60
5 Straight	43	34	110
6 Serpentine	N/A	N/A	N/A
7 Serpentine	56	41	136
Average	**39**	**26**	**90**

8.4.4 Track Confidence

Track confidence was evaluated by first removing all INS data that was outside of the declared performance envelope for the radar (2.5 km range, 120 Deg Horizontal FOV, and 80 Deg Vertical FOV). It should be noted that the radar demonstrated detection range in excess of the stated 2.5 km range, however.

Figure 6060 presents a sample of the analysis conducted to determine which data points were within the stated range/FOV of the radar. The solid blue line represents the ground track of the Cessna 172 in UTM coordinates as recorded by the INS. The blue circle shows the position of the radar, and that two dashed black lines represent the 120 degree horizontal field of view out to a maximum range of 2.5 km. The cyan x's represent the INS track data that is within the stated range/FOV of the radar, whereas the red X's represent the radar tracks as recorded by the Pegasus A3S system.

Once the both the INS and radar data had been restricted to the range/FOV constraints, the confidence was then determined by the ratio of the total time the aircraft was tracked by the A3S divided by the total time it spent within the range/FOV.

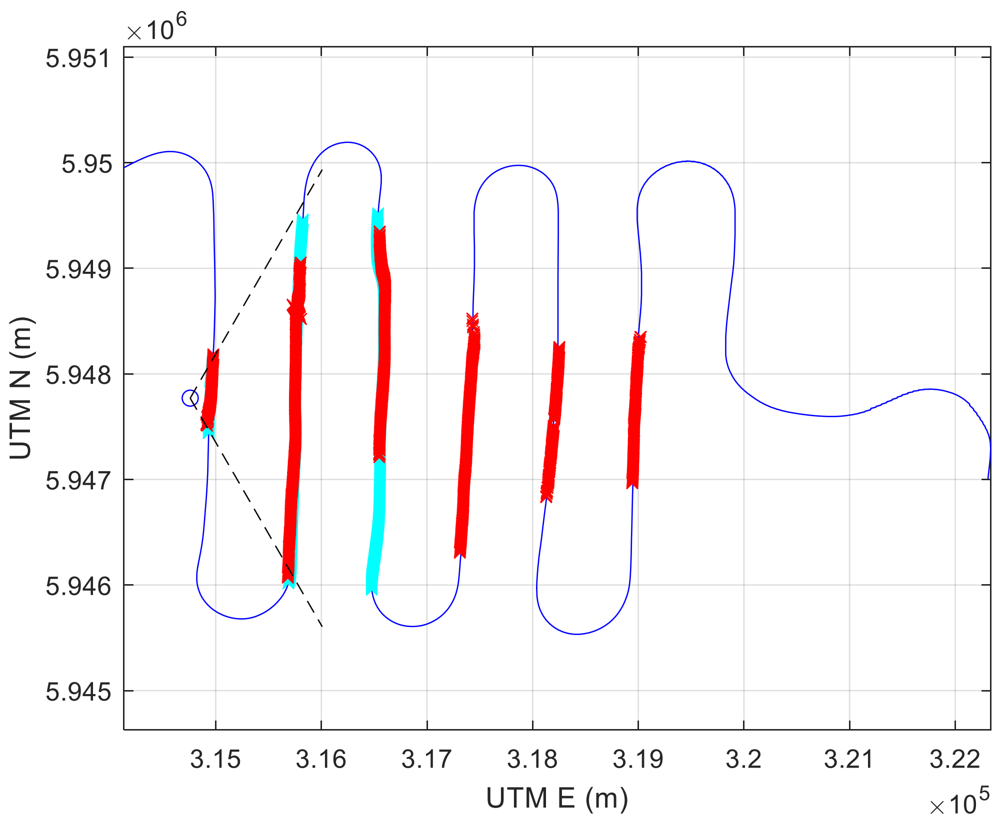

Figure 60: Mission 7 Trackplot Showing FOV/Range Analysis

Table 8 contains the track confidence analysis data for each of the missions. It can be seen that the track confidence is high (above 99%) for the straight maneuvers, however drops to 78% for the serpentine.

Table 8: Track Confidence

Mission #/Description	Time Aircraft was inside FOV/Range	Time Tracked	% Confidence
Straight 1	98.3 s	98.0 s	99.7 %
Straight 2	95.5 s	94.9 s	99.4 %
Straight 3	94.1 s	93.7 s	99.6 %
Straight 4	97.6 s	97.2 s	99.6 %
Straight 5	98.0 s	97.6	99.6 %
Serpentine 1	N/A	N/A	N/A
Serpentine 2	161.2 s	127.1 s	78.8 %

Since the radar track data collected from Pegasus did not include any maneuvering targets the analysis above can be considered as valid for non-maneuvering targets only.

8.4.5 Maximum Range

Table 9 below presents the maximum range at which the Cessna was tracked during the course of each mission. On average, the A3S system was able to track the Intruder aircraft up to 3.4 km range.

Table 9: Maximum Range

Mission #/Description	Maximum Tracked Range (m)
Straight 1	3147
Straight 2	3036
Straight 3	3032
Straight 4	3132
Straight 5	3785
Serpentine 1	N/A
Serpentine 2	4291
Average	3404

8.4.6 Overall Detection and Tracking Performance

The performance tables demonstrate that the A3S system, as tested with the selected COTS radar, can operate at up to 3.4 km range with 95% position confidence established within 90 meters of the actual target location, and a 99% confidence in establishing track for a straight and level target. Pegasus did not provide any threat classification/warning output generated by their system. It is possible that none was available since the flight testing analyzed herein was conducted without an RPA being present. Pegasus conducted flight test demonstrations of automatic avoidance initiated by A3S during the trial, however neither the data nor test procedure was reviewed for this report.

Airborne integration of the COTS radar data requires conversion to world coordinates through the use of an aircraft inertial navigation system. The A3S system exhibited reduced accuracy when the boresighting information was provided from the PX4 autopilot INS, and highlights potential integration challenges when converting the radar track data to world coordinates; especially with low cost/quality navigation solutions.

9.0 DISCUSSION AND CONCLUSIONS

This report presented the flight test data and analysis of two developmental radar based detect and avoid systems. Both systems show significant potential for use in RPAS operations BVLOS, however further development and testing is recommended prior to conducting operations in ARC-C airspace.

The CUAVs Sparrowhawk ground based DAA system demonstrated the ability to operate at up to 14 km range with 95% position confidence established within 274 meters of the actual target location, to a speed within 14 m/s (30 knots), and to a velocity track within 20 degrees. The low velocity and track accuracy of the system will inhibit the utility of any routines that attempt to calculate the estimated closest point of approach between the RPA and the intruder. CUAVs did not provide any threat classification/warning output generated by their system, and it is believed that this type of processing will greatly improve the human factors associated with correctly interpreting system data. The Sparrowhawk system exhibited reduced accuracy while the Intruder aircraft was maneuvering, and may suggest that improvements to the tracking algorithm are warranted. The data provided to NRC for analysis appeared to be pre-filtered to remove any false positives, precluding an assessment of false positive rate.

The Pegasus A3S system, as tested with the COTS radar, can operate at up to 3.4 km range with 95% position confidence established within 90 meters of the actual target location, and a 99% confidence in establishing track for a straight and level target. While Pegasus did not provide details regarding any threat classification/warning output generated by their system, they did conduct flight test demonstrations of automatic avoidances using A3S. Airborne integration of the COTS radar data requires conversion to world coordinates through the use of an aircraft inertial navigation system. The A3S system exhibited reduced accuracy when the boresighting information was provided from the autopilot INS, and highlights potential integration challenges when converting the COTS radartrack data to world coordinates; especially with low cost inertial navigation solutions.

Both the CUAVs Sparrowhawk and Pegasus A3S system data contained boresighting errors which were compensated/corrected using post processing techniques. It is recommended that the system developers investigate means to reduce these errors via procedural techniques as the boresighting positional errors can become significant at large ranges. For example, a 2 degree heading error represents 350 meters of positional error at a 10 km range.

Both the CUAVs Sparrowhawk, and Pegasus A3S system data demonstrated time-stamp issues, most notably using UTC time, and claiming that it was GPS time. The A3S data also appeared to contain a variable time offset whose origin could not be identified. This may be indicative of a poor quality system clock that was being periodically reset via a network time protocol. It is recommended that a more stable clock source be identified.

Neither Canadian UAV, nor Pegasus provided details regarding any automatic threat classification and indication algorithms. The performance of such algorithms is believed to be a key component of the human machine interface for any DAA system, and may also be employed in the automatic initiation of avoidance maneuvers. While the data collected during the flight test campaigns described herein are sufficient to provide a preliminary assessment of the sensor detection and tracking performance, the end-to-end performance requires an assessment of the threat classification and indication system as well as the deconfliction maneuver performance. Developmental testing of these sub-systems may be performed using simulated intruder data prior to conducting trials with live intruders.

Neither CUAV, nor Pegasus's flight test plans contained sufficient detail to describe the test conditions and test objectives. Further, neither proponent supplied data cards containing supplemental observations of the conditions of either the system or the environment. It is recommended that for future flight test campaigns that a review of the material referenced in Sections 2 and 3 of this report be reviewed.

10.0 APPENDIX A – FLIGHT TEST PLAN REVIEWS

This section presents the review, and questions as conducted by an NRC test pilot experienced with the conduct of Detect and Avoid flight test.

10.1 Canadian UAVs

Refs:

A. CUAVs Test Plan - LN - DAA Demo in BVLOS Ops.pdf, file dated 7 Feb 2020

B. Questions to Proponents - CUAVS.pdf, file dated 31 Jan 2020

The series of questions below is presented to help the reviewer thoroughly assess and understand the safety and technical risks of the test plan as presented in the references. The plan as understood is likely to be successful if the intruder aircraft is flown by a pilot with a commercial pilot licence.

1. The test plan Demonstration Details describes simultaneous flights of the RPA and the intruder C172, yet no details are presented as to the flight path of the RPA. There is a comment in Testing Method that they will always be separated by altitude to ensure no risk. This is insufficient to understand the risk and mitigations. A detailed description of where the RPA will be flying, its route and planned altitude is required. This should be presented alongside a similar plan for the intruder if it assists with clarity. For example, the first test described has two intruder altitudes identified – 400’ and 2000’. Where will the RPA be when the intruder is at 400’ and where will it be when the intruder is manoeuvering between tests such as changing altitudes for the next test point? Planning the transitions between test points is as important as the points themselves.

2. One objective is assessing the effectiveness of the avoidance maneuvers. What is the intended trigger for these avoidance manoeuvers? Are they real or simulated “threats”? If real threats further detail on the procedure used to place the two aircraft in proximity is required. This must also include the plan for what each aircraft will do during the avoid, what they will do if an avoid does not occur, and what they will do if an unanticipated avoid (or manoeuver by either aircraft) occurs. If threats are simulated, what is the method being used to simulate the threat?

3. For the ascending/descending tests, what are the maximum/minimum heights above ground for the intruder. At any time is there a chance that this will this place the intruder in the ground clutter of the radar?

4. Is an ADS-B capability required on the intruder, or is it only a “nice to have”? If ADS-B is present and there is a discrepancy between the radar return and the ADS-B output, which has precedence or can either of them trigger an avoidance response by the RPA operator?

5. There is no mention of the use of a 2-way radio during the test. Will the intruder and the GCS be equipped and capable of communication during the test? If yes, is this a dedicated frequency or one shared by multiple users?

6. Will all manoeuvering by the intruder be within CYR 234 and CYR 236? What is the search volume of the radar during the test? Where will the radar be located? The plan suggests a location near the Foremost airport orientated south. With a horizontal buffer of 3507m it seems possible that non-participant aircraft operating out of the airport or north of the airport could be within the threat volume and still clear of the CYR. What is your intent if this were to occur during the test? Ie: two intruders, only one of which you may be in direct communications with?

7. Will an in-person test brief occur with the intruder pilot the day of the test or is it a virtual brief?

8. What is the minimum ceiling and visibility you are using for this test?

9. What is the procedure for the intruder and RPA pilots if the test is put on hold once begun? Where do they fly to and how do they resume testing when ready?

10.2 Drone Delivery Canada

Refs:
A. DDC_DAA Test Plan_LOOKNorth Project 2020-01-28 (1126).pdf, file dated 28 Jan 2020
B. LN Questions to Proponents v 2.0 - Drone Delivery Canada.docx, file dated 24 Jan 2020

The information reviewed was insufficient to enable the reviewer to thoroughly assess and understand the safety and technical risks of the test plan as presented as a copy of the draft MOPS used is required. Although more information is desired on the plan, the tasks for the intruder pilot are likely to be successful if flown by a pilot with a commercial pilot licence.

The series of questions below is presented to help the reviewer thoroughly assess and understand the safety and technical risks of the test plan as presented in the references.

1. What is missing to help understand the test better is the location of the radar required in order to have the observation bubble along the RPA's flight path. It is assumed that the radar needs to stand off a fair distance if the blind zone is 20-90 degrees of elevation (from Ref B), but that does not appear to be the case based on Fig 3 of Ref A.

2. It is unlikely that the vertical rate success criteria for test point 1005 can be achieved with the test approach, making it unlike that this MOP can be met. What is the minimum rate you need to observe in order to declare success?

3. Is the intent to conduct the minimum resolution Test Point 1006 test (1000' vertically and 1500' horizontally) using procedure C? If so, how do you intend to coordinate the two intruder aircraft to assess this criteria?

4. What is your intended truth source to assess Test Point 1007 false tracks? Will this only be assessed using the intruder aircraft?

5. Will the 1 Hz position data requirement from para 7.2.3 of Ref A be sufficient to assess the Test Point 1008 500ms latency requirement?

6. Planning for Test Point 1009 would benefit from an estimation of where the bottom of the declaration volume is (radial distance from radar) for an intruder aircraft at 500' AGL.

7. More detail on the deconfliction procedures used to set up test point 7009 would help to understand any potential safety risks. For example, what is the altitude of the intruder and RPA, what is then intended vertical separation? Is the intent to intentionally trigger the 500m proximity alert?

10.3 Pegasus

Refs:
A. Pegasus Investment Proposal - AARAS - DAA Demonstrations.pdf, file dated 5 June 2020
B. TC Questions to Proponents re DAA, Pegasus Response.pdf, file dated 1 June 2020

The information reviewed was insufficient to enable the reviewer to assess and understand the safety and technical risks of the test plan as presented in the references.

The adequacy of a forward scanning +- 60 deg azimuth radar on a 42kt platform is questionable as a general aviation aircraft travelling at 90 kts could easily overtake the RPA undetected from most azimuths. This could be a good demonstration of the use of an airborne radar, but the coverage gaps are too large.

11.0 APPENDIX B – PROPONENT ANSWERS TO QUESTIONS RE: SYSTEM

11.1 Canadian UAVs

1. **Do you know the specifications of your proposed DAA system:**
   a) **Field of View:** 360 Deg Horizontal, 20 Deg Vertical
   b) **Revisit Rate (of sensor):** 2.4 seconds, 26 RPM
   c) **Blind Zone(s) if any:** Ground clutter dependant
   d) **Altitude output (if present):** Via ADS-B if equipped, otherwise none
   e) **Nominal detection range for a 1m^2 (or other known reference) target:** 6 nautical miles
   f) **Accuracy/resolution:** 200m horizontal position, 1 degree beam width
2. **How does your DAA system output its detections? E.g. Does it only display a PPI (or image output), or automatically run a tracker on detections?**

   The software runs a detection process that classifies the tracks as flying objects within a set amount of radar scans and target size, and forwards the identified tracks to Ground Control Station used currently to fly drone. There is also consolidation of data from other sources (i.e. ADSB).

3. **Does your system present Detections/Tracks in world referenced coordinates (Lon/lat). If so, how do you calibrate/boresight your system?**

   Yes, via external GPS dongle. Boresight and calibration process unspecified.

4. **How does your system know where the RPA is with respect to DAA system detections? (E.g. GCS integration, ADS-B, none, etc…)**
   a) Is your DAA system (and display) integrated with the RPA GCS? If so, how?

   Yes, our detection system is integrated with the GCS, as a visual layers that enriches the GCS viewer and adds the element of risk assessment.

   b) If your system command the RPA to perform automatic avoidance maneuvers, how does the pilot know it is performing correctly, and not a loss of control?

   We do not currently support automatic avoidance maneuvers, instead the operator is advised to implement the emergency response plan.

   c) What will your DAA system do in the event of a lost link?

   Post a warning alert on the GCS indicating loss of DAA Capability and need to execute emergency response plan if not within VLOS range.

5. **How does your DAA system assess whether a detection (and/or track) is a threat to your RPA operation?**

The system calculates the worst-case scenario for a collision an intruder, calculated now to be 3.5km operational area.

a) **Is this performed automatically, or solely by experienced operator determination (e.g. by viewing a display)?**

Performed automatically.

b) **If automatic, what assumptions are present (e.g. non-maneuvering intruder)?**

Assumptions were not specified in the response.

c) **Is the threat assessment distance based (e.g. 1 km range), or time based (e.g. 30 seconds to a closest approach less than 500 feet), or something else…provide details.**

Speed and distance are used to determine conflict time.

d) **What nominal 'miss distance' are you trying to protect? (e.g. 500 ft lateral, 100 vertical)**

3.5 Km horizontally, and 400 feet vertically.

e) **How does the system discriminate between real and false alarms? Do you have an estimate of the 'false alarm rate'? Here, a false alarm means that a mitigation maneuver/procedure was performed when it was not necessary.**

Not answered.

6. **If a detection is considered a threat, what is they system/CONOP response to mitigate collision risk?**

a) **What procedure with the system (and crew) perform (maneuvering, communicating etc.)**

The UAV shall always maintain 300ft AGL and transit back to the T/O Landing point. The transit home altitude shall be planned and loaded in the Return Home (RH) logic of the UAV. This shall be performed by the PIC, during the pre-flight actions, using the pre-flight checklist. The PIC shall recheck the RH point (icon) on the map prior to engaging the Launch flight mode.

b) **To what extent is this automated?**

The detection and classification of the threat is automated by the DAA system, the response to the threat is operator-initiated after being notified of threat via GCS interface.

c) **What does the RPA pilot need to do?**

The PIC shall immediately give way to the manned aircraft, by commanding from the GCS, to either manoeuvre away from the aircraft or by descending to a lower altitude, If the conflict is not resolved, the UAV shall be commanded to land from the GCS, at the present position.

7. **Once the threat mitigation maneuver/procedure is performed, how do you assess that it is safe to resume the mission? (i.e. clear of conflict)**

   Once the software indicates that the operational zone is clear of any immediate manned aircraft, the mission would be resumed.

8. **What is your proposed CONOP in terms of range, altitude(s), speed(s), terrain, airspace density?**

   Looking for an operational range of 5kms, where the vehicle would not fly higher that 400ft,

9. **How much extra endurance (fuel/battery) will you plan for performing avoidance maneuvers?**

   That is inherent in the UAV being used, Indago 3, as it factors a return home path that will be invoked regardless of avoidance maneuvers being performed.

10. **To what extent does your CONOP rely on visual observers?**

    There is no reliance on visual observers.

11. **How do you define your mission in relation to the performance of the DAA system as specified above (e.g. how much bigger of an observation bubble do you need relative to your operations)**

    Canadian UAVs provided a time budget associated with the detection, tracking, threat declaration and avoidance maneuvering:

    - 7.5 seconds to declare a track after first detection
    - 5 seconds human factors delay for radar operator to declare a threat
    - 5 seconds human factors delay for the PIC to initiate the avoidance maneuver (descend from 300 ft to 100 ft)
    - 3 seconds of C2 latency
    - 20 seconds for the RPA to complete the descent

    Canadian UAVs provided calculations using the closing rate to a Cessna 172 resulting in a largest detection distance of 1.89 nm from the RPA.

11.2 Drone Delivery Canada

1. **Do you know the specifications of your proposed DAA system:**
    a) **Field of View (Horizontal and Vertical, angular measurements):** 360 Degrees Horizontal, 20 Degrees vertical
    b) **Revisit Rate (of sensor):** 2.4 seconds, 24 RPM
    c) **Blind Zone(s) if any:** Dependant on clutter, obstacles.
    d) **Altitude output (if present):** ADS-B, if equipped
    e) **Nominal detection range for a 1m^2 (or other known reference) target. Specify the reference:** The anticipated maximum detection range for a 1m^2 target is expected to be approximately 20 km with the type of radar being employed, under ideal conditions. Weather and clutter will inhibit theoretical performance. However, the testing done as part of this project will validate actual performance in the specific operating environment.
    f) **Accuracy/resolution?** The anticipated accuracy and resolution are a function of the waveform selected (short, medium, or long pulse) and the signal to noise ratio (SNR) of the target in question, as seen by the receiver. The testing done as part of this project will validate actual performance for targets of interest in the specific operating environment.
2. **How does your DAA system output its detections? E.g. Does it only display a PPI (or image output), or automatically run a tracker on detections?**

    The proposed system does both. It displays the radar image on Radar Remote Controller (RRC), and currently also outputs the object's track on a Common Operating Picture (COP) platform. The final solution will be to have the track output to be displayed on DDC's patented FLYTE platform.

3. **Does your system present Detections/Tracks in world referenced coordinates (Lon/Lat). If so, how do you calibrate/boresight your system?**

    Yes, the proposed GBSAA system uses latitude/longitude as the basis for the positional information. The radar provides a North reset pulse that is used to indicate North for each revolution. A radar tuning process allows us to software-align to true North either based on clutter mapping or using ground-truth targets.

4. **How does your system know where the RPA is with respect to DAA system detections? (E.g. GCS integration, ADS-B, none, etc…)**

    The location of our RPA is reported through the C2 Link to the control station and displayed on the FLYTE system management display and/or on the IRIS display. In addition, we have the ability to use ASD-B Out data from our RPA as positional information which can use several pathways to get the data to our display systems (FLYTE or IRIS).

    a) **Is your DAA system (and display) integrated with the RPA GCS? If so, how?**

        Initially, there will be two separate display systems (FLYTE and IRIS) being used, which will display conflicting traffic and the positional information of our RPA. The final solution will have all information displayed on the same display to provide the PIC with a common operating picture of the surrounding airspace, which will provide the PIC better situational awareness.

b) If your system command the RPA to perform automatic avoidance maneuvers, how does the pilot know it is performing correctly, and not a loss of control?

For these trials our GBSAA system will not perform automated de-confliction maneuvers. The PIC will be responsible for initiated any required maneuvers. As the system is developed further, the intent is to incorporate automated maneuvering capabilities.

c) What will your DAA system do in the event of a lost link?

If the system loses connection to the radar then the detected targets will stop updating. The PIC and/or GBSAA observer will be notified if the GBSAA system stops providing data. Additionally, radar targets which are not updated for 30 seconds or more will be removed from the display. The PIC actions in the case of such a situation will depend on the phase of flight the RPA is in. For example, if the RPA is about to start its landing sequence, the PIC would not likely take any actions as it would be quicker and safer for the RPA to simply follow its preplanned landing.

If the RPA C2 Link experiences a failure, the PIC will follow the established AFM emergency procedures to attempt to re-establish the C2 Link. The aircraft has preprogrammed procedures that will enable the RPA to either return to home, land at the established landing location or land at one of the predetermined emergency landing zones (depending on the phase of flight).

5. How does your DAA system assess whether a detection (and/or track) is a threat to your RPA operation?

a) Is this performed automatically, or solely by experienced operator determination (e.g. by viewing a display)?

This is done automatically. As the aircraft enters the radar coverage area, the radar creates a track which is sent to and displayed on the IRIS station in the OCC. The IRIS station assesses the trajectory of the intruder and our RPA. If a risk of collision exists, the system alerts the PIC/ GBSAA observer who would initiate an avoidance maneuver, as appropriate.

b) If automatic, what assumptions are present (e.g. non-maneuvering intruder)?

IRIS does not make any assumptions with respect to the type of contact. IRIS will automatically provide real-time alert updates based on the available track updates. For example, on each track update, tracks are validated against defined airspace zones. No fly zones are airspaces with a configured rule to detect when a track enters the airspace volume. If an airspace volume is defined around the RPA operational area then an airspace alert is generated if the airspace will be breached by an intruding track. An airspace alert includes an audible warning as well as geospatial representation of the breach on the IRIS display. The visualization is represented as a highlighted halo surrounding the intruding track. The PIC can then acknowledge the alert and take and required actions as defined by the CONOPS.

In addition, IRIS calculates the vertical and horizontal separation between the RPA and surrounding aircraft based on available track updates. IRIS will raise a conflict alert if either one of these constraints (vertical or horizontal) are breached. Similar to an airspace alert, a conflict alert includes an audible warning and situational awareness cue depicting the separation and an estimated time of collision if both track vectors are predicted to meet at a specific point.

c) **Is the threat assessment distance based (e.g. 1 km range), or time based (e.g. 30 seconds to a closest approach less than 500 feet), or something else…provide details.**

Both. DDC's DAA has multiple threat structure (referred to alert structure in below), for different alert levels: None, Proximate, Preventive, Corrective and Warning. The separation criteria (which is threat assessment criteria in the question) are based on Horizontal Time Threshold (τmod), Modified Distance Threshold (DMOD) and Vertical Distance Threshold (ZTHR) if altitude information is provided by ADS-B correlated to the radar track. The alert levels are differentiated by Lookahead Time.

d) **What nominal 'miss distance' are you trying to protect? (e.g. 500 ft lateral, 100 vertical)**

The intent of our GBSAA system is to ensure a minimum 500 feet lateral and 100 feet vertical miss.

e) **How does the system discriminate between real and false alarms? Do you have an estimate of the 'false alarm rate'? Here, a false alarm means that a mitigation maneuver/procedure was performed when it was not necessary.**

The radar DAA Detect function is a contributor to the system false alarm rate. However, the radar's false alarm rate can be adjusted to be more or less sensitive during system testing and system false alarm rate modeling. Validation testing with the collected target data from the radar used as well as validation through assessment of the entire mitigation maneuver/procedure testing will be carried out to optimize radar sensitivity and reduce false alarm rates.

It should be noted that the ARC class and detection performance requirements will ultimately dictate the radar sensitivity set for each location.

6. **If a detection is considered a threat, what is they system/CONOP response to mitigate collision risk?**
   a) **What procedure with the system (and crew) perform (maneuvering, communicating etc.)**

Based on the potential conflict and what risk that track is presenting there are various procedures the PIC will initiate. These could include:

- Taking no action as the track is not on a conflicting course, or

- Selecting one of the avoidance maneuvers (Hold Now, Hold 150/100/50 (stop, descend to 150/100/50ft and hold), or Land Now).

For the planned scenarios it is unlikely that communications with ATC will be established/required.

The current procedures will be updated based on results of these trials.

b) To what extent is this automated?

The system will automatically asses the trajectories of the RPA and intruders and makes a determination if there is a risk of a collision. If so, an audible and visible collision warning will be provided to the PIC. Actual avoidance maneuvers are not automated as the PIC will decide on the appropriate course of action.

c) What does the RPA pilot need to do?

The pilot needs to react to the automated collision warning, assess the situation and then decide which (if any) avoidance maneuver / command to execute.

7. Once the threat mitigation maneuver/procedure is performed, how do you assess that it is safe to resume the mission? (i.e. clear of conflict)

The assessment for this case is done according to Horizontal Time Threshold (τmod), Modified Distance Threshold (DMOD) and Vertical Distance Threshold (ZTHR) if altitude information is provided by ADS-B correlated to the radar track. The alert levels are differentiated by Lookahead Time. When none of the criteria among Warning, Corrective, Preventive and Proximate (seen in Table 1), is met, yet the aircraft is still within detection range, the system will assess that it is safe to resume the fight.

8. What is your proposed CONOP in terms of range, altitude(s), speed(s), terrain, airspace density?

For the GBSAA trials:

Range: The horizontal range of airspace to be surveilled is formed by crating circles around the position of RPA, flying between the two ends of the flight route. In this case, point A: 43°46'46.12"N, 79°38'5.46"W and point B: 43°46'28.78"N, 79°38'2.14"W.

Vertical: 0—1575 ft AGL based on the slope of the radar system deployed.

Altitude: Flights will be conducted at 100 ft AGL which is slightly higher than the surrounding buildings.

Airspeed: 10 nm/hr (10m/s)

Terrain: The operating area is relatively flat will little height variance.

Airspace density: 6.41 aircraft in the 3-D detection volume every hour, based on data from Sep. 4 – Sep.19, 2019, according to ADS-B data received by DAA system deployed on DDC rooftop. Additional work is required to determine the actual number of total tracks (based on radar observations). However, given the very low altitude of the proposed operation, it is anticipated that there will be very little air traffic in the vicinity of the proposed operation.

9. How much extra endurance (fuel/battery) will you plan for performing avoidance maneuvers?

This varies depending on the length of the flight route however, as a minimum, as per the DDC Flight Operations Manual, a 20% fuel reserve is maintained/required for every flight.

10. To what extent does your CONOP rely on visual observers?

11. How do you define your mission in relation to the performance of the DAA system as specified above (e.g. how much bigger of an observation bubble do you need relative to your operations)

The GBSAA system needs to be capable of observing a 4.9nm/9 km (horizontal) by 2300ft/700 m (vertical) envelope around the flight route to ensure detection of intruding aircraft far enough ahead of time to perform any required avoidance maneuvers.

11.3 Pegasus

1. **Do you know the specifications of your proposed DAA system:**
    a) **Field of View (Horizontal and Vertical, angular measurements)**: +/-60 Deg Horizontal, +/-40 Deg Vertical
    b) **Revisit Rate (of sensor):** Nominal 1 Hz for 120 Deg azimuth and 20 Deg elevation
    c) **Blind Zone(s) if any:** None specified
    d) **Altitude output (if present):** None
    e) **Nominal detection range for a 1m^2 (or other known reference) target. Specify the reference.:** 2.5 km to Cessna 172
    f) **Accuracy/resolution:** +/-3.2m range, +/-0.85 m/s velocity
2. **How does your DAA system output its detections? E.g. Does it only display a PPI (or image output), or automatically run a tracker on detections?**

    The DAA Radar will initially report a target detection with an azimuth and elevation of the target. Additional information includes the range to the target, the relative velocity of the target, the RF power of the target in addition to the SNR associated with that target. Once a target is identified, it is assigned a "track" status in which case its estimated x, y and z velocities, the estimated time of closest approach (TOCA) and distance of closest approach (DOCA) are generated as well as azimuth/elevation/range to the target.

3. **Does your system present Detections/Tracks in world referenced coordinates (Lon/Lat). If so, how do you calibrate/boresight your system?**

    All data is relative to the radar's pointing frame.

4. **How does your system know where the RPA is with respect to DAA system detections? (E.g. GCS integration, ADS-B, none, etc…)**

    All detections/tracks are relative to the RPAS present position.

    a) **Is your DAA system (and display) integrated with the RPA GCS? If so, how?**

        DAA target detections and autopilot override commands will form part of the complete list of aircraft telemetry relayed to the GCS.

    b) **If your system command the RPA to perform automatic avoidance maneuvers, how does the pilot know it is performing correctly, and not a loss of control?**

        As with 4(a) above, DAA status/detections/interventions are part of the telemetry bundle sent to the GCS. The Autonomous Airborne Radar Avoidance System (AARAS) will indicate to the pilot that an intruder aircraft has been detected and if necessary what action is being taken.

    c) **What will your DAA system do in the event of a lost link?**

As the system is completely on board the RPAS, this system will continue to function normally even in the event of a lost link. In addition, this system would then allow the RPAS to safely navigate back to the landing zone and land in that lost link scenario.

5. **How does your DAA system assess whether a detection (and/or track) is a threat to your RPA operation?**

   a) **Is this performed automatically, or solely by experienced operator determination (e.g. by viewing a display)?**

   Automatically based on approach vector of intruder and a set of avoidance rules which are based on the rules governing general aviation.

   b) **If automatic, what assumptions are present (e.g. non-maneuvering intruder)?**

   The only assumption is that the intruder will be manned and appropriate actions are based upon this.

   c) **Is the threat assessment distance based (e.g. 1 km range), or time based (e.g. 30 seconds to a closest approach less than 500 feet), or something else…provide details.**

   The threat assessment is both distance and time based. A combination of computed closest approach distance and computed time to closest approach determines a relative measure of urgency which dictates the degree of autopilot intervention (i.e. gentle turn vs. quick tight turn)

   d) **What nominal 'miss distance' are you trying to protect? (e.g. 500 ft lateral, 100 vertical)**

   Our goal is to always err on the side of caution. Therefore, our minimum miss distance target is 1000 ft lateral and 250 ft vertical.

   e) **How does the system discriminate between real and false alarms? Do you have an estimate of the 'false alarm rate'? Here, a false alarm means that a mitigation maneuver/procedure was performed when it was not necessary.**

   Our avoidance algorithm is tailored to always try to keep the intruder in view during all avoidance maneuvers, if possible. This mechanism may initially intervene but then will automatically resume course if that intervention later proves to be premature (too cautious)

6. **If a detection is considered a threat, what is they system/CONOP response to mitigate collision risk?**

   a) **What procedure with the system (and crew) perform (maneuvering, communicating etc)**

   Our avoidance algorithm will turn away from any threat following the rules for collision avoidance governing general aviation.

   b) **To what extent is this automated?**

The AARAS system will be a fully automated intervention, with the pilot able to take control at any stage of the AARAS intervention.

c) What does the RPA pilot need to do?

The system is designed to be fully automatic. However, the pilot may intervene at any stage of the process to override it.

7. Once the threat mitigation maneuver/procedure is performed, how do you assess that it is safe to resume the mission? (i.e. clear of conflict)

Given the system's propensity to try and keep the intruder in view during avoidance maneuvers, determining when a threat has passed is straightforward and automatic. The GCS may also intervene to command the aircraft to resume course.

8. What is your proposed CONOP in terms of range, altitude(s), speed(s), terrain, airspace density?

The intention of the AARAS system is to allow RPAS that are capable of detecting and avoiding other aircraft to safely integrate into the same airspace as general aviation. Initially the AARAS system will be integrated into the Pegasus Eos. This RPAS has the following capabilities:

o Endurance 6-9 hours

o Max Altitude 10,000ft ASL

o Speed 42kts

9. How much extra endurance (fuel/battery) will you plan for performing avoidance maneuvers?

The RPAS will carry a 15% fuel reserve for emergency conditions, this will include avoidance maneuvers. As an example, if the Eos RPAS equipped with the AARAS system intended to fly a task for 7 hours there would be additional fuel for another 63 minutes emergency reserve.

10. To what extent does your CONOP rely on visual observers?

Our system only relies on visual observers during take-off and landing. It is the intent that this system will enable BVLOS integrated into the same airspace as general aviation.

11. How do you define your mission in relation to the performance of the DAA system as specified above (e.g. how much bigger of an observation bubble do you need relative to your operations)

The AARAS will allow for a reduction in the observation bubble currently required for RPAS flight. This system will allow for the integration of equipped RPAS into the same airspace as general aviation, and dramatically reduce the need of visual observers and ground based DAA systems. Thus allowing RPAS to fully realize their potential and be able to dramatically influence several key areas, improving safety and access to critical information. Example Wildfire monitoring, an RPAS equipped with the AARAS would be able to pass on real time fire information while water bombers and helicopters continue to fight the fire in the same airspace.

APPENDIX C – NRC INS OPERATING INSTRUCTIONS

11.4 INS Installation Instructions

This section describes how to install the INS within the desired intruder aircraft. The NRC INS is considered as removable hardware and does not require a fixed installation within the intruder aircraft.

11.4.1 Determination of INS Location

While the NRC INS is considered removable hardware, it is important that the INS be prevented from rotation once installed. It is recommended to use double sided tape, or hook-and-loop fasteners to install the INS. When selecting an installation location the following factors should be considered:

1. Access to power – cable length
2. Access to GPS antenna – cable length
3. Ability to connect the Ethernet cable to a laptop/tablet device for status monitoring
4. Ability to observe the status LED's – this is an optional consideration provided that a laptop/tablet is being used for monitoring the INS status

The INS can be installed in any orientation with one side ideally parallel to the aircraft's floor. The details of the installation orientation must be known, and configured in an orientation configuration file. This allows the INS to correlate its gyro and accelerometer readings to the standard aircraft convention of forward, right, down. The INS is marked with lines indicating the normal directions of the three axes, labelled as 1, 2, and 3. It is essential to know the orientation of these axes relative to the aircraft nose, right wing, and down directions in order to properly configure the orientation configuration file. This file will be configured by NRC staff prior to delivery of the INS, provided sufficient details regarding the desired mounting location are received prior to shipment of the unit. Alternatively, NRC staff can configure the orientation configuration file, and the proponent can deploy the file to the INS using the FTP instructions provided later in this section.

11.4.2 GPS Antenna Location

This section describes the factors involved in determining a suitable GPS antenna location for the INS. Receipt of good GPS signals is critical to the operation of the INS, and to the establishment of high quality 'truth data' for these DAA trials.

A 3 meter GPS antenna cable has been supplied, and should allow for a high degree of flexibility in mounting locations for both the INS and the GPS antenna. The GPS antenna itself is a circular unit with a flat non-magnetic base, which should present little to no interference with the aircraft compass. The antenna needs a good view of the sky, and as such it is recommended to install it on the glare-shield of the aircraft using double sided tape or hook-and-loop fasteners.

When selecting a GPS antenna location be mindful of potential interference to other aircraft instruments. One method to test this is to repeatedly place and remove the GPS antenna while looking for any indications of needles/gauges being affected by the antenna. At the same time, using the webserver, monitor the GPS performance page to determine what position results in the highest number of satellite observations used in the GPS solution.

Once a suitable antenna location has been found, the excess cable can be coiled, ty-wrapped, and stowed in a location that will not interfere with the operation of the aircraft, including ingress and egress. Adhesive ty wrap clips will be provided with the INS/GPS to enable the cable to be secured to the aircraft if necessary.

11.4.3 Lever Arm Determination

Once the GPS antenna and INS position have been determined it is necessary to determine the lever arm distance between them. This allows the INS to translate the GPS position readings to its own internal reference position. The measurements of the lever arms should be done in meters, and with the following convention:

- Forward – positive means the GPS antenna is closer to the nose than the INS
- Right – positive means the GPS antenna is to the right of the INS when looking out the nose
- Down – positive means the GPS antenna is below the INS location

Once the lever arms are known, NRC staff can supply a lever configuration file provided sufficient details regarding the desired mounting location are received prior to shipment of the unit. Alternatively, NRC staff can configure the lever arm configuration file, and the proponent can deploy the file to the INS using the FTP instructions provided later in this section.

11.4.4 Configure your Computer's IP Address and Network Settings

In order to communicate with the INS your computer will need to have wired network connection with an IP address that is compatible with the INS's. Figure 2 presents sample settings for connecting to the INS as configured for a MS-Windows operating system. It is essential that the first 3 tuples of the IP address match those printed on the sticker on top of the INS housing. Further, the last tuple of the IP address you assign must be different than that of the INS.

The subnet mask field should be 255.255.255.0. This configuration places the INS and your host computer on the same subnet, and enables more direct communication.

Test your connection by opening a terminal (or command window), and attempting to 'ping' the INS. For example: "ping 10.0.0.95". You should see a response from the INS such as "Reply from 10.0.0.95: bytes=32 time=3ms TTL=64". This indicates that your network adapter configuration is correct.

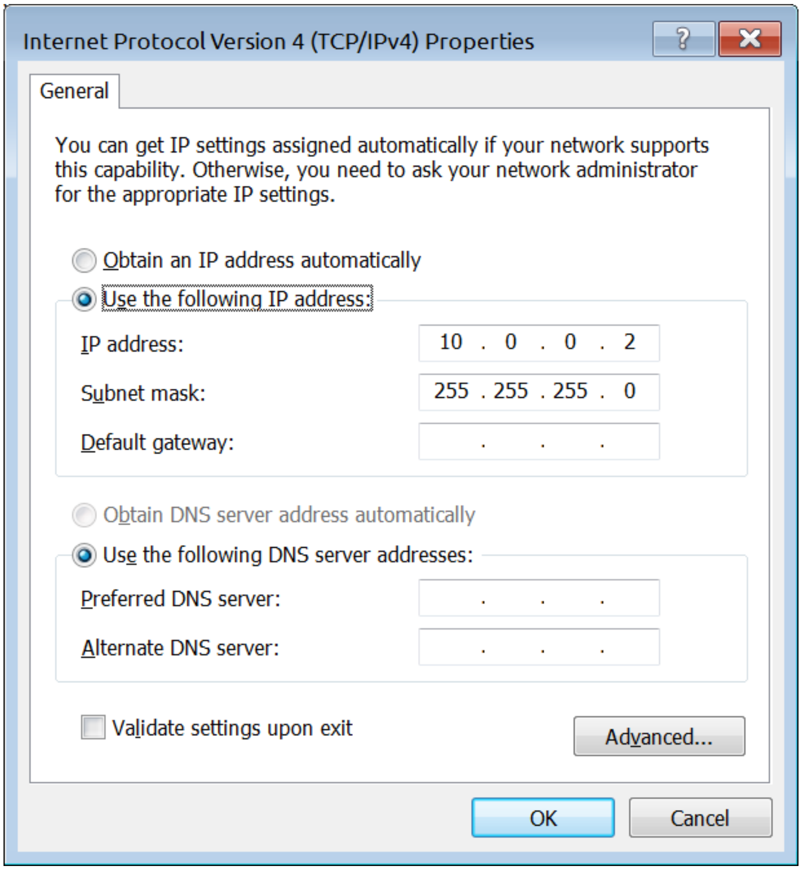

Figure 2: Windows network settings to connect to the INS

11.4.5 Data Download

The data files are recorded on a flash card installed in the back side of the INS. The cards are formatted with the Linux EXT4 format, and require a Linux computer to extract directly from the media. It is not recommended to extract the files this way, however, as the cards are fragile, and can be prone to damage, improper insertion, and even get lost inside the INS box itself.

It is instead recommended to use an FTP client to pull the files from the card to your computer. The recommended FTP client is FileZilla, which is available for Windows, Mac, and Linux hosts here: https://filezilla-project.org/

The NRC INS uses a secure FTP server so you cannot use the “Quick Connect” feature in the top bar of FileZilla. Instead, it is necessary to create a new ‘site’ and configure the properties appropriately. To create a new site, click on the top left icon under the menu bar as shown in Figure 3.

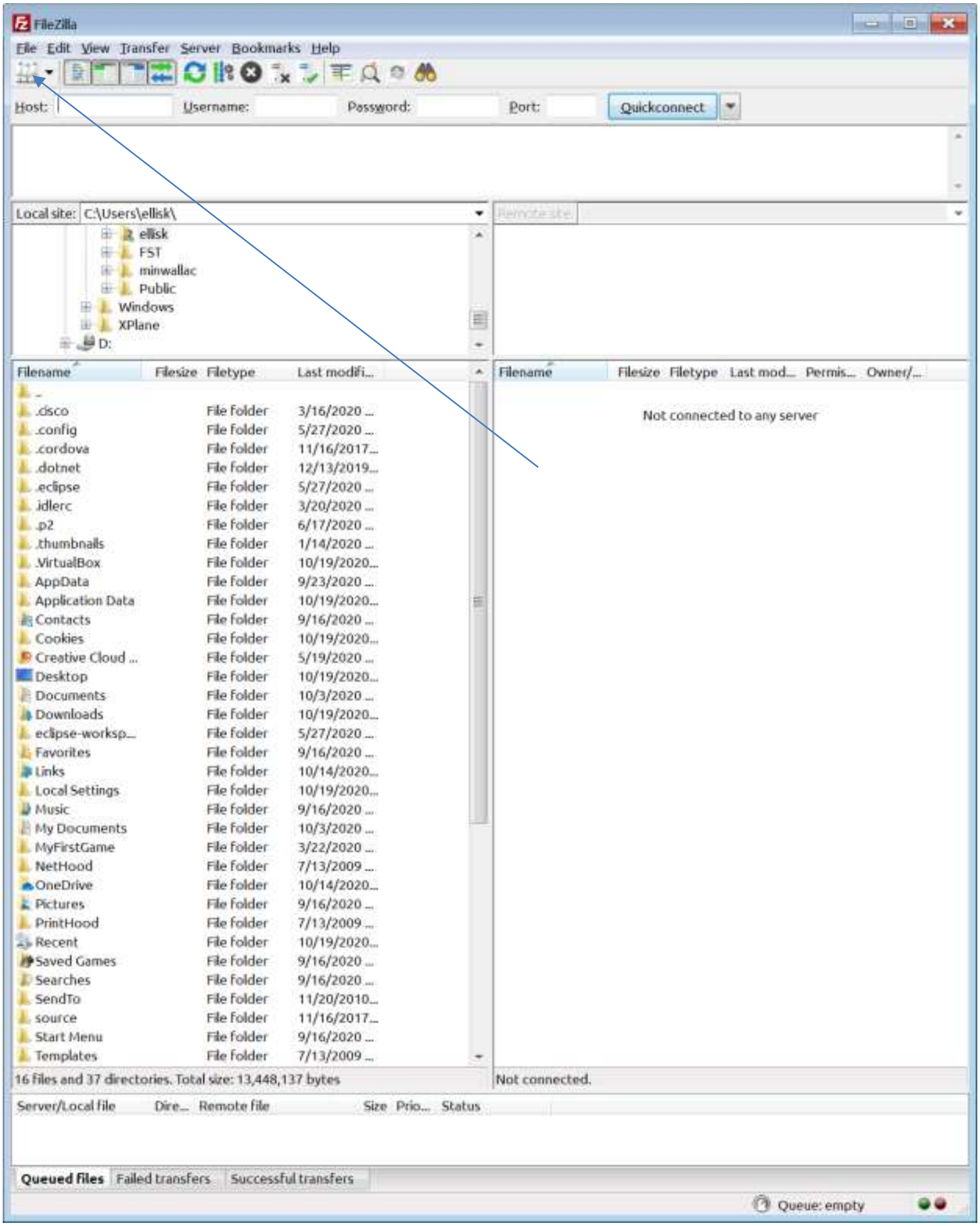

Figure 61: FileZilla new 'site' configuration icon

This will bring up a site confirmation window. Click on the ‘New site’ button to create a site for the NRC INS. The site will need to be configured as shown in Figure 4. The protocol needs to be SFTP as opposed to legacy FTP, and the user name must be ‘root’ (all lowercase). The password and port fields can be left blank.

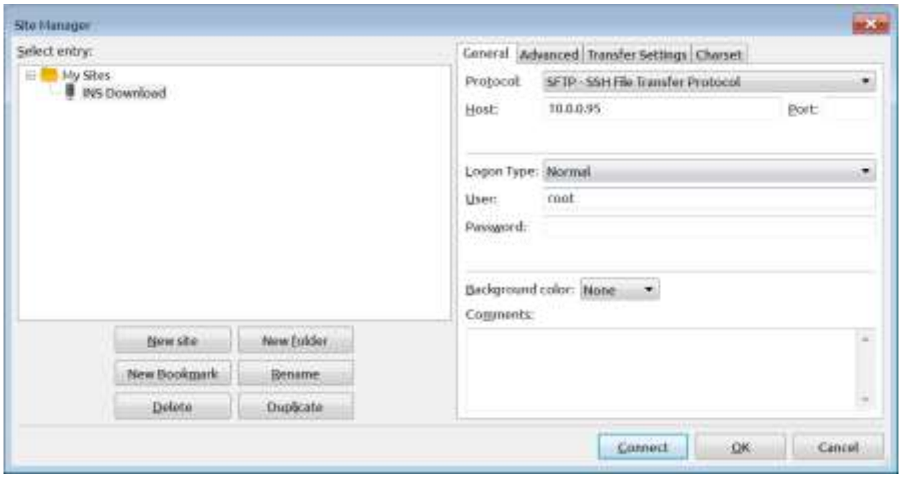

Figure 4: FileZilla site configuration details

Now you can test the connection by clicking on the ‘connect’ button. On first connection you may encounter a warning message indicating the server’s host key is unknown as shown in Figure 5. Click on the ‘Always trust this host, add this key to the cache’ checkbox to prevent this message from occurring on subsequent connections.

Figure 5: FileZilla connection warning message

Once you connect to the SFTP server FileZilla will display the directory structure of the INS in the right pane of the window. You must navigate to the /media/card directory using the right pane to locate the files logged to the removable flash card. Once you have navigated to the correct directory your window should look similar to the example in Figure 6 6.

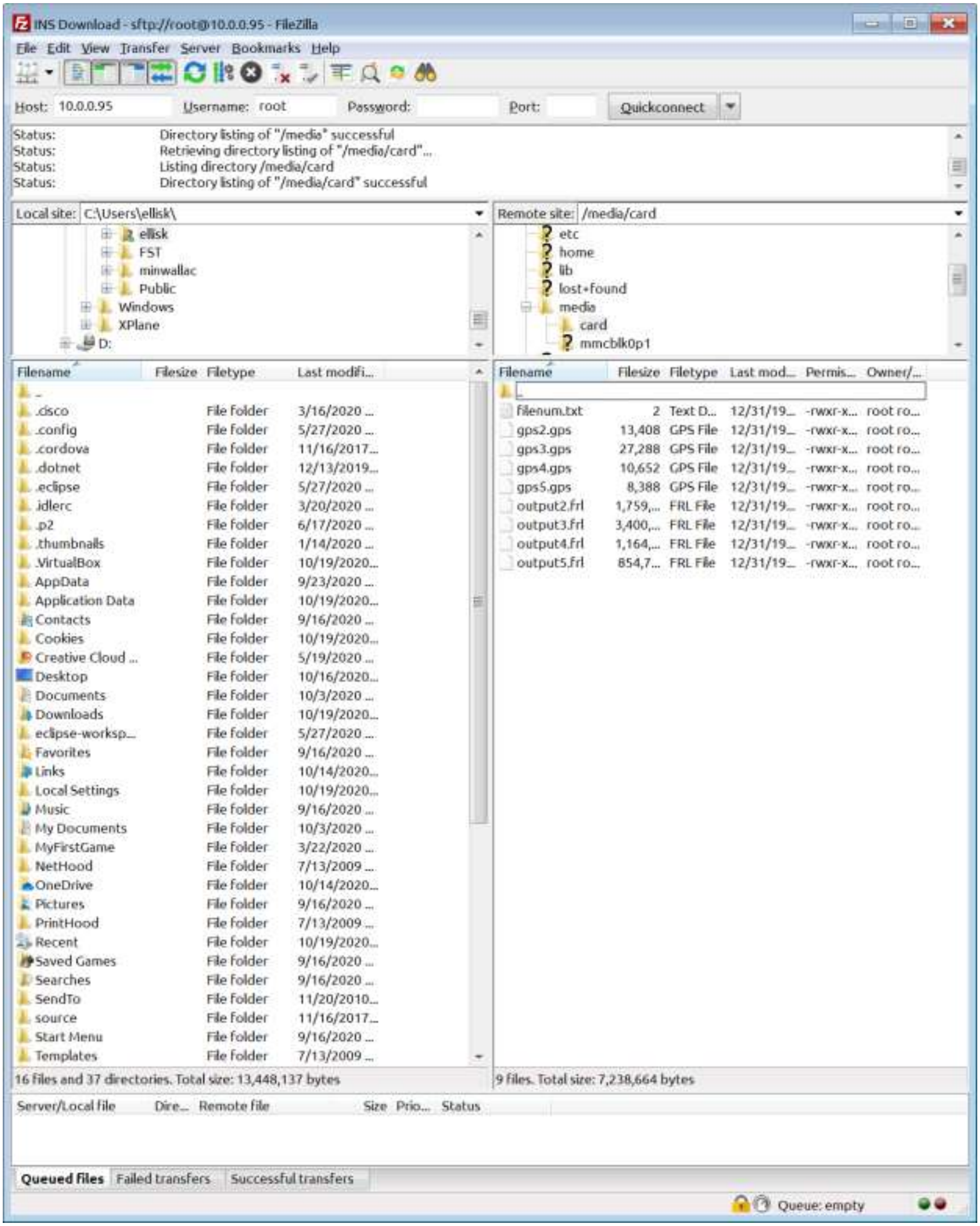

Figure 6: FileZilla window ready for file transfer

At this point you can drag and drop from the right pane to the left pane to initiate the SFTP files transfer.

11.4.6 Operating Instructions

The NRC INS has been configured to automatically start and begin recording upon application of DC power. Basic operating status can be monitored by the front panel LEDs, which indicate the following (from left to right):

2. Valid GPS Position – Solid green indicates a valid GPS Position
3. Pulse-per-second (PPS) – Flashes once per second provided the PPS circuit on the GPS card is working
4. Power rail 1 – Solid green if system 1 is receiving proper DC voltage
5. Power rail 2 – Solid green if system 2 is receiving proper DC voltage
6. Project LED 1 – Project specific LED
7. Project LED 2 – Project specific LED
8. Project LED 3 – Project specific LED

The INS toggles project LED 1 and 2 when the inertial navigation software is running. In the event of a system crash one of the LED's may remain lit, however cycling will stop.

The NRC INS also features a status webserver. Using a standard web browser, navigate to the IP address printed on the top of the box (e.g. http://10.0.0.94). Provided that the network adapter has been set up as specified earlier, and that the INS software is running, you should see a main status page similar to that shown in Figure 7. The figure numbers the various fields present on the page:

1. The Align lamp, and link to the rapid align page. The low cost INS will not illuminate the background of the ALN field with green since it is unable to sense Earth rate and resolve the heading. Instead, the unit will attempt an in flight alignment while moving.
2. GPS status – the background of this field will turn green if a valid GPS solution has been achieved; otherwise it is black. The letters GPS form a hyperlink to the GPS status page of the webserver.
3. Rapid ALN – the background of this field will turn green if a rapid alignment (by sending the true heading to the INS) has been performed
4. IN FLT ALN – the background of this field will turn green if the INS has been aligned by sending aircraft motion via GPS
5. INS FAIL – the background of this field will turn red if the INS has detected a navigation failure (e.g. excess rejected GPS measurements). An in-flight re-alignment is recommended if this indication occurs.
6. PPS FAIL – the background of this field will turn red if there is a problem with the pulse per second circuit. Should this situation occur, the INS requires maintenance.
7. IMU FAIL – the background of this field will turn red if there is a detected problem with the inertial measurement unit. Should this situation occur, the INS requires maintenance.
8. Time – the local time on the computer. Note that in Figure 77 the computer had been reset to the Unix epoch. It is expected that this time field will be replaced with UTC time for the INS units sent to the DAA trial proponents.
9. Data file details – this field shows the full path and filename of the data file currently being logged. It also indicates the current size of the file being logged (in MegaBytes), which should be continually growing.
10. INS WARNINGS – this field presents up to 5 messages representing important warning information regarding the operating status of the INS. The most recent messages will appear at the top, and will have a red background.
11. INS MESSAGES – this field presents up to 5 messages representing status messages regarding the INS's operation. The most recent messages will appear at the top, and will have a red background.
12. GPS PERFORMANCE – A hyperlink to the GPS performance page
13. Event – The Event button allows the user to mark the start and end of significant events within the flight test. This button should be used to correlate written notes to the data. Typically an event is marked ON at the start of a new flight test maneuver, and OFF at the conclusion. The event number

is displayed in the text field and should be recorded on the flight test card. The text label of the button changes to indicate what the function of the button is. In the figure, clicking on the button would mark the start of Event 1.

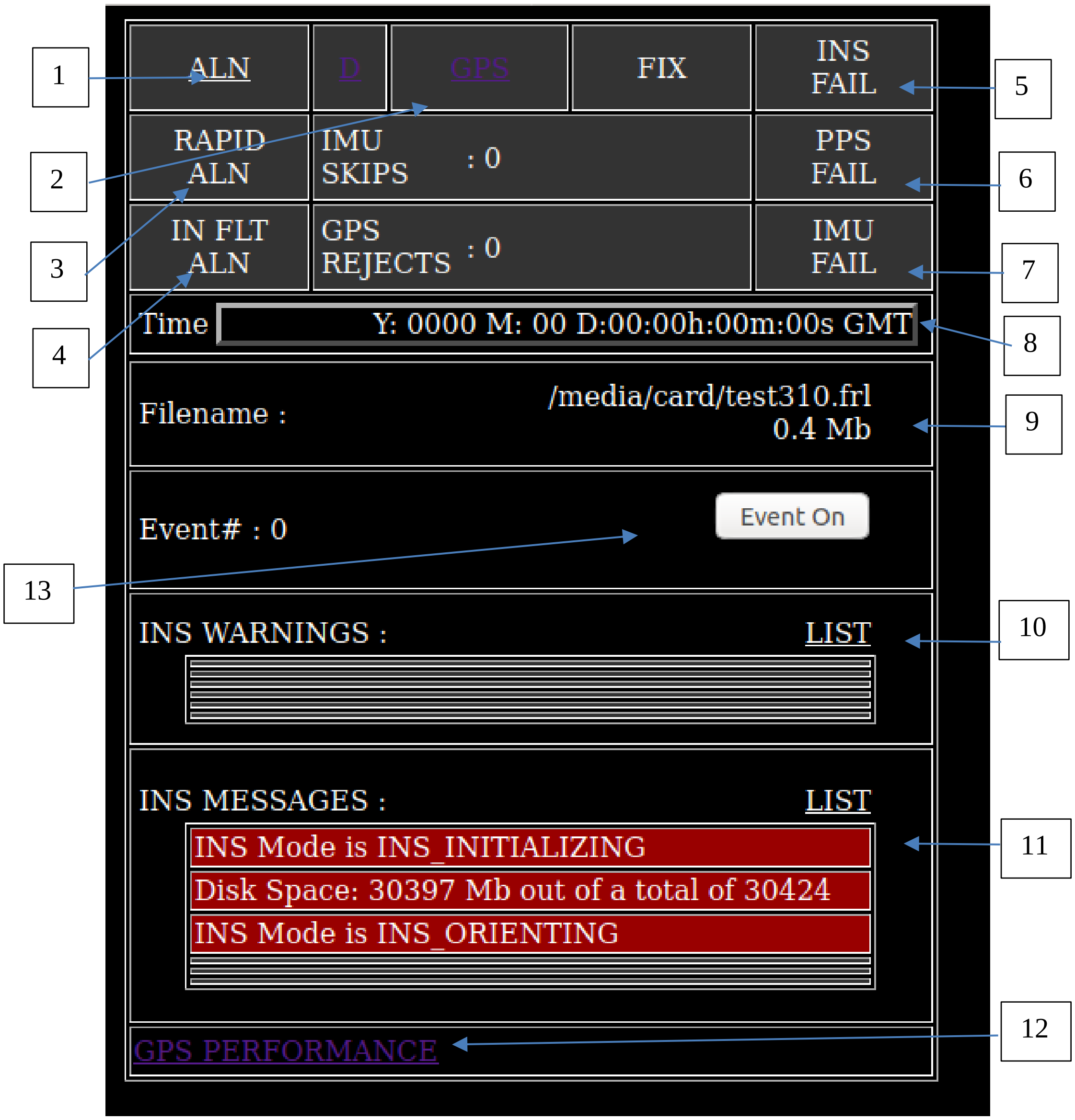

Figure 7: INS status main page

The GPS performance page provides details regarding the GPS data received, as well as the INS's estimates of its output states and performance. An example of the GPS performance page is shown in Figure 88. Some fields of particular note include:

1. GPS DATA - 'Num Obs' – This indicates the number of satellites currently used in the GPS solution. This can be helpful for identifying a suitable GPS antenna location.

2. NAV DATA – INS Mode – This is an enumerated number that indicates the current operating state of the INS solution, with higher numbers indicating greater accuracy. The INS Mode number is detailed in the figure below.

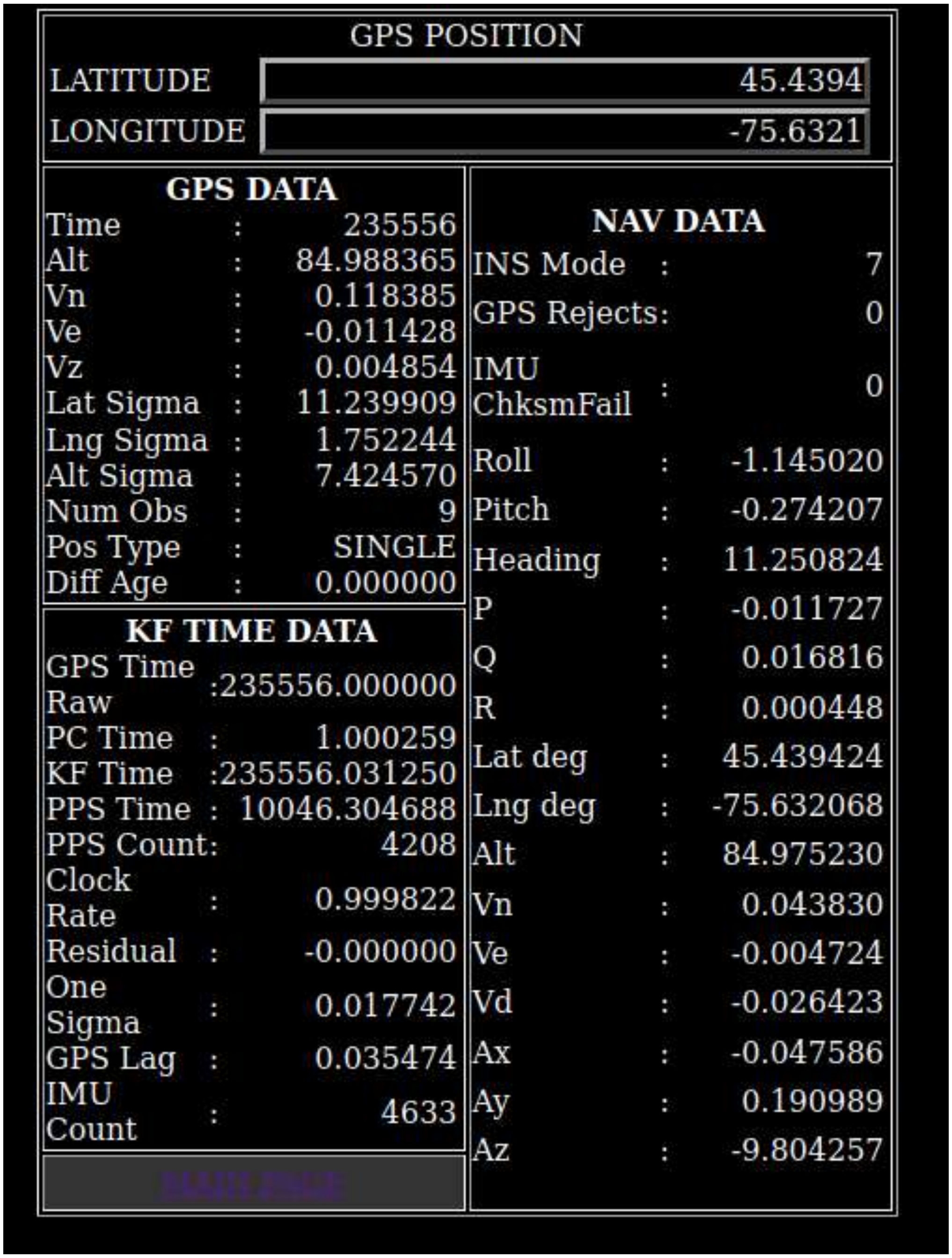

Figure 8: INS GPS performance page

The NRC navigation system has 10 different operating modes which indicate the current state of the system. These modes are:

Mode #	Mode Name	Description
0	**IMU_FAIL**	This mode is entered if the IMU flags a problem in its operation.
1	**INS_SIM**	This mode is to be set if the INS output is currently being simulated. Hardware INS units should never enter this mode.
2	**IMU_ONLY**	This mode is entered if the GPS receiver fails to operate (i.e. no information is received from the GPS receiver at all) for at least 30 seconds. The navigation system only outputs rates and accelerations.
3	**INS_ORIENTING**	This is the initial mode on startup and after realignment. This mode is only maintained for 1 second while coarse alignment (to determine pitch and roll) occurs, then Mode 4 is entered. NOTE: The aircraft must be in a steady level condition (on ground, flying straight and level) for good coarse alignment while in this mode.
4	**INS_INITIALIZING**	Mode 4 is always entered after mode 3. Mode 4 transitions to mode 7 as soon as the INS is receiving good GPS data.
5	**INS_DIVERGED**	Mode 5 occurs if the navigation Kalman Filter is consistently rejecting GPS data. If measurement updates begin to be accepted, the navigation system will return to higher modes, if it continues to reject data it will reset the navigation system (equivalent to commanding realignment).
6	**INS_SOLNFREE**	Mode 6 occurs if the GPS receiver does not have a valid solution for 300 seconds. If the GPS receiver obtains a valid solution the navigation system will return to higher modes.
7	**INS_ALIGNING**	Mode 7 is entered from mode 4 when valid GPS data is being received. It transitions to mode 8 when the navigation system has converged to a solution.
8	**INS_HIGHVAR**	Mode 8 indicates that the navigation system has converged, but has high heading variance. Functionally the same as mode 7, it transitions to mode 9 when heading uncertainty is < 1 deg.
9	**INS_GOOD**	Highest operating mode. Functionally the same as 7 and 8, but indicates good solution with heading uncertainty < 1 deg.

11.4.6.1 Initial Start Up

1. Ensure aircraft is in stable condition on ground
2. Power on NRC INS box and connect to webserver via appropriate IP address
3. Verify that INS mode transitions from 3->4->7, and that GPS data is updating on the GPS tab
4. Note what the file name is, write on test card
5. Make sure file size is increasing
6. Enter an initial true heading on the ALN tab, at this point INS mode should reach 8
7. Begin the flight, INS mode should reach 9 after a short time in flight (performing some turning manoeuvres will help the INS reach mode 9 faster)

11.4.6.2 In-Flight Realignment

In normal operations the INS should always transition through modes 3->4->7->8->9.
Once the navigation system has reached mode 8 it should maintain mode 8 or 9 for the rest of the flight. Transitions may occur between 8 and 9, this is normal behaviour, and just serves as indication of the level of heading uncertainty.

If a lower mode is entered at any time during the flight (mode 6 or below) the in-flight realignment command can be used to help the navigation system recover. The procedure for in-flight realignment is:

1. Ensure aircraft is in straight and level flight
2. Command realignment from the ALN tab
3. Verify that INS mode transitions from 3->4->7, and that GPS data is updating on the GPS tab
   NOTE: During in-flight realignment initial heading is automatically estimated from GPS track, no initial heading command is required
4. Perform S turns to speed up fine alignment, INS mode should reach 8 and then 9

It is possible for the navigation system to recover automatically from mode 5 or 6. However, if it is possible to hold the aircraft in straight and level flight it is usually quicker to command in-flight realignment than to wait for the solution to converge by itself.

11.4.6.3 Troubleshooting

The following troubleshooting points have been developed based on operational experiences with the low cost INS:

- If the navigation system is stuck in mode 4 GPS measurement updates are not being received
- It is possible for the navigation system to reset to mode 3 automatically if it has diverged, this is equivalent to commanding in-flight realignment
- If mode 3 is entered while not in straight and level flight (e.g. if INS automatically resets while aircraft was turning) the navigation system will likely diverge again, if this happens it is best to maintain straight and level flight and command in-flight realignment as soon as possible

APPENDIX D – RADAR FUNDAMENTALS

11.5 Radar Range Equation

The theoretical maximum can be utilized to gauge the range detection performance of the radar system. The general form of the radar range equation [Reference 13] is as follows (Eq. $R \cong \left[\frac{P_t G_t^2 G_r^2 \lambda^2 \sigma}{(4\pi)^3 S_{min}}\right]^{\frac{1}{4}} \cong \left[\frac{P_t G_t^2 G_r^2 c^2 \sigma}{(4\pi)^3 f^2 S_{min}}\right]^{\frac{1}{4}}$ 11.1),

$$R \cong \left[\frac{P_t G_t^2 G_r^2 \lambda^2 \sigma}{(4\pi)^3 S_{min}}\right]^{\frac{1}{4}} \cong \left[\frac{P_t G_t^2 G_r^2 c^2 \sigma}{(4\pi)^3 f^2 S_{min}}\right]^{\frac{1}{4}} \quad 11.1$$

where R_{max} is the maximum range to the target, P_t is the peak pulse transmit power, G_t the transmit antenna gain, G_r, the received antenna gain, λ the pulse wavelength (or alternatively, f is the frequency and c, the speed of light), σ, the radar cross-section (RCS) of the target, and S_{min} the minimum detectable signal (MDS). This equation can be applied to both pulsed and continuous-wave (CW) radar systems. In pulsed radar, the system periodically transmits an RF pulse and then switches to receiving mode to listen for echoes. Since the pulses tend to be quite narrow in time, pulsed radar systems often employ high peak powers in order to increase the energy-on-target.

The antenna (G_t) and received (G_r) gain values can be computed from the radar as follows,

$$G_t = \frac{4\pi A_e}{\lambda^2}, \; G_r = \frac{4\pi\sigma}{\lambda^2} \quad 11.2$$

where the former is the property of the radar's effective antenna area A_e, and the latter, a function of the target RCS (in metres) in the centre of the beam. Pulsed radar systems are often monostatic i.e. the same antenna is utilized for both transmission and reception; isolation between the transmitter and receiver is achieved using a T/R switch. As such $G_t = G_r = G_a$, where G_a is the antenna gain.

In general, the detection performance will be limited by both average white Gaussian noise (AWGN) and echoes from targets-not-of-interest such as land, sea or weather, commonly referred to as clutter returns. Target detection in presence of clutter is a complex area of research and the associated analysis is beyond the scope of this report. In addition, the practical significance of clutter on detection performance is strongly related to the capabilities and specifications of the associated radar as well as operational parameters such as the type of environment, height of the radar above ground, among others. For convenience, it is assumed that the maximum detection range is limited solely by AWGN; a derating or loss factor may be applied to account for detection in the presence of clutter. The maximum range performance of the radar is crucial to ascertain the precise zone of protection around the UAS. As the radar is stationary for ground based DAA, this zone is a function of the UAS operational range.

11.6 Receiver Noise and Range Resolution

The receiver noise power, P_n, can be expressed as,

$$P_n = F_n k T B_n \quad 11.3$$

where F_n is the receiver noise figure, k is the Boltzmann constant, T is the temperature (Kelvin) and B_n is the noise-equivalent bandwidth of the pulse. A standard temperature of T = 290K is assumed and the Boltzmann constant is known at K_b=2.0836e10 Hz/K. The range resolution of the radar, ΔR, is defined as follows,

$$\Delta R = \frac{v_p}{2B_n} \qquad 11.4$$

where v_p is the velocity of propagation associated with the radar wave. Note that in free space, $v_p = c$, where c is the speed of light in a vacuum. It is noted that ΔR is inversely proportional to B_n, indicating a tradeoff between improved resolution and increased receiver noise.

11.7 System Losses

A wide variety of loss mechanisms exist in practical radar systems, both due to hardware limitations and processing capability. Hardware effects may be encapsulated within the receiver noise figure F_n for simplicity. Losses due to signal processing artifacts include imperfect matched filtering, straddle loss in range and/or Doppler, beam-shape loss, Fast Fourier Transform (FFT) windowing, target correlation effects and losses due to constant false alarm rate (CFAR) processing. Individual losses can be combined into a single signal processing loss term, L_{sp}. Now, the minimum signal (MDS) associated with a pulsed radar system can be expressed as,

$$S_{min} = \frac{P_n \rho_l L_{sp}}{G_{pc} G_{pp}} = \frac{F_n k T B_n \rho_l L_{sp}}{G_{pc} G_{pp}} \qquad 11.5$$

where ρ_1 is the required single-pulse SNR, G_{pc}, the gain from pulse compression and G_{pp}, the gain associated with pulse processing. Derivations of the gain values as well as the single-pulse SNR are described subsequently. Other values are as described earlier. Incorporating losses into the radar range equation reveals the following,

$$R_{max} = \left[\frac{P_t {G_a}^2 \lambda^2 G_{pc} G_{pp}\, \sigma}{(4\pi)^3 F_n k T B_n \rho_l L_{sp}}\right]^{\frac{1}{4}} \qquad 11.6$$

which can be used to predict the detection range for a target in free-space positioned along the antenna axis.

11.8 Pulse Compression and Blind Range

For systems employing unmodulated and rectangular shaped pulses, the pulse duration, τ_p, is equivalent to the inverse of the noise-equivalent bandwidth, such that $\tau_p \simeq B_n^{-1}$. Shorter pulses yield improved range resolution at the cost of increased noise, which can only be mitigated by increasing the peak transmit power. For this reason, many non-coherent radar systems employ high-power magnetrons capable of generating short pulses with peak powers in the kilowatt and megawatt ranges. Such peak powers are difficult to achieve in solid-state systems and pulse compression is utilized instead. Pulse compression relies on employing long pulses with varying frequency (“chirp”) or phase modulation to increase the signal bandwidth, and by extension the range resolution. For predicting radar range, pulse compression can be treated as a gain factor, G_{pc}, expressed as,

$$G_{pc} = \tau_p B_n \qquad 11.7$$

where the gain is unity in the absence of pulse compression. Note that a primary drawback of pulse compression is that the use of long pulses increases the radar blind range, R_b, expressed as,

$$R_b = \frac{v_p(\tau_p+\tau_i)}{2} \qquad 11.8$$

where τ_i is the time associated with internal delays from switching between transmit and receive modes. Practical radar systems employing pulse compression must take this factor into account. For GBDAA, the blind zone limits how close the radar can be placed to the start of the concept of operations.

11.9 Pulse Processing

Typical radar systems utilize a mechanically steered antenna that is moving continuously while sending and receiving pulses. The antenna dwell time refers to the amount of time a particular region in space is illuminated by the antenna beam in one sweep. If illuminating a target, multiple pulse returns may be associated with a single antenna dwell, where the pulse count is determined by the PRF. For a radar performing an azimuthal scan, the number of pulses within a single dwell, N_p, can be denoted as,

$$N = \frac{\alpha f_p}{\omega_p} \qquad 11.9$$

where α is the azimuthal half-power beam width (HPBW), f_p is the PRF and ω_p is the scan rate. These pulse returns can be processed to improve detection performance, denoted as the pulse processing gain, G_{pp}, as follows,

$$G_{pp} \propto N_p^{\alpha} \qquad 11.10$$

where α is bounded such that $0.5 \leq \alpha \leq 1$. Traditional radars often employ non-coherent pulse integration to boost the effective SNR of the received signal. The value of G_{pp} in this case can be estimated using Shnidman's equation [Reference 14]. However, it is useful to note that α is always less than unity in this case, and approaches 0.5 as N_p grows large.

Fully coherent radar systems are capable of performing coherent pulse processing, usually in the form of an FFT. Since the frequency variable relates to the Doppler shift associated with a given pulse return, this is commonly referred to as pulsed-Doppler processing. In this case $\alpha = 1$ as long as the antenna dwell is less than the coherence time of the target. When this is not the case, it may be suitable to break N_p into a collection of coherent processing intervals which are processed separately, then perform non-coherent integration over the resulting Doppler spectra [Reference 15]. In the context of this report it will be assumed that pure coherent or non-coherent processing has been applied to all of the pulses.

Perhaps the most important benefit to pulse-Doppler processing is the fact that targets exhibiting non-zero Doppler shift relative to the radar can be readily separated from clutter returns, which tend to reside near 0 Hz in the Doppler spectrum. The result is what is known as sub-clutter visibility (Figure 9). With the signal-to-clutter ratio (SCR) of -6 dB in this case, detection would be very challenging for a non-coherent system. However, the target is readily detected through the use of pulsed-Doppler processing since it need only be compared to a threshold set based on the background noise level in a localized section of the Doppler spectrum. Therefore, coherent radar systems employing pulsed-Doppler processing exhibit significantly better detection performance for moving targets in the presence of clutter. Note that hovering or radially orbiting targets will exhibit very small Doppler shifts, and performance in these cases will be similar to that achieved with a non-coherent system[1].

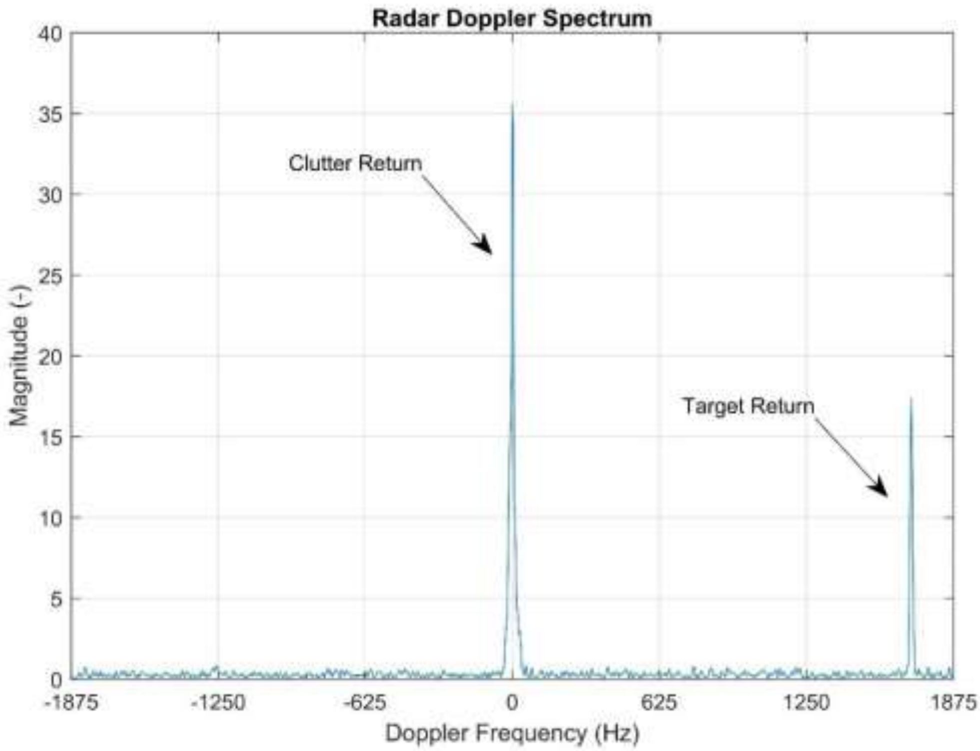

Figure 9: Sample Doppler spectrum demonstrating sub-clutter visibility

Increasing the number of pulses on target is beneficial in the context of pulse processing, as G_{pp} will grow regardless of whether the processing is coherent or non-coherent. However, there are practical constraints placed on the antenna dwell. For fast-moving targets, too long an antenna dwell will result in range and Doppler walk, which must be compensated in order to achieve the desired G_{pp}. Range and Doppler walking refers to smear introduced in the slant and cross-range directions of the range and velocity estimate between successive pulses, contributing to the uncertainty in the range and velocity accuracies. Compensation for walking can significantly increase the complexity of the receiver depending on the radar design. Widening the antenna HPBW will reduce G_a, resulting in an overall reduction in range performance. Reducing the scanning rate will increase the scan update interval, which would increase the time required for track acquisition, thereby degrading the tracking performance.

An effective way of increasing N_p, and by extension G_{pp}, is to maximize the PRF employed by the radar. This is also beneficial in the context of pulsed-Doppler processing, since the maximum unambiguous Doppler speed, v_u, is given by,

$$v_u = \frac{\lambda f_p}{4} \qquad 11.11$$

[1] Neither of the GBDAA systems in these trials used Doppler processing

Targets exhibiting Doppler shifts which exceed v_u will be aliased and appear as slower moving targets. Unfortunately, the PRF is also inversely related to the maximum unambiguous range, R_u, associated with the radar, expressed as follows,

$$R_u = \frac{v_p}{2f_p} \qquad 11.12$$

The resulting tradeoff leads to the definition of three distinct PRF regimes: low-PRF, with unambiguous range, high-PRF, with Doppler shift ambiguity, and medium-PRF, with range and Doppler shift ambiguity. For surveillance radar, operating in the low-PRF range is most common since an unambiguous range measurement is more useful from a tracking perspective, and PRF is chosen such that R_u is minimized and N_p is maximized. In the GBDAA scenario, Doppler walk is not a pressing concern. Typical pulse trains are on the order of microseconds (10^{-6} seconds), and since there are ~1000 pulses within one pulse train, the interval pulse time interval equates to ~10^{-9} seconds. In Class G airspace, the maximum intruder airspeed (assuming head-on collision) is limited to 128.5 m/s (250 kts). At 10^{-9} seconds, the relative change in the intruder position is ~0.1 microns, which can safely be considered negligible. Nonetheless, Doppler walk is an important concept for high-speed intruders, including jet-propelled UAVs, rockets or other airborne self-propelled objects.

11.10 Target Fluctuation

Radar returns from complex targets exhibit fluctuations as a function of the variable reflectivity and the incidence angle of the radar wave. As a result, it is common to model the fluctuation in received intensity as a probability density function (PDF). This can be achieved by first selecting a representative RCS value for use in the radar range equation, then assuming a PDF and the desired probabilities of detection and false alarm, P_D and P_{FA} respectively, to compute the required minimum SNR. The required single-pulse SNR, ρ_1, can be written as,

$$\rho_1 = \frac{\ln P_{FA}}{\ln P_D} - 1 \qquad 11.13$$

Detection performance for dynamic and complex targets is an extensive area of research. For convenience, the traditional Swerling model [References 8, and 9] will be considered, with particular emphasis on Swerling I (Rayleigh/exponential distribution, uncorrelated from scan to scan) or Swerling II (Rayleigh/exponential distribution, uncorrelated from pulse to pulse) variants, since these are often applied to fixed or rotary wing aircraft.

Extensive work has been conducted on Swerling models since the 1950s. A popular analytic approximation is given by Albersheim [References 8, and 9]. In practice, the RCS varies significantly with aspect. The observed aspect for a collision course intruder is a function of the collision geometry that can vary from head-on to a 180-degree azimuthal offset. This variety of collision geometries results in drastically different observed RCS profiles for the same target. Small single engine fixed-wing aircraft exhibit a nose-on nominal RCS of +5 dB per square meter (3 m^2) and a broadside nominal RCS of +20 dB per square meter (100 m^2, Reference 16). This gives rise to both large-scale fluctuations based on the general orientation of the target and small-scale fluctuations due to interfering returns from different sections of the target for a given orientation. These small-scale fluctuations are likely to fall somewhere between the Swerling I and II cases, since some degree of pulse-to-pulse correlation is to be expected. In order to mitigate these complications, a conservative RCS is often chosen.

Table 10: Common Swerling Model Types and Descriptions

Swerling Model	Description
0, 5	Non-fluctuating target, no scatterer interaction. Exponential PDF only
1, 2	Fluctuating with a cluster of interacting equal-RCS scatterers
3, 4	Fluctuating with dominant scatterer surrounded by equal-RCS scatterers

11.11 Radar Cross Section

The radar cross section of the target aircraft is a critical parameter to understand in the assessment of the DAA system performance.

Figure 10 below presents RCS of typical light general aviation aircraft [Reference 10].

Summary of RCS Probability Density Data

	MEAN OF "MOST LIKELY" EXPONENTIAL DIST' (m^2)	FRACTION OF TOTAL OBSERVATION	SMALLEST MEAN OBSERVED (m^2)	OVERALL MEAN RCS (m^2)
Cherokee 140				
Nose	6.1	0.8	0.5	5.1
20° -70°	2.6	0.8	1.0	2.5
110°- 160°	1.3	0.8	1.0	2.2
Tail	2.3	0.7	0.8	3.0
Cessna 177 Cardinal				
Nose	7.5	0.6	2.0	5.4
20°-70°	1.6	0.8	1.0	2.4
110°- 160°	1.5	0.9	1.3	1.5
Tail	1.6	0.8	0.25	1.3
Cessna 172 Skyhawk				
Nose	10.0	0.9	1.5	8.9
20° -70°	8.0	0.9	0.7	7.3
110° 160°	8.2	0.7	1.0	6.5
Tail	5.4	0.8	0.8	4.8

Figure 10: Tpical RCS Values for Light GA Aircraft [from Reference 10]

The authors of this report were unable to find good RCS data for helicopters, however some reports suggest that the RCS for a helicopter is approximately 50% greater than a comparable airplane.

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