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Small UAS Detect and Avoid Requirements Necessary for Limited Beyond Visual Line of Sight (BVLOS) Operations: Final Report

October 25, 2022

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16. Abstract

The demand for Beyond Visual Line Of Sight (BVLOS) operations using small Uncrewed Aircraft Systems (sUASs) is high. A major impediment to realization of these operations is the Detect And Avoid (DAA) function. This effort explored many DAA challenges through execution of numerous tasks, results of which are described subsequently.

The Operational Framework effort resulted in a slight expansion of a previously-developed use case taxonomy and identification of technologies that are now being operationally utilized. Minimal additional information regarding expansion of the operational framework based on Radio Line Of Sight (RLOS) coverage was identified.

A significant simulation effort to evaluate DAA system and Uncrewed Aircraft System (UAS) characteristics that impact maintenance of well clear was conducted. DAA characteristics that had the greatest impact are range and Field of View (FoV). Update rate and latency impacts were not as dramatic, while horizontal and vertical resolution were the least impactful. UAS characteristics that strongly impact maintenance of well clear are response time (i.e., the time required to initiate a maneuver) and UAS speed.

An overarching test plan was developed. This test plan describes test locations/performers, dates of testing, DAA systems used in tests, overarching test objectives, individual test plan structure, methods for maintenance of safety during testing, data collection approaches, the structure of test reports, and test metrics/artifacts.

Seven rounds of flight tests were completed. Important outcomes from these tests include development of a systematic approach for evaluating DAA systems, identification of test metrics/artifacts, test data collection methods/best practices, methods for enabling flight test safety, methods for executing both horizontal and climb- and descend-into encounters, evaluation of DAA systems (especially the detection component), and utilization of results in American Society for Testing Materials (ASTM) committees to support standards development.

This effort involved a broad set of tasks designed to inform Federal Aviation Administration (FAA) regulations and industry standards regarding sUAS DAA systems. Through execution of these tasks and application of the numerous methods required to do so, the team has significantly advanced sUAS DAA, which will enable more rapid integration of sUAS into the National Airspace System (NAS)—especially for BVLOS operations.

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Acronym	Meaning
A&G	Alerting and Guidance
AC	Air Conditioner
ACUASI	Alaska Center for Unmanned Aircraft Systems Integration
ADS-B	Automatic Dependent Surveillance-Broadcast
AGL	Above Ground Level
ASTM	American Society for Testing Materials
BVLOS	Beyond Visual Line Of Sight
CA	Crewed Aircraft
CPA	Closest Point of Approach
DAA	Detect And Avoid
DCAPS	Data Collection and Processing System
DJI	Da-Jiang Innovations
DTEM	Detect, Track, Evaluate, and Maneuver
EFP	Encounter Focal Point
EO	Electro-Optical/Electronic Observer
FAA	Federal Aviation Administration
FoR	Field of Regard
FoV	Field of View
FTD	Flight Test Director
GBDAA	Ground-Based Detect and Avoid
GCS	Ground Control Station
HEFP	Horizontal Encounter Focal Point
IMU	Inertial Measurement Unit
IR	InfraRed
KSU	Kansas State University
LRE	Launch and Recovery Element
MESA	Metamaterial Electronically Scanning Array
MP	MegaPixel
MSL	Mean Sea Level
NAS	National Airspace System
NMAC	Near Mid-Air Collision
NMSU	New Mexico State University
NPRM	Notice of Proposed RuleMaking
OSU	Ohio State University
PIC	Pilot In Charge
RLOS	Radio Line Of Sight
RMRC	Ready Made RC
RTCA	Radio Technical Commission for Aeronautics
SARP	Science And Research Panel
SBSS	Surveillance and Broadcast Services Subsystem
SME	Subject Matter Expertise
SMS	Safety Management System
sUAS	small Uncrewed Aircraft System
SUI	Straight Up Imagery
SWaP	Size, Weight, and Power
UA	Uncrewed Aircraft
UAS	Uncrewed Aircraft System
UAF	University of Alaska Fairbanks
UASTS	UAS Test Site
UND	University of North Dakota
UTM	Unmanned Traffic Management

VAS	Value Added Service
VO	Visual Observer
VTOL	Vertical Take-Off and Landing

EXECUTIVE SUMMARY

The demand for Beyond Visual Line Of Sight (BVLOS) operations using small Uncrewed Aircraft Systems (sUASs) is high. A major impediment to realization of these operations is the Detect And Avoid (DAA) function. Several challenges exist for sUAS DAA. This effort explored many of these challenges through execution of numerous tasks, results of which are described subsequently.

Given the broad set of tasks, multiple methods were applied to execute them. These include review of previous efforts, analysis and synthesis, simulation, and testing and validation.

The Operational Framework effort resulted in a slight expansion of the previously-developed use case taxonomy (Cathey and Hottman 2017) and identification of technologies that are now being operationally utilized. Minimal additional information regarding expansion of the operational framework based on Radio Line Of Sight (RLOS) coverage was identified.

Maintenance of a DAA systems inventory indicated that the characterization provided by Askelson et al. (2017) still applies. This includes strengths and limitations of on/off board systems identified by Askelson et al. (2017). Some of the most promising systems identified in this task were utilized during evaluation of DAA test methods.

A significant simulation effort to evaluate DAA system and Uncrewed Aircraft System (UAS) characteristics that impact maintenance of well clear was conducted. DAA characteristics that had the greatest impact are range and Field of View (FoV). Update rate and latency impacts were not as dramatic, while horizontal and vertical resolution were the least impactful. UAS characteristics that strongly impact maintenance of well clear are response time (i.e., the time required to initiate a maneuver) and UAS speed.

An overarching test plan was developed. This test plan describes test locations/performers, dates of testing, DAA systems used in tests, overarching test objectives, individual test plan structure, methods for maintenance of safety during testing, data collection approaches, the structure of test reports, and test metrics/artifacts.

Seven rounds of flight tests were completed. Important outcomes from these tests include:

- A systematic approach for evaluating DAA systems
- Identification of test metrics/artifacts
- Test data collection methods/best practices
- Methods for enabling flight test safety
- Methods for executing both horizontal and climb- and descend-into encounters
- Evaluation of DAA systems (especially the detection component of DAA systems)
- Utilization of results in American Society for Testing Materials (ASTM) committees to support standards development

This effort involved a broad set of tasks designed to inform Federal Aviation Administration (FAA) regulations and industry standards regarding sUAS DAA systems. Through execution of these tasks and application of the numerous methods required to do so, the team has significantly advanced sUAS DAA, which will enable more rapid integration of sUAS into the National Airspace System (NAS)—especially for BVLOS operations.

1 INTRODUCTION

The demand for Beyond Visual Line Of Sight (BVLOS) operations using small Uncrewed Aircraft Systems (sUASs) is high. A major impediment to realization of these operations is the Detect And Avoid (DAA) function. Several challenges exist for sUAS DAA. This effort explored many of these challenges.

The purpose of this project, "A18_A11L.UAS.22 – Small UAS Detect and Avoid Requirements Necessary for Limited Beyond Visual Line of Sight (BVLOS) Operations: Separation Requirements and Testing" (A18), was to inform Federal Aviation Administration (FAA) regulations and industry standards regarding sUAS DAA systems. The A18 scope included the following questions:

- What are the use cases requiring DAA for BVLOS operations?
- What DAA systems are available, what are their capabilities and limitations, and are they mature enough to support BVLOS operations?
- What characteristics of DAA systems and Uncrewed Aircraft Systems (UASs) must be considered to ensure maintenance of well clear status?
- How should sUAS DAA systems be evaluated to ensure they provide safe separation services in the National Airspace System (NAS)?
- What is the recommended test method(s) to evaluate different DAA systems?

This project was conducted with the following tasks:

1. Development of an Operational Framework for sUAS BVLOS Operations—New Use Cases, Industry Focus, and Framework Expansion
    a. sUAS Use Case Data Collection/Analysis
    b. Exploration of Framework Expansion
    c. Revision of sUAS Radio Line Of Sight (RLOS) Boundary Recommendation with Collected Use Case Data and for Expanded Operational Frameworks
2. Update of sUAS DAA Solutions Inventory
3. Coordination with Standards Agency to Establish Framework
4. Development of Separation Framework
    a. Impacts of Characteristics of DAA System on Maintenance of Well Clear
    b. Impact of Uncrewed Aircraft (UA) Characteristics on Maintenance of Well Clear
5. Development of a Testing Plan
6. Testing of a) the recommended DAA testing plan and b) candidate DAA systems
    a. Conduct Flight Tests
    b. Testing of Well Clear Definition
    c. Testing of Separation Framework
    d. Testing of DAA Test Plan
    e. Revision of Safety Management System (SMS)/Safety Risk Management Output
7. Final Report

This report is the product of Task 7: Final Report. To manage the length of this report, tasks for which separate reports were produced are summarized herein. For greater detail, the interested reader may review those reports.

2 NON FLIGHT-TEST REPORTS

2.1 Task 1: Operational Framework

The Task 1 effort was to prepare a report on the Development of an Operational Framework for sUAS BVLOS Operations. A report titled "Development of an Operational Framework for Small UAS Beyond Visual Line of Sight (BVLOS) Operations—New Use Cases, Industry Focus, and Framework Expansion" was completed submitted to the FAA on 9 October 2019, and later revised on 8 November 2019 (Cathey et al. 2019).

2.1.1 Objectives

The Cathey et al. (2019) report provided detail regarding the three distinct Task 1 subtasks:

- Subtask 1a: sUAS Use Case Data Collection/Analysis
- Subtask 1b: Exploration of Framework Expansion
- Subtask 1c: Revision of sUAS RLOS Boundary Recommendation with Collected Use Case Data and for Expanded Operational Frameworks

The sUAS Use Case Data Collection/Analysis effort provided an extended assessment of use cases following a previous analysis (Cathey and Hottman 2017). The objective was to provide an update to this previous work in the three areas noted above.

2.1.2 Methods

Potential sUAS use cases were gathered to assess prospective BVLOS applications that may use DAA approaches. The uses cases gathered were focused on advancements or operations within the last approximately two years. The goal was to identify any new use cases and to further flesh-out some of the categories and applications. This period has been a growth and expansion stage for the industry. Most use cases in the past few years have adjusted and abide by the FAA Part 107 rules that limit operations to altitudes of ≤ 400 ft. The previously-developed Cathey and Hottman (2017) use case taxonomy was used as an initial basis for categorization of the different types of flights/missions.

2.1.3 Summary of Results

The previously developed taxonomy was slightly revised to include twelve distinct categories:

- Aerial Data Collection
- Aerial Photography/Videography
- Aerial Surveying/Mapping
- Agriculture
- Emergency Services
- Flight Training/Education
- Inspection
- Marketing
- Research
- Search/Rescue
- Surveillance/Monitoring, etc.
- Other

Forty seven different subcategories capture different aspects of these top-level uses. As noted, low-altitude sUAS and Crewed Aircraft (CA) operations use cases and expressed industry needs are evolving. New applications and reports appear almost daily. To refine the scope of this effort, the approach was to explore use cases from when the Cathey and Hottman (2017) report was issued until the release of the Cathey et al. (2019) report. The team further drilled down on key use cases where there is broad industry need or application to further flesh out these front-line emerging areas.

Specific examples of all of the various use case areas are included. There was no attempt made to document every published application; the goal was to present representative applications within each area. The examples were almost limitless. The use cases found and detailed once again demonstrate the statement that UAS applications are only limited by one's imagination. It was also clear from assessing the user operations that many applications do not fall cleanly within any one set of particular categorization lines. For example, aerial data collection may also include photography and mapping, and may be used for agricultural applications or inspections. The applications and use cases often cover multiple areas during one mission. The key applications using UAS include survey/mapping, imaging, environmental monitoring, patrol/security, disaster response, precision agriculture, and reconnaissance/surveillance/intelligence. Almost all use multiple elements and many are being fueled by better detector/sensor systems, improved data handling, and artificial intelligence.

Also gathered from the use cases was the common adoption of some of these technologies so they are not now new and cutting edge, but are common tools that are part of the normal work process. This has been observed in many engineering assessment applications, marketing, public safety, and environmental monitoring applications. The technology and uses are maturing. Published articles tend to highlight specific new unique applications or first-time or unique events. A new category, "other", is a catch-all category that includes unique operations that do not fit well in any of the other categories and are not vibrant enough to stand uniquely alone. One potential new use case area is "Outdoor and Recreation". This area will likely expand over time.

Minimal additional information was available concerning expansion of the operational framework based on RLOS coverage. Again, with many users now operating under Part 107, the user base has trended toward working within these set FAA structures. To that end, the use cases collected and detailed, for the most part, did not provide any useful or actionable information related to RLOS boundaries or issues. The literature search turned up no real references to limitations, lost link, or communication issues. Articles and information focused on capabilities and not limitations. Producers did not provide detailed data or information that provided additional insight. Even with the available data, the testing performed up to the time of the Cathey et al. (2019) report was predominantly executed within Line Of Sight and well within RLOS. None of the testing on this task has pushed the limits to provide new or revised information regarding the limits. Without specific targeted testing, expanding RLOS understanding is not possible. There is no recommendation at this point for the revision or expansion of the operational framework based on the previous sUAS RLOS Boundary Recommendations based on the collected new and revised use cases or use case data.

An operational framework that defines the environment and conditions under which the recommended requirements will enable sUAS operations BVLOS is presented. Considerations for BVLOS operations involve a number of interrelated elements that are needed for safe flight. These elements result in potential constraints on the systems and operations. The three elements of significant interest are:

1) The conditions or locations in which one flies must be conducive to safe flight operations;
2) The operator must operate in a safe fashion; and
3) The aircraft must be capable of reliable and safe BVLOS operations.

A series of assumptions and limitations that can facilitate BVLOS operations are provided. The Exploration of Framework Expansion effort takes three things into consideration. First, the use cases were collected. Second, potential changes due to newly gathered information related to RLOS operations were gathered. Third, other external drivers such as new FAA regulations or industry/community recommendations from the ASTM, the Science And Research Panel (SARP), etc., were reviewed. Considering Part 107, the FAA's direction toward allowing night operations and flights over people, the SARP's "Well Clear Hockey Puck", and the like, minimal changes are recommended from the original framework proposed. The trade space has not evolved significantly since the initial Cathey and Hottman (2017) report. The framework may not be prescriptive nor does it include an exhaustive set of actions; the framework includes strategies that can build upon FAA and industry actions that should result in an increase in BVLOS flights in the near term.

2.1.4 Lessons Learned

Below is a summary of all of the primary strategies and recommendations to help facilitate sUAS BVLOS operations in the NAS [based upon Cathey et al. (2019)]:

1. Require a minimal set of limitations for BVLOS operations
    a. Operating time
        i. Daytime
        ii. Nighttime – following recent FAA 2019 Notice of Proposed RuleMaking (NPRM) for Night Operations
    b. Meteorological conditions: Visual Meteorological Conditions
    c. Altitude: ~400 feet Above Ground Level (AGL) (altitude modified to follow Part 107)
    d. Overflight
        i. No densely populated areas
        ii. Operations over people – following recent FAA 2019 NPRM for Operations over People
    e. Airport proximity limitations: greater than or equal to 5 miles
    f. Critical operating limitations: greater than or equal to 3 miles of critical infrastructure
    g. Operational control: RLOS will determine distance; no daisy chaining of control stations
    h. Aircraft visibility: optimize color, lighting, and design for conspicuity
    i. Ensure safe separations as defined by the SARP "Well Clear Hockey Puck" of 2,000 ft horizontal separation and 250 ft vertical separation
2. Develop a consensus-based and research-based design strategy
3. Utilize common phases of flight to facilitate recommendations and potential regulatory input to the FAA
4. Develop a taxonomy and use cases that result in a manageable set of recommendations for regulatory and recommendation purposes

5. ASTM could lead the development of design and other data for BVLOS operations based upon current and proposed research (ASTM is doing a portion of this in the ASTM DAA Performance Requirements Task Group)
6. A DAA system—either airborne or ground-based—must be operational with the system
7. sUAS BVLOS operations in the NAS can take place without extensive and very expensive infrastructure
8. International operations and requirements should be considered in formulating the BVLOS requirements for the United States
9. Develop a more robust/realistic RLOS model for BVLOS that more accurately predicts the environment, links, and limitations
10. Utilize SMS to assess risk as BVLOS evolves
11. Utilizing candidate DAA and other enabling BVLOS technologies, develop, verify, and validate test methodologies for these current systems and apply this to future systems
12. Anticipate that the near future will demand autonomous BVLOS without a human pilot due to the large number of anticipated flights within an airspace

2.2 Task 2: Update of sUAS DAA Solutions Inventory

2.2.1 Objectives

The objective of this task was to track developments associated with DAA systems designed to work with sUAS.

2.2.2 Methods

Data regarding sUAS DAA systems were gathered through extraction of information provided publicly (e.g., at presentations or on web sites) and through interactions with industry. The annual Association for Uncrewed Vehicle Systems International XPONENTIAL conference was a useful venue for collecting information regarding evolving DAA systems and systems that could be used as components of DAA systems.

2.2.3 Summary of Results

Results of this task indicated that the characterization of DAA systems provided by Askelson et al. (2017) for the project “A2_A11L.UAS.22 – Small UAS Detect and Avoid Requirements Necessary for Limited Beyond Visual Line of Sight (BVLOS) Operations” (A2) still applies. Askelson et al. (2017) identified the major steps/components of DAA as Detect, Track, Evaluate, and Maneuver (DTEM). The characteristics of DAA systems relate to DTEM and can be organized using the categories (Askelson et al. 2017):

- Modality: Cooperative vs. Noncooperative (D and T)
- Sensor Type: Active vs. passive, non-cooperative sensing method (D)
- Location: On/off board (DTEM)
- Degree of Autonomy: Human In The Loop, Human Over The Loop, etc. (DTEM)

It is noted that non-cooperative sensing methods that have been identified for sUAS DAA systems include:

- Radar
- Light Detection And Ranging
- Electro-Optical/InfraRed (EO/IR)
- Acoustic

The strengths and limitations of on/off board systems identified by Askelson et al. (2017) continue to apply. Off board systems provide required performance but are costlier and commonly require more personnel to operate. On board systems are much less expensive and resource intensive, but struggle to provide the required performance.

Because the set of DAA systems and supporting technologies is constantly evolving, a list is not provided herein. Some of the most promising systems were utilized during evaluation of DAA test methods (Section 3). Types of DAA systems utilized during tests include those that leveraged cooperative [Automatic Dependent Surveillance-Broadcast (ADS-B)] and non-cooperative (EO and radar) sensors. Characteristics of DAA systems utilized during testing are provided in Section 3 of this report.

2.2.4 Lessons Learned

Two key take-aways for this task are:

1. The technologies that can be applied to sUAS DAA are evolving rapidly.
2. Some entities operate in a "silent" mode in which they reveal very little regarding their technologies, which is likely driven by a desire for competitive advantage.

2.3 Task 3: Coordination with Standards Agency to Establish Framework

2.3.1 Objectives

The objective of this task was to establish a standards agency framework to address sUAS DAA and to translate lessons learned from this research into industry standards. ASTM was identified as the proper organization for this task.

2.3.2 Methods

The A18 team coordinated with others within the industry to establish the required framework. In fact, others within the industry had already developed a foundation for this. Thus, the A18 team supported the efforts that were already underway and provided Subject Matter Expertise (SME). The primary A18 team members who supported this task were Kansas State University (KSU) and the University of North Dakota (UND).

2.3.3 Summary of Results

Within ASTM, two working groups were established:

1. WK62668: Detect and Avoid Performance Requirements Task Group
2. WK62669: DAA Test Methods Task Group

The DAA performance group produced a standard that was published in July 2020 (ASTM 2020). KSU provided significant support to development of ASTM (2020), including participating in working group meetings and completing writing tasks. During development of ASTM (2020), key elements that were identified include:

1. Identification and significance of test artifacts.
2. The roles of flight test and simulation in gathering DAA system performance data.
3. The linkage between flight test and simulation test methods.

While A18 team engagement was important to development of ASTM (2020), its engagement is even more significant with the DAA test methods group. In addition to SME support for this group, one of the A18 Principal Investigators (Askelson) also serves as a co-chair for this group.

Although the DAA test methods group has not yet reached the ballot phase for its draft standard, it has made significant progress. Many of the findings from A18 have supported the DAA test methods group, including test procedures and metrics. These are described in more detail in Section 3.

2.3.4 Lessons Learned

The ASTM DAA working groups have driven significant advancements. These include exploration of metrics for evaluation of DAA systems, an enhanced understanding of the DAA steps/timeline, and requirements of entities demonstrating compliance. Some of the greatest challenges, which likely relate to most standards, have been:

- Identification of proper metrics for required performance
- Identification of metrics used to demonstrate performance
- Determining the "mix" of simulation and testing (both bench and field testing)
- Delineating requirements that enable applicant flexibility and broad application given the variability in NAS traffic characteristics (types of intruders, density of intruders, etc.)

Additional information is provided in the following subsections.

2.3.4.1 Metrics

The significance and type of data were an initial stumbling block within the working groups. While performance standards are generally agnostic to any specific technology, the types of data collected by a given sensor may be more specific – e.g., data collected with an optical sensor may differ from that collected with an airborne radar. Initial discussions focused on ensuring that test methods, test metrics, and other sources of data remained agnostic of any particular technology.

2.3.4.2 Simulation and Flight Testing

Early in the development of the standard, it was noted that there was benefit to utilizing simulation for modeling encounters, as simulations enable relatively inexpensive execution of a very large number of simulations and evaluation of performance for encounters that would be hard to conduct safely through flight tests. This is especially true, as the repository of airspace encounter models developed by MIT Lincoln Labs (Weinert 2021) provides a starting point for defining simulated encounters for use in determining DAA system performance. However, it was also noted that flight testing can be used to validate assumptions used for encounters that may be devised to evaluate unique characteristics of given DAA systems and sensors. Discussions centered upon how and when simulation and flight testing should be employed and at what point each is most practical for a system manufacturer and/or integrator.

Similar to the identification of the roles of flight test and simulation, the test methods group discussed how to link test data gathered from flight test and simulation. Discussions regarding the linkage of flight test and simulation test methods are still ongoing.

At the time of this report, the working group is adjudicating proposed test methods at test artifacts internally. This process is intended to identify test methods that correlate to individual test requirements, resolve conflicts that may exist regarding the wording of test requirements, and ultimately prepare the standard for initial ballot within the ASTM F38 committee.

2.4 Task 4: Separation Framework

2.4.1 Objectives

The objective of this task was to determine the characteristics of DAA systems and of UAS that must be considered to ensure maintenance of well clear status. Answering this question provides insight into questions regarding the ability of existing DAA systems to enable maintenance of well clear and regarding evaluation/test methods for small UAS (sUAS) DAA systems.

2.4.2 Methods

An automated approach to simulating UA encounters with CA was developed based upon previous simulation work described by Askelson et al. (2017). Encounter simulations involved a simulated CA intruder (a Cessna 182T turbo) and either a fixed-wing or multi-rotor sUAS. The baseline characteristics of the simulated sUAS were designed to align with typical performance characteristics of the respective types of sUAS. Encounters were divided into three sets: co-altitude, climbing/descending, and stress. Stress encounters involved the intruder flying in two different directions relative to ownship while maintaining a minimum safe horizontal separation distance that would not trigger a DAA alert before turning (left- or right-) into the ownship's path at the last minute. All encounter geometries were conservatively designed to be collision geometries (with no action taken, the aircraft would collide).

Impacts of DAA characteristics and sUAS characteristics were evaluated. For DAA characteristics, four sensors classes—control sensor (theoretically 'perfect' sensor), EO/IR, radar, and acoustic—were considered. For these sensor classes, seven characteristics were evaluated: latency, update rate, range, horizontal and vertical FoV, and horizontal and vertical resolution. Impacts of variations in these characteristics were evaluated by 'sweeping' through values for one characteristic while holding the values of the other characteristics constant.

Dependence upon sUAS characteristics was explored by examining variations with maximum and minimum indicated airspeed, maximum climb and descent rate, maximum yaw rate/bank angle, and pilot response time. As with DAA system characteristics, impacts were explored by varying the values of one characteristic while holding the values of the other characteristics constant.

The risk ratio, which is the probability of an event with a DAA system divided by the probability of an event without a DAA system, is the metric used herein to evaluate performance and risk. The risk ratio has been adapted by the ASTM WK62668 Detect and Avoid Performance Requirements Task Group as the fundamental metric for evaluating DAA system performance. Due to the nature of the encounter sets used [all encounters result in a Near Mid-Air Collison (NMAC) when run unmitigated], herein the risk ratio is the number of encounters for which well clear or NMAC distances using the currently loaded aircraft or sensor configuration could not be maintained vs. all encounters in a simulation sweep. Thus, encounters are not weighted according to likelihood of occurrence. It is further noted that because risk ratios are commonly determined using a larger set of simulations than executed in this task, the results from this task are commonly referred to as 'estimated risk ratios'.

2.4.3 Summary of Results

An example of results is provided in Figure 1. As shown in Figure 1, estimated risk ratio drops with increasing detection range, as expected. The lowest value for estimated risk ratio is driven by the limited FoV of the assumed DAA sensor [cf. Kaabouch et al. (2020) for details]. Distances to the well clear volume, for encounters in which well clear is retained, increase and then stabilize with increasing detection range. For the assumed conditions and these simulations, maintenance of well clear starts to be possible for detection ranges in the 7000-8000 ft range.

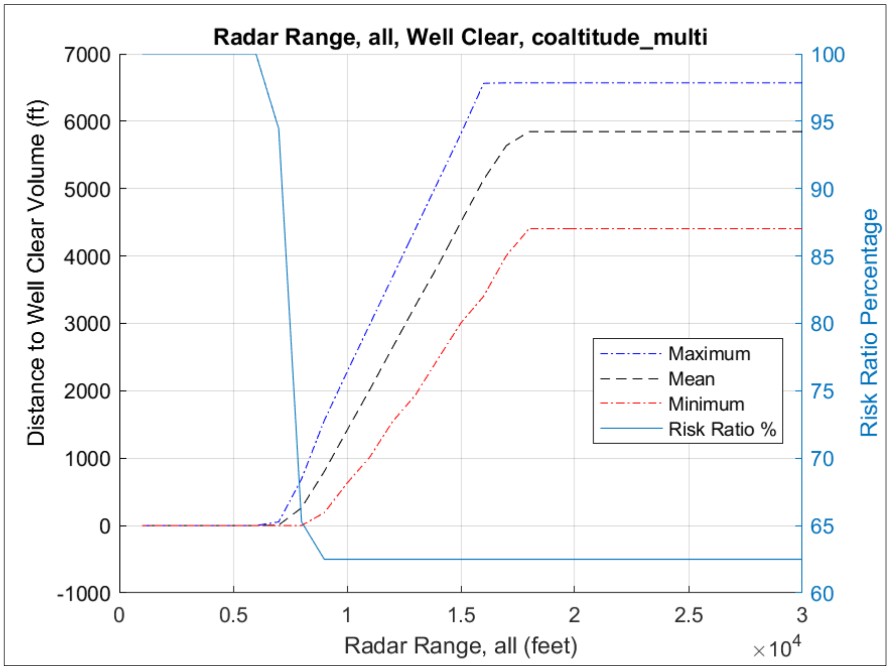


Figure 1. Example separation framework results for a radar-based DAA system [cf. Figure 19 of Kaabouch et al. (2020)]. Lefthand y-axis is distance to well clear volume (minimum, mean, and maximum) for encounters in which well clear was maintained and righthand y-axis is estimated risk ratio. X-axis is radar detection range in 10^4 ft. Results are for co-altitude encounters, an assumed multi-rotor aircraft, and a radar-based DAA system with limited FoV in both the horizontal and vertical directions. For further details, see Kaabouch et al. (2020).

The DAA characteristics that had the greatest impact on estimated risk ratio were range and FoV. Update rate and latency impacts were not as dramatic, while horizontal and vertical resolution were the least impactful.

EO/IR had very low success in maintaining well clear, to the point that baseline performance was less sufficient as a tool for well clear maintenance than as a tool for avoiding NMACs. In the EO/IR range test, regular success for well clear did not start occurring until roughly 7,000-8,000 ft detections. This is large and double the average range of sensors on the market at the time of this evaluation (4,000 ft baseline). The acoustic sensor class required detections at greater ranges (10,000 ft and greater) to maintain well clear status owing to the slower speed of sound. The radar sensor class enabled maintenance of well clear at similar detection ranges as the EO/IR sensor class.

Radar appears to be the best sensor class of the three under consideration; however, it is also arguably the most challenging for sUAS, especially copters given the Size, Weight, and Power (SWaP) characteristics of the sensor. It may be a reasonable candidate, especially if commercial systems improve, for midsized and larger fixed-wing vehicles.

Given no sensor limitations, the greatest defense a UAS has to maintain well clear is a vigilant and fast-responding pilot. A reasonable delay/response time for a pilot of average skill is 5 s.

Reduction of maneuver delays, even by a couple of seconds, can have an impact that is larger than most characteristics evaluated in these simulations. Moreover, operating a faster UAS enables significant risk reduction. Such risk reductions occur for relatively low UAS performance gains, which is encouraging for average aircraft in the UAS commercial fleet since normal performance is enough to garner the best gains in a DAA context.

2.4.4 Lessons Learned

The separation framework effort produced results that:

- Elucidate the most important DAA system characteristics for maintaining well clear—detection range and FoV
- Illustrate the most important UA characteristics for maintaining well clear—(pilot) response time and aircraft speed
- Underscore the significant challenges associated with onboard DAA systems—providing the required performance given SWaP limitations
- Indicate that many current onboard DAA systems may be better considered to be NMAC and/or collision-avoidance systems given their performance (e.g., detection range and FoV)

2.5 Task 5: Test Plan

2.5.1 Objectives

The high-level objective for this task was to provide an overarching test plan for flight tests events conducted during A18.

2.5.2 Methods

Previous research and experience from previous test campaigns were used to develop an overarching test plan.

2.5.3 Summary of Results

Test locations/performers are described. For these, dates of testing and high-level test characteristics are provided. Seven rounds of flight tests were completed. Tests included evaluation of individual components (e.g., the Detect step) and evaluation of total DAA system performance, including metrics identified in the existing sUAS DAA performance standard (ASTM 2020).

DAA systems used in testing are described. Four different DAA systems were used, including off-board (ground-based) radars, on-board radars, on-board electro-optical sensors, and cooperative (ADS-B) sensors.

A description of overarching test objectives is provided. This includes how these objectives relate to evaluation of DAA element performance, to the separation framework (validation of simulations performed under Task 4 of A18), and to ASTM standards regarding sUAS DAA.

The structure of a test plan is delineated, including descriptions of test plan elements. Testing is grounded in a geometric approach, which leverages varying encounter geometries (horizontal and vertical) to evaluate DAA system performance. Other variables to be considered when testing DAA systems include trajectory type (straight vs. curved, collision vs. non-collision, etc.), intruder speed, sUAS speed, and clutter severity.

Maintenance of safety during testing is paramount. Approaches for ensuring safety during both horizontal and vertical encounters were developed and tested. In addition, example tests scripts were developed. For some tests, different scripts were used for different roles for each encounter, which can be helpful with eliminating confusion and enhancing efficiency in the field.

Data collection was enabled through either data collection sheets or digital collection tools. Two types of data collection sheets were used: static for collection of metadata that are constant for multiple encounters and an encounter sheet that is used for an individual encounter.

The structure of test reports is delineated. This includes types of information that should be provided. Information types can be divided between test structure/design and test results. Metrics were described, including metrics utilized by ASTM (2020) (e.g., risk ratio), metrics that provide an overview of overall encounter performance [e.g., Closest Point of Approach (CPA)], and metrics that provide information regarding performance during the DTEM components of DAA.

2.5.4 Lessons Learned

While the team learned a great deal as the overarching test plan and flight tests co-evolved (e.g., metrics to be used, methods for maintaining safety, etc.), perhaps the most important lesson was the overall approach to testing. DAA system testing could be conducted by emulating conditions experienced with real-world use cases (e.g., pipeline inspection) or by systematically varying factors that affect DAA system performance (e.g., encounter angle, intruder speed, etc.). Because use of real-world use cases produces results that likely could not be easily transferred to other environments/use cases, the latter approach is recommended and was developed in the overarching test plan. However, testing using the conditions associated with specific use cases could enable acceptance of certain DAA systems for those use cases (e.g., shielded operations).

3 FLIGHT-TEST REPORTS

3.1 UAF March 2019

3.1.1 Objectives

The objectives of this flight test were:

- Evaluate when alerts are provided from DAA systems versus human observers.
- Evaluate DAA systems in the context of real-world use cases (e.g., emulated pipeline inspection and survey).

3.1.2 Dates/Schedule

Tests were conducted during the week of 25-29 March 2019. The planned daily schedule is provided in Table 1.

Table 1. Planned daily schedule for the March 2019 UAF ACUASI campaign.

Local Time [Alaska Daylight Time]	Activity
8:00-9:00	Mission overview
9:00-9:45	Travel to range
9:45-10:00	Range and safety overview
10:00-10:30	Ground checks (communication, pre-flight)
10:30-2:25	Test flights
2:25-2:45	Pack up
2:45-3:30	Drive to UAF
3:30-4:00	Debrief

3.1.3 Location

Tests were conducted at the Poker Flat Research Range (https://www.pfrr.alaska.edu/content/welcome-poker-flat) and were conducted by the University of Alaska Fairbanks (UAF) Alaska Center for Unmanned Aircraft Systems Integration (ACUASI). The Poker Flat Research Range is illustrated in Figure 2.

Figure 2. Overhead view of the Poker Flat Research Range.

3.1.4 System Tested

Systems tested during this campaign were Echodyne ground-based radars, Iris EO system, and ADS-B.

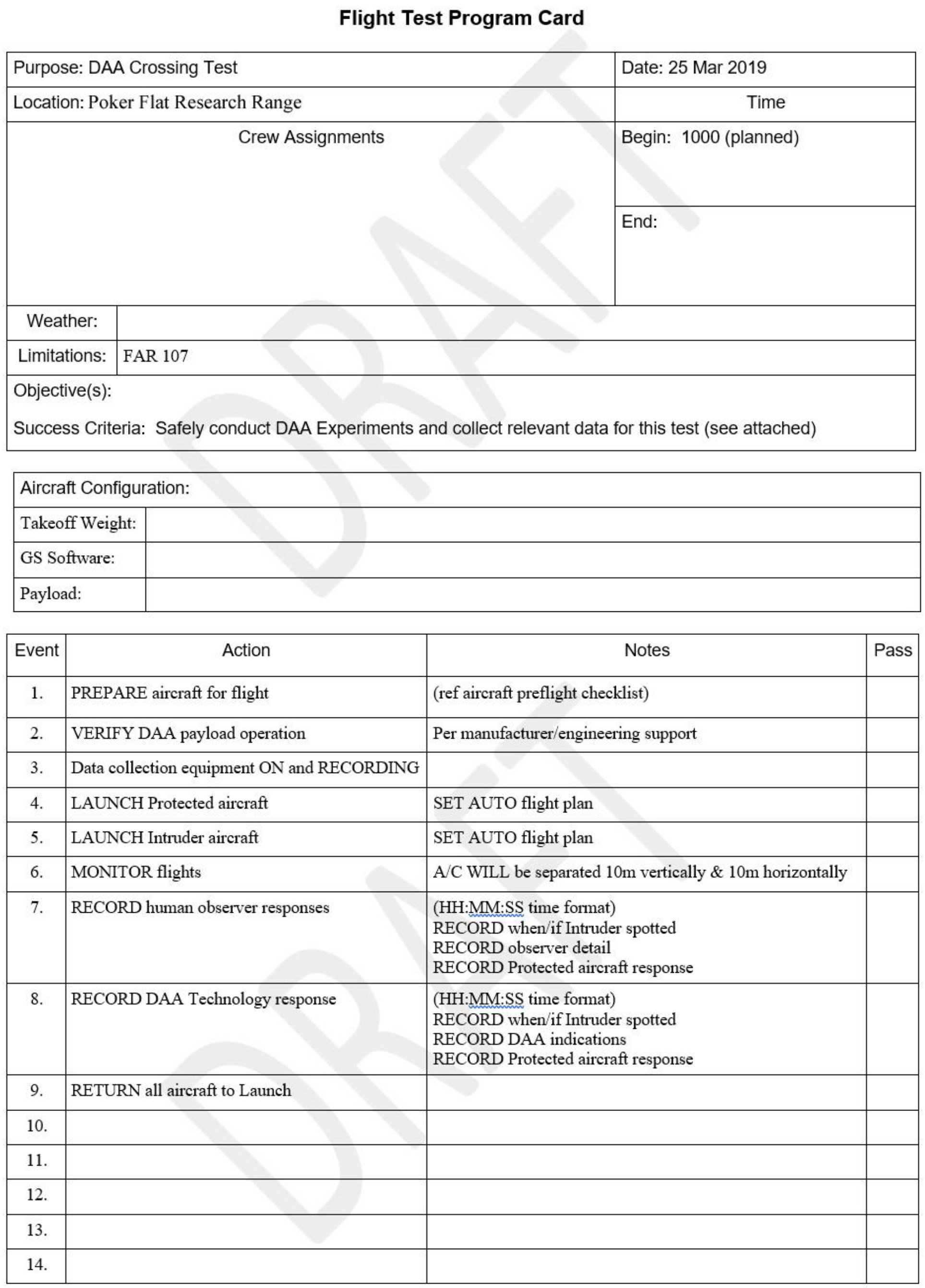
3.1.5 Test Plan Overview

The test plan was comprised of:

- Testing of detection component of DAA systems
- Encounters that were scenario-driven (use-case based—pipeline inspection and survey)
- 5 test profiles
- Ownship UA
- Varied intruders (fixed- and rotary-wing CA and UA)

3.1.6 Sample Test Cards

A sample test card used during this campaign is shown in Figure 3. It is noted that test cards evolved during A18 as the team learned from previous test campaigns.



Flight Test Program Card

Purpose: DAA Crossing Test	Date: 25 Mar 2019
Location: Poker Flat Research Range	Time
Crew Assignments	Begin: 1000 (planned)
	End:

Weather:	
Limitations:	FAR 107
Objective(s):	
Success Criteria: Safely conduct DAA Experiments and collect relevant data for this test (see attached)	

Aircraft Configuration:	
Takeoff Weight:	
GS Software:	
Payload:	

Event	Action	Notes	Pass
1.	PREPARE aircraft for flight	(ref aircraft preflight checklist)	
2.	VERIFY DAA payload operation	Per manufacturer/engineering support	
3.	Data collection equipment ON and RECORDING		
4.	LAUNCH Protected aircraft	SET AUTO flight plan	
5.	LAUNCH Intruder aircraft	SET AUTO flight plan	
6.	MONITOR flights	A/C WILL be separated 10m vertically & 10m horizontally	
7.	RECORD human observer responses	(HH:MM:SS time format) RECORD when/if Intruder spotted RECORD observer detail RECORD Protected aircraft response	
8.	RECORD DAA Technology response	(HH:MM:SS time format) RECORD when/if Intruder spotted RECORD DAA indications RECORD Protected aircraft response	
9.	RETURN all aircraft to Launch		
10.			
11.			
12.			
13.			
14.			

Figure 3. Example test card used during the March 2019 UAF ACUASI campaign.

3.1.7 Summary of Results

Results indicated that the DAA systems commonly detected intruders before ground observers, though not always. If data were available, ADS-B outperformed ground observers, as expected.

3.1.8 Lessons Learned

The primary lessons from this initial flight test campaign were:

- Evaluating DAA systems by systematically varying factors that affect their performance is generally favored relative to evaluating them by emulating conditions experienced with real-world use cases (e.g., pipeline inspection).
- Greater distances are needed to ensure safe separation of aircraft during testing.

3.2 NMSU July 2019

The New Mexico State University (NMSU) conducted a number of DAA flight tests addressing part of Task 6, Subtask 6a, conducting flight tests of a candidate DAA system. Multiple different flight tests of various DAA systems were part of the testing conducted. A report titled, "A18 – Small UAS Detect and Avoid Requirements Necessary for Limited Beyond Visual Line of Sight (BVLOS) Operations: Task 6 NMSU July 2019 Testing of Candidate DAA System Test Report" was submitted to the FAA on 5 December 2019, and after multiple exchanges with the FAA, a revised report was submitted on 16 April 2020 (Cathey et al. 2020). This report documented the planning, testing, and results of flight testing at the NM UAS Flight Test Site in July 2019 at the Jornada Experimental Range, North of Las Cruces, NM. The following sections provide a summary of this flight testing.

3.2.1 Objectives

The approach was to set up various encounters of a UAS equipped with an onboard DAA system with different crewed and uncrewed intruders. A focus of this testing was to assess the sensor system for sensor performance, rather than a complete DAA system that included maneuvers. The testing approach was to present various intruder vehicles in different geometries. The testing included two different CA, a light sport and an ultralight, as well as a small UAS. The DAA system was placed on both a multi-copter as well as a fixed wing aircraft.

3.2.2 Dates/Schedule

The overall arc of this round of testing took place over a four-day period from Monday, July 15, to Thursday, July 18, 2019. The four days were set up with the system checks to start on day one, and then different encounter scenarios on the follow days. A short summary of the events is as follows:

- Day 1 (15 July 2019) – Review of mission plan and check flights of vehicles
- Day 2 (16 July 2019) – Multi-copter with Iris system installed, flights at different altitudes, and light sport intruder encounters at various angles and crossing patterns
- Day 3 (17 July 2019) – Fixed wing with Iris system installed, flights at different altitudes, and light sport intruder encounters at various angles and cross patterns
- Day 4 (18 July 2019) – Multi-copter with Iris system installed, flights at different altitudes, ultralight intruder encounters at various angles and cross patterns, and pop ups with small UAS

3.2.3 Location

The testing took place at the Jornada Experimental Range near Las Cruces, NM. This location is on gated access United States Department of Agriculture property where the NMSU Flight Test Site regularly performs operations. This is a remote area with only a limited number of personnel in the area. The location is shown in Figure 4.

Figure 4. Test location, just North of Las Cruces, NM, for the July 2019 NMSU campaign.

This location has been used by the NMSU UAS Flight Test Site team as a primary test location. It is just to the West of the White Sands restricted airspace. There are limited overhead flights of manned aircraft. The area has a dirt airstrip that was used for flights, provided a visual geometric marker for the intruder pilots to align encounter runs, and as an emergency landing location if needed for the manned aircraft (Figure 5).

Figure 5. Dirt runways on the Jornada Experimental Range.

NMSU has a trailer on site for flight control. Because of the large number of participants and observers, the team added a second "personnel trailer" with air conditioning, power, tables, chairs, coffee, microwave, mini-fridge, and a Wi-Fi hot spot. Sunshades, generators, and designated safety areas for personnel were provided. Images of the test setup location are provided in Figure 6.

Figure 6. Trailer setup.

3.2.4 System Tested

An airborne visual system from Iris Automation called Casia was used on the UAS's for this testing. The Casia DAA hardware is shown in Figure 7. Previous testing of this system was completed by the University of Alaska Fairbanks team. The planning to test this specific system was coordinated with the FAA in advance. The system consists of the Casia Module (processing unit) and a camera. The system is integrated into an aircraft and provides situational awareness via DAA technology (https://www.irisonboard.com/). The system tested was their originally released "standard design", and has a 1.6 MegaPixel (MP) camera. Iris advertised that the system had a 65° x 50° field of view, 416 m (1,365 ft) average detection range, and a system mass of 73 g.

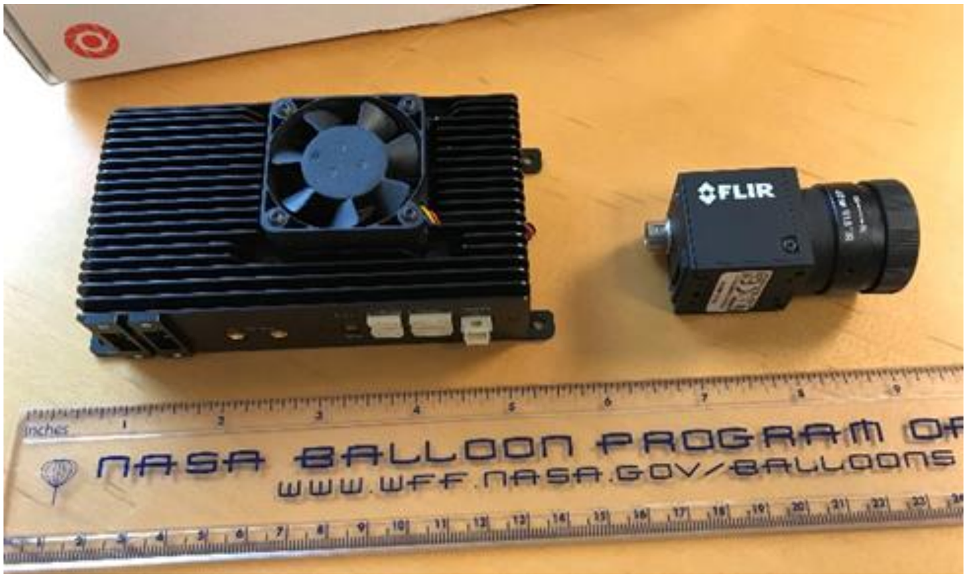


Figure 7. The Casia system.

It is important to note the advertised horizontal FoV of 65°. The specific test planning was designed around testing within, to the edges of, and beyond this FoV. This is clear in the geometries of the testing shown in the testing approach section below. This is noted here because Iris has recently released an improved system with a wider FoV and greatly increased detection range. It has a much-improved camera, updated software, and a few other improvements. For all of these tests, the following system was used:

- System Description – Original Casia System
- Software – Software Version 20.1
- Camera – 1.6 MP, Standard Camera

A number of different flight assets were used as part of these tests. Iris Automation brought primary and back up aircraft for both fixed wing and multi-copter platforms. The two different platforms used by Iris Automation that were equipped with the Iris Casia DAA were:

- Ready Made RC (RMRC) Anaconda (fixed wing)
- Straight Up Imagery (SUI) Endurance (multi-copter)

NMSU flew three different intruders against the Casia DAA system. The first was a manned light sport aircraft and the second was an ultralight aircraft. Both of these vehicles were flown with a pilot and co-pilot that served as an onboard Visual Observer (VO). The last day of testing, the NMSU team used a small multi-copter to simulate popup encounters. The three different platforms used by NMSU were:

- CTLS Light Sport aircraft
- Spyder Ultralight aircraft
- 3D Robotics Solo

Images of all of these vehicles are provided in Figures 8-11.

Figure 8. NMSU’s CTLS light sport aircraft.

Figure 9. NMSU’s Spyder ultralight aircraft.

Figure 10. Iris's RMRC Anaconda (fixed wing).

Figure 11. Iris's SUI Endurance (multi-copter) and NMSU's 3D Robotics Solo.

3.2.5 Test Plan Overview

The plans for the initial round of testing were provided to the FAA in two complimentary formats for review. The first was a text description of the "DAA System Encounter Scenarios" and the second was a PowerPoint presentation titled "A18 Encounters rev1". The "DAA System Encounter Scenarios" had the goal of mapping detection range under various encounter scenarios that included Head On, Overtaking, Cross FoV, and Pop-Up Encounters.

The overall approach utilized the following:

- CA at 500 ft elevation
- Lateral separation of (generally) ~100 ft
- UA with Iris Onboard will be at 100 ft, 200 ft, and then 400 ft elevation
- UA with Iris Onboard flown along a straight track (direction determined on flight day – cardinal direction, along dirt runway, or in/out of the wind) nominally 100 ft to 500 ft long (aircraft dependent) with a minimal loop at the end of the track

3.2.5.1 CTLS and Multi-Rotor Tests

The conditions for these tests were:

1) Circle Pattern for system check (start of each flight day)
    a. CA
        i. CTLS
        ii. ~100 kts
        iii. 500 ft altitude
        iv. Several circles of varied diameter to ensure system check
    b. UA
        i. Multi-copter
        ii. 5 m/sec along encounter line
        iii. 100 ft altitude
2) Head-On Encounters
    a. CA
        i. CTLS
        ii. ~100 knots
        iii. 500 ft altitude
        iv. Flight along one side of runway (ex. only on the North or West sides) as defined by encounter direction based on conditions
    b. UA – Multi-copter
        i. 5 m s^{-1} along encounter line
        ii. 100 ft altitude
        iii. Flight along one side of runway (ex. only on the South or East sides)
    c. Profile
        i. View head on and trigger
        ii. Stop, rotate vehicle 180°, and procced again at 5 m s^{-1}
        iii. Attempt to watch vehicle exit FoV
3) Possible repeat the above with approach from opposite/other direction
4) Repeat with different oblique angles
    a. Encounters at 10°, 20°, 30°, and 40° off direct head on
5) Repeat steps above with UAS at 200 ft altitude (possible that only a portion of these steps will be repeated at this altitude)

6) Repeat steps above with UAS at 400 ft altitude
7) Possibly repeat selected steps above with multi-rotor in fixed position (i.e., no 5 m s^{-1} forward speed)
8) Overtaking Encounters
    a. CA
        i. CTLS
        ii. ~100 knots
        iii. 500 ft altitude
        iv. Flight along one side of runway (ex. only on the North or West sides) as defined by encounter direction based on conditions
    b. UA
        i. 5 m s^{-1} along encounter line
        ii. 100 ft altitude
        iii. Flight along one side of runway (ex. only on the South or East sides)
    c. Profile
        i. View 180° out from head on
        ii. Trigger and attempt to watch vehicle exit FoV
9) Repeat with different oblique angles
    a. Encounters at 10°, 20°, 30°, and 40° off direct head on
10) Repeat steps above with UAS at 200 ft altitude (possible that only a portion of these steps will be repeated at this altitude)
11) Repeat steps above with UAS at 400 ft altitude
12) Possibly repeat selected steps above with multi-rotor in fixed position (i.e., no 5 m s^{-1} forward speed)
13) Cross FoV
    a. CA
        i. CTLS
        ii. ~100 knots
        iii. 500 ft altitude
        iv. Flight at various distances beyond UAS track line
            1. 500 ft
            2. 1,000 ft
            3. Others possible
    b. UA—Multi-copter
        i. 5 m s^{-1} along encounter line
        ii. 100 ft altitude
        iii. Flight along one side of runway (ex. only on the South or East sides)
    c. Profile
        i. View head on and trigger
        ii. Halt vehicle and with no rotation, attempt to watch vehicle exit FoV
14) Repeat steps above with UAS at 200 ft altitude
15) Repeat steps above with UAS at 400 ft altitude
16) Possibly repeat selected steps above with multi-rotor in fixed position (i.e., no 5 m s^{-1} forward speed)

Additional retests can be performed as desired.

3.2.5.2 CTLS and Fixed-Wing UAS

The conditions for these tests were:

17) Circle pattern check (see 1 above)
18) Repeat all or selected steps 2 to 16 using CTLS as CA and small fixed-wing UAS with Iris onboard

3.2.5.3 Ultralight Spyder and both Multi-Rotor and Fixed wing UAS's

The conditions for these tests were:

19) Circle pattern check (see 1 above)
20) Repeat selected steps 2 to 16 using Ultralight Spyder as CA and multi-copter and small fixed-wing UAS with Iris onboard

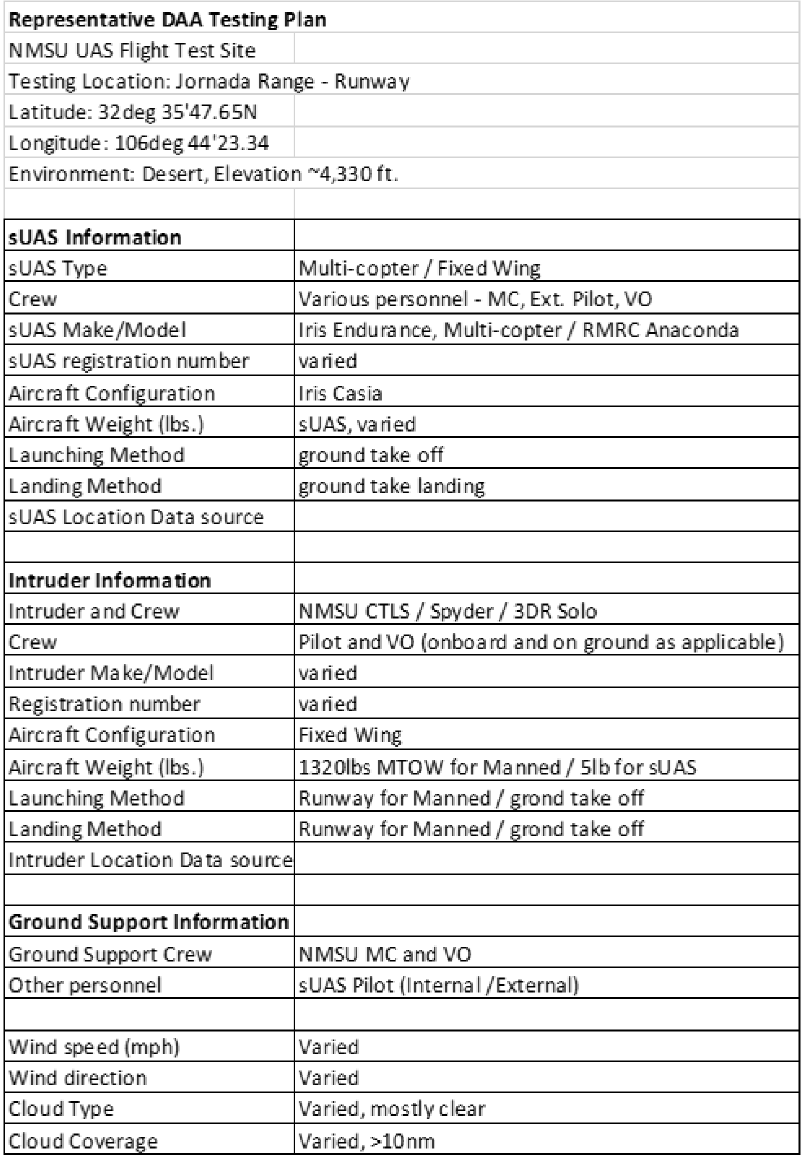
3.2.5.4 Pop-up Encounters

The conditions for these tests were:

- Pop-up sUAS will be used at the end of each day or during periods where there are issues with the CA
- Various locations within the detection system FoV will be employed
    - UAS altitudes of 100 ft, 200 ft, and 400 ft
    - Pop-up ranges from 500 to 1000 ft (or more) at various positions within the detection wedge

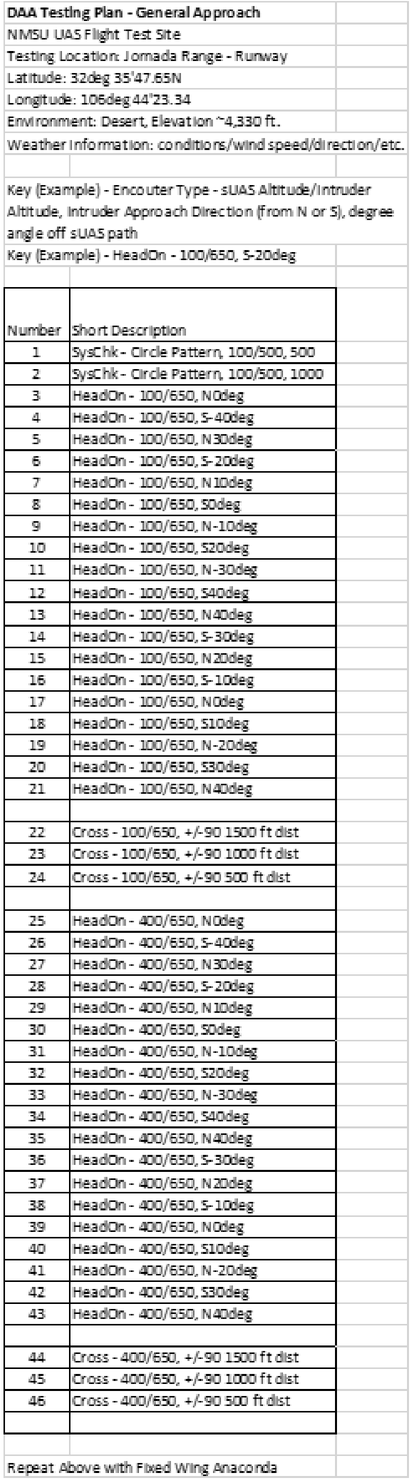
3.2.6 Sample Test Cards

As noted above, the planning was provided to the FAA in two documents, the "DAA System Encounter Scenarios" and the PowerPoint presentation "A18 Encounters rev1". Initial test card formats provided to the FAA are shown in Figures 12 and 13.



Representative DAA Testing Plan	
NMSU UAS Flight Test Site	
Testing Location: Jornada Range - Runway	
Latitude: 32deg 35'47.65N	
Longitude: 106deg 44'23.34	
Environment: Desert, Elevation ~4,330 ft.	
sUAS Information	
sUAS Type	Multi-copter / Fixed Wing
Crew	Various personnel - MC, Ext. Pilot, VO
sUAS Make/Model	Iris Endurance, Multi-copter / RMRC Anaconda
sUAS registration number	varied
Aircraft Configuration	Iris Casia
Aircraft Weight (lbs.)	sUAS, varied
Launching Method	ground take off
Landing Method	ground take landing
sUAS Location Data source	
Intruder Information	
Intruder and Crew	NMSU CTLS / Spyder / 3DR Solo
Crew	Pilot and VO (onboard and on ground as applicable)
Intruder Make/Model	varied
Registration number	varied
Aircraft Configuration	Fixed Wing
Aircraft Weight (lbs.)	1320lbs MTOW for Manned / 5lb for sUAS
Launching Method	Runway for Manned / grond take off
Landing Method	Runway for Manned / grond take off
Intruder Location Data source	
Ground Support Information	
Ground Support Crew	NMSU MC and VO
Other personnel	sUAS Pilot (Internal /External)
Wind speed (mph)	Varied
Wind direction	Varied
Cloud Type	Varied, mostly clear
Cloud Coverage	Varied, >10nm

Figure 12. Example test “metadata” card for the NMSU July 2019 campaign.



DAA Testing Plan - General Approach
NMSU UAS Flight Test Site
Testing Location: Jornada Range - Runway
Latitude: 32deg 35'47.65N
Longitude: 106deg 44'23.34
Environment: Desert, Elevation ~4,330 ft.
Weather Information: conditions/wind speed/direction/etc.

Key (Example) - Encouter Type - sUAS Altitude/Intruder Altitude, Intruder Approach Direction (from N or S), degree angle off sUAS path
Key (Example) - HeadOn - 100/650, S-20deg

Number	Short Description
1	SysChk - Circle Pattern, 100/500, 500
2	SysChk - Circle Pattern, 100/500, 1000
3	HeadOn - 100/650, N0deg
4	HeadOn - 100/650, S-40deg
5	HeadOn - 100/650, N30deg
6	HeadOn - 100/650, S-20deg
7	HeadOn - 100/650, N10deg
8	HeadOn - 100/650, S0deg
9	HeadOn - 100/650, N-10deg
10	HeadOn - 100/650, S20deg
11	HeadOn - 100/650, N-30deg
12	HeadOn - 100/650, S40deg
13	HeadOn - 100/650, N40deg
14	HeadOn - 100/650, S-30deg
15	HeadOn - 100/650, N20deg
16	HeadOn - 100/650, S-10deg
17	HeadOn - 100/650, N0deg
18	HeadOn - 100/650, S10deg
19	HeadOn - 100/650, N-20deg
20	HeadOn - 100/650, S30deg
21	HeadOn - 100/650, N40deg
22	Cross - 100/650, +/-90 1500 ft dist
23	Cross - 100/650, +/-90 1000 ft dist
24	Cross - 100/650, +/-90 500 ft dist
25	HeadOn - 400/650, N0deg
26	HeadOn - 400/650, S-40deg
27	HeadOn - 400/650, N30deg
28	HeadOn - 400/650, S-20deg
29	HeadOn - 400/650, N10deg
30	HeadOn - 400/650, S0deg
31	HeadOn - 400/650, N-10deg
32	HeadOn - 400/650, S20deg
33	HeadOn - 400/650, N-30deg
34	HeadOn - 400/650, S40deg
35	HeadOn - 400/650, N40deg
36	HeadOn - 400/650, S-30deg
37	HeadOn - 400/650, N20deg
38	HeadOn - 400/650, S-10deg
39	HeadOn - 400/650, N0deg
40	HeadOn - 400/650, S10deg
41	HeadOn - 400/650, N-20deg
42	HeadOn - 400/650, S30deg
43	HeadOn - 400/650, N40deg
44	Cross - 400/650, +/-90 1500 ft dist
45	Cross - 400/650, +/-90 1000 ft dist
46	Cross - 400/650, +/-90 500 ft dist

Repeat Above with Fixed Wing Anaconda

Figure 13. Example test script/plan for the NMSU July 2019 campaign.

The test card format evolved over time. The ones above are not in the 'Test Card' format which was developed later for this project. Similar information was included for the test planning. This round of testing was used as part of the basis for the later development of the standard test card format developed by the team for later test campaigns.

The encounter geometries were based on the Iris Casia's systems 65° FoV. The desire was to fly the UAS along a set line and then have the intruder aircraft enter the field of view at different angles relative to this flight path. The encounters were set to vary in 10° increments across the FoV from opposite directions. As the intruder entered the FoV, the UAS was to turn and watch the intruder exit the FoV to obtain an additional data point. A schematic of the encounter geometry with overlays of the planned flight location is shown in Figure 14.

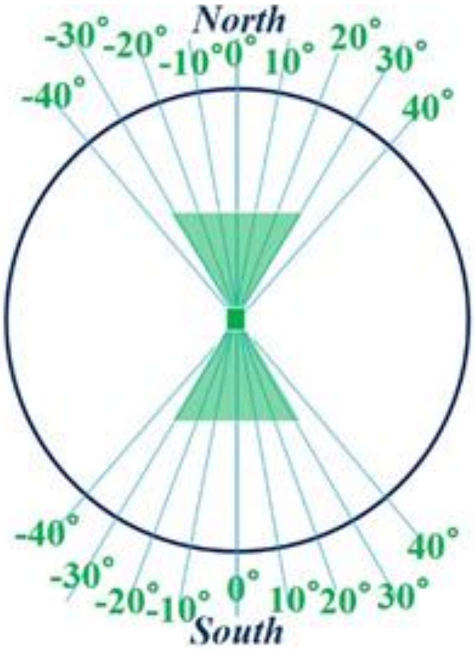


Figure 14. Encounter geometry with overlays of the planned flight location.

Taking into account the Iris system's detection range, the desire was to have the intruder aligned on the desired encounter geometry outside of the systems detection range. Intruder runs were set to be on course at ~2 mi out, well beyond the detection range (noted by the manufacturer as 416 m or 1,365 ft average detection range) of the system. Maintaining the exact geometries was not paramount since the desire was to prepare a system detection map. Focus was on detection and not avoidance maneuvers. The overall encounter geometry mapped onto the flight test location is provided in Figure 15, while Figure 16 shows an example multi-copter UAS flight path.

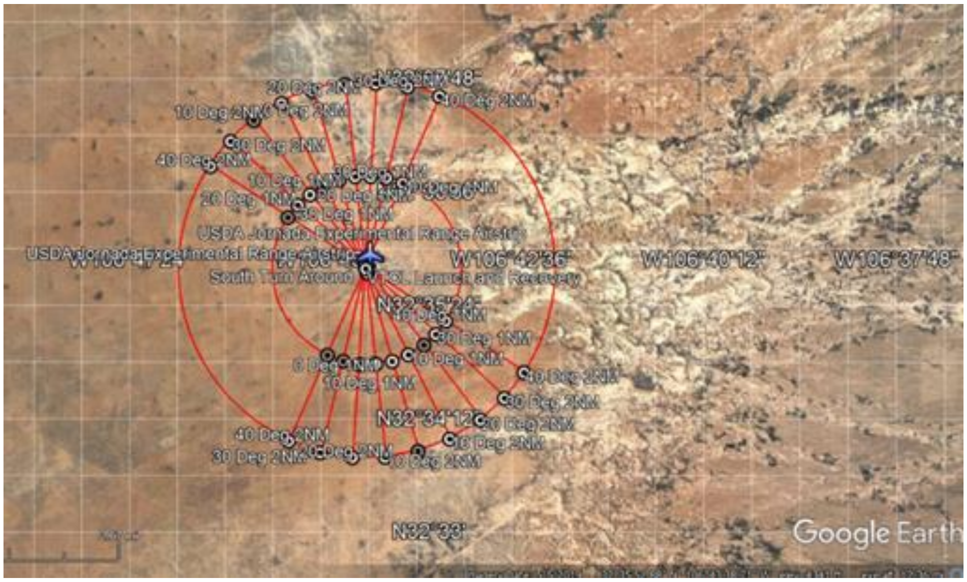


Figure 15. Overall encounter geometry mapped onto the flight test location.

Figure 16. Example multi-copter UAS flight path. The fixed wing UAS path doubles this length and loops at the ends.

3.2.7 Summary of Results

Detailed flight logs and plots for each flight day are included in Cathey et al. (2020). To provide a sample of the types of information presented, a few representative examples of the flight-testing information gathered are provided. A 1 and 2 mi square box was set up as reference for this testing with the 2 mi range as a point to ensure that the intruder was aligned on the intended encounter angle outside the detector range, and the 1 mi box defining the points where the encounters started. Plots of flights conducted on the first day of testing are provided in Figures 17 and 18.

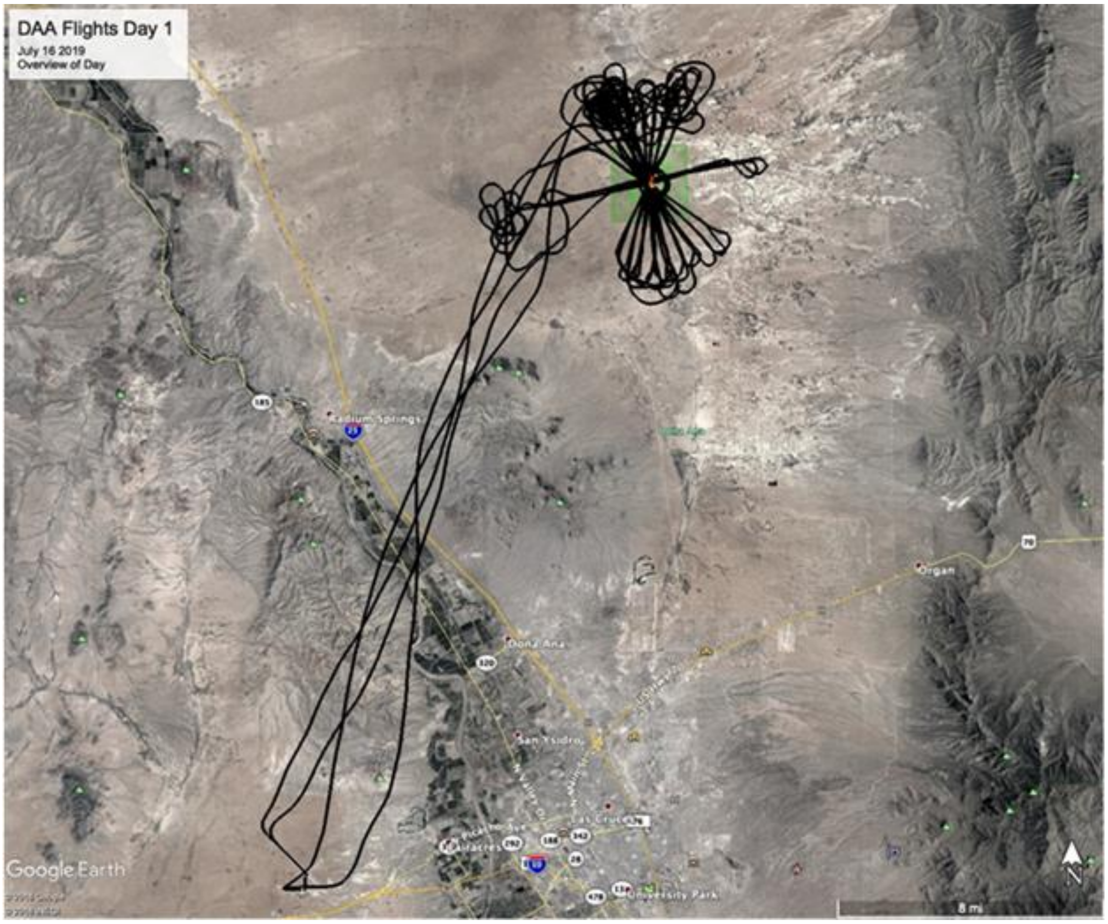


Figure 17. DAA testing flights on day 1—full flights.

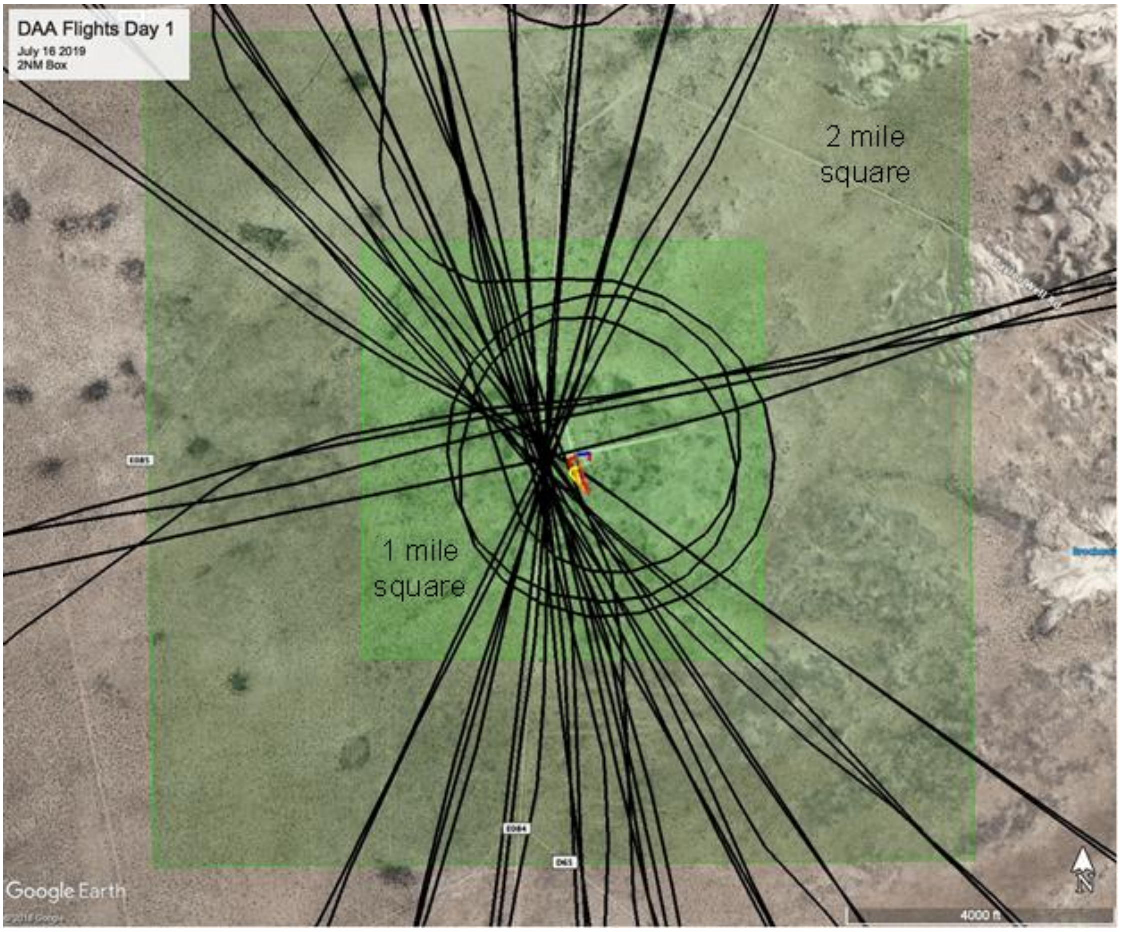


Figure 18. DAA testing flights on day 1—near testing location.

An example of the flight altitude profiles is provided in Figure 19, with both the encounter periods and DAA triggers highlighted. Two images of an encounter are provided in Figures 20 and 21.

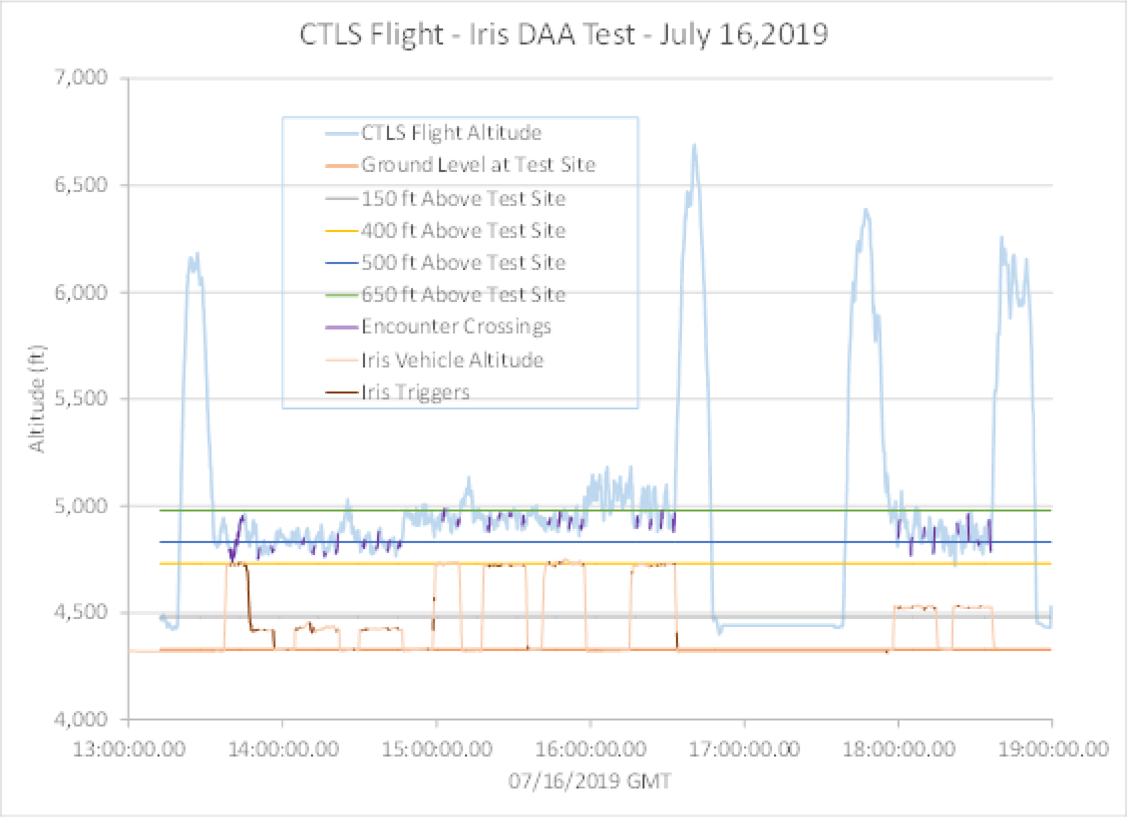


Figure 19. Day 1 flight altitudes. Encounter crossings and detections are highlighted.

Figure 20. Crossing encounter DAA test.

Figure 21. DAA test encounter after turn had been initiated.

Multiple pages of encounters were captured in a spreadsheet format that included the following information:

- Date
- DAA System
- DAA System Vehicle
- Intruder
- Time Intruder enters 1 nm box
- Time Intruder exits 1 nm box
- Encounter Type
- Encounter Geometry
- Flight Direction
- DAA Trigger Detection Time
- DAA Orientation 0=along flight path, CW angles
- Encounter Angle
- DAA Vehicle Lat at detect time
- DAA Vehicle Lon at detect time
- DAA Vehicle altitude at detect time
- Aprox. DAA Vehicle alt above ground
- Closest Intruder Time Stamp
- Intruder Vehicle Lat at detect time
- Intruder Vehicle Lon at detect time
- Intruder Vehicle altitude at detect time
- Detection Range (km)
- Detection Range (ft)
- Notes

These files are not provided within this report because of the size of the files.

A mapping of the detections by day is provided in Figure 22. These have all been nominalized to distances and encounter angles as if the DAA system was stationary and represents the origin point. The distances at which the DAA system detected the intruder are shown. An overlay on this shows a function of the encounter angle. Detections along the flight track, represented by the 0° angle, represent most of the detections. The other encounter angles show clear detections mostly along the 10°, 20°, and 30° radials on either side of this center line. A few detections occurred outside these ranges as well. Essentially, Figure 22 is a map of all of the detections shown in summary tables. The crossing patterns, circular detection patterns, and pop-up flights are included but are difficult to identify with this full mapping.

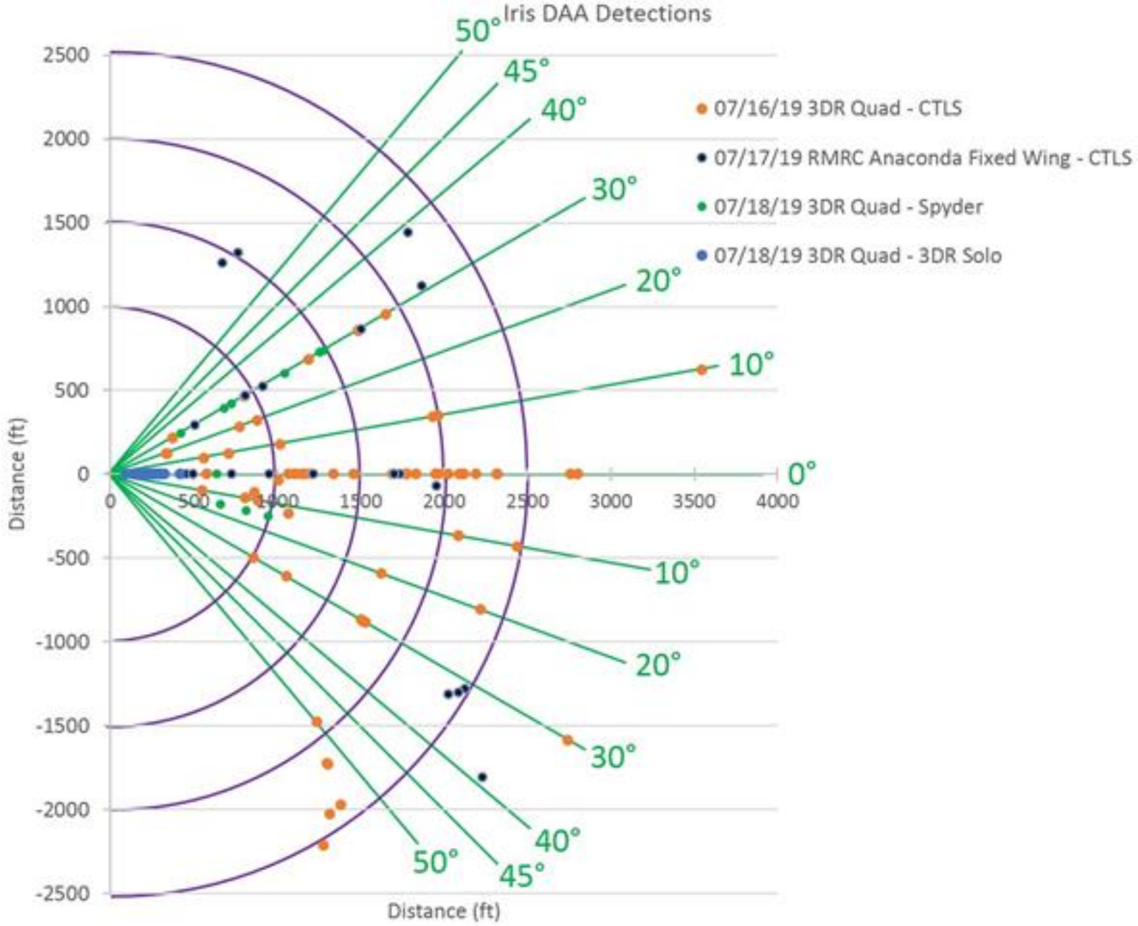


Figure 22. Mapping of Iris DAA detections based on encounter angle and distance.

An added complication was that the UAS was indicating AGL altitudes and the CA provided Mean Sea Level (MSL) altitudes. A post flight review of the vertical separation was completed to assess the vertical separation at CPA. a vertical separation distance of 250 ft was set for the testing (no margins were used—just 250 ft). It was concluded that the flights did violate this vertical separation distance. A summary of vertical separations at CPA each day for the is:

Day 1 – CTLS versus multi-copter
  32 total passes (13 passes were < 250 ft)
  435.92 ft Max
  291.66 ft Average
  163.72 ft Min
Day 2 – CTLS versus fixed wing
  24 total passes (5 passes were < 250 ft)
  467.29 ft Max
  324.26 ft Average
  189.84 ft Min
Day 3 – Spyder Ultralight versus multi-copter
  4 total passes (3 passes were < 250 ft)
  253.23 ft Max
  231.88 ft Average
  211.19 ft Min
Summary of all Crossings
  60 total passes (21 passes were < 250 ft)
  467.29 ft Max
  300.72 ft Average
  163.72 ft Min

The less than 250 vertical feet violations are a lesson learned for future testing. Most of these closest points of approach had significant lateral separation (> 1,000 to 1,500 ft) as well, but were within 2,000 ft lateral separation.

This testing design provided a large number of encounter geometries and configurations to test the Iris DAA system. The different flight assets provided a number of different presentations for detection. It was noted that some false triggers occurred when the system was first turned on, during the flights at lower altitudes, and on other occasions. The flights at higher altitude had fewer false detections. A number of times the aircraft was not oriented along the desired track, and this resulted in fewer detections than could have been obtained with the testing. This also was a lesson learned.

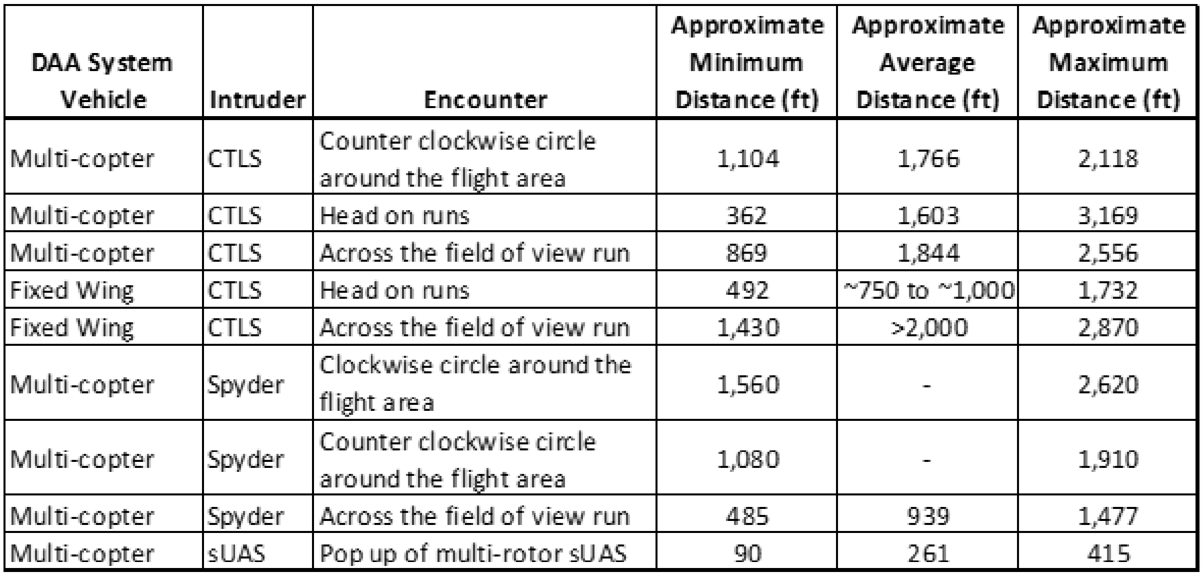
The various encounter scenarios are different and it is difficult to compare results for different aircraft in a head-on approach, a cross-FoV approach, and a pop up encounter. Each represent different aircraft, geometries, and conditions. As noted, the flight altitude of the UAS carrying the DAA system has an impact as well. The following are a few summary points for detection distances:

- Multi-copter with CTLS in a counter clockwise circle around the flight area – Maximum distance of ~2,118 ft and minimum distance of ~1,104 ft, with an average detection distance of ~1,766 ft.
- Multi-copter with CTLS in head on runs – Maximum distance of ~3,169 ft and minimum detection distance of ~362 ft, with an average detection distance of ~1,603 ft.
- Multi-copter with CTLS in across the field of view runs – Minimum distance of ~869 ft and a maximum of 2,556 ft, with an average of 1,844 ft detection distance.
- Fixed Wing with CTLS in head on runs – Detections were in the ~492 ft to over ~1,732 ft range. Most were in the ~750 to ~1,000 ft range.

- Fixed Wing with CTLS across the field of view runs – Detections between ~1,430 and over ~2,870 ft. Most were in the > 2,000 ft range.
- The Iris system had no issues identifying the manned Spyder ultralight at ranges beyond 2,500 ft from the DAA system location.
- Multi-copter with Spyder in in a clockwise circle around the flight area – Detections ranged from ~2,160 ft to the East, ~2,030 ft to the West, ~2,325 ft to the North, and ~1,560 ft to the South. The furthest distance in the "fishhook" to the south was ~2,620 ft.
- Multi-copter with Spyder in in a counter clockwise circle around the flight area – Detections ranged from ~1,450 ft to the East, ~1,910 ft to the West, ~1,815 ft to the North, and ~1,080 ft to the South.
- Multi-copter with Spyder – Detection distances were between ~1,080 ft and up to ~2,620 ft.
- Multi-copter with Spyder in across the field of view runs – The Spyder was detected at ranges between ~485 ft to ~1,477 ft, with an average distance of 939 ft.
- All of the sUAS pop up flights were detected at ranges from ~90 ft to ~415 ft, with an average of ~261 ft, and generally at altitudes comparable to the Iris aircraft.

In tabular form, a summary of the DAA system encounter parameters is provided in Table 2.

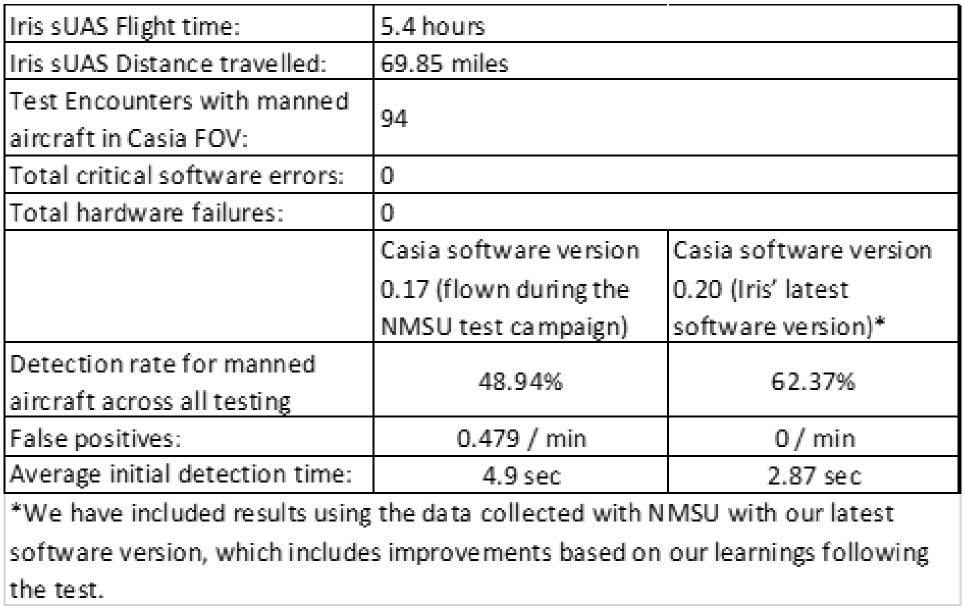
Table 2. Summary of DAA test encounter parameters for the July 2019 NMSU campaign.



DAA System Vehicle	Intruder	Encounter	Approximate Minimum Distance (ft)	Approximate Average Distance (ft)	Approximate Maximum Distance (ft)
Multi-copter	CTLS	Counter clockwise circle around the flight area	1,104	1,766	2,118
Multi-copter	CTLS	Head on runs	362	1,603	3,169
Multi-copter	CTLS	Across the field of view run	869	1,844	2,556
Fixed Wing	CTLS	Head on runs	492	~750 to ~1,000	1,732
Fixed Wing	CTLS	Across the field of view run	1,430	>2,000	2,870
Multi-copter	Spyder	Clockwise circle around the flight area	1,560	-	2,620
Multi-copter	Spyder	Counter clockwise circle around the flight area	1,080	-	1,910
Multi-copter	Spyder	Across the field of view run	485	939	1,477
Multi-copter	sUAS	Pop up of multi-rotor sUAS	90	261	415

As noted, this flight test report was provided to the FAA for review. Comments and feedback were provided to the authors. After completion of this report, two additional supplemental reports were provided to the FAA. The supplemental reports include "Casia Detect and Avoid System Stress Test Results Summary" and "July 2019 Iris DAA System Testing Results Comparison" (dated 18 February 2020 – revised 16 April 2020) for further performance assessment. These are not fully repeated here, and can provide some additional information related to posttest assessment. Key findings are provided in Table 3.

Table 3. Iris detection results for July 2019 NMSU campaign.



Iris sUAS Flight time:	5.4 hours	
Iris sUAS Distance travelled:	69.85 miles	
Test Encounters with manned aircraft in Casia FOV:	94	
Total critical software errors:	0	
Total hardware failures:	0	
	Casia software version 0.17 (flown during the NMSU test campaign)	Casia software version 0.20 (Iris' latest software version)*
Detection rate for manned aircraft across all testing	48.94%	62.37%
False positives:	0.479 / min	0 / min
Average initial detection time:	4.9 sec	2.87 sec

*We have included results using the data collected with NMSU with our latest software version, which includes improvements based on our learnings following the test.

The FAA reviewers desired additional insight into the internal sensor processing. While this was not an intent of this effort, manufacturer-provided system information was supplied to the FAA for review.

3.2.8 Lessons Learned

Numerous lessons learned were gained as part of this testing. These lessons were shared within the A18 research team and with the FAA. Some of these lessons learned resulted in onsite changes in real time to the testing process. Some were beneficial toward making changes in future testing. Some of these changes were immediately implemented in the flight testing that followed in Alaska. This bullet list captures the post testing list of lessons learned:

- Better defined mission approach in advance:
  - Approach was developed in advance and reviewed between Iris and NMSU
  - Review by all stake holders
  - Revise as necessary
  - Define options
  - Ensure flexibility and fall back plans (Option B, C, etc.)
- Mission status
  - Highlight status and where in the sequence during the mission
  - Call out at start of various phases (e.g., noting where in script)
- Ensure using consistent data references – e.g., MSL or barometric altitude
- Ensure better transfer of mission status to observers
  - External speaker to track commanding and detections
  - Visual of command screens (TV or computer console)
  - Status board on which all can see progress

- Post brief as soon as possible after – standing in less than comfortable conditions (crammed in a trailer, outside in the sun, or in a cold locations with no chairs) makes the inputs short, relevant, and succinct.
- Data collection
    - Provide sample data files in advance to ensure compatibility and that teams know what to expect
    - Download data each day if possible
    - Ensure download process and infrastructure can handle the quantity of data in a timely fashion
- Flight altitudes and separation
    - Originally planned for UAS at 400 ft and Intruder at 500 ft and 100 ft lateral separation
    - This was to address FAA's desire to have encounters the same as with previous flights in Alaska
    - Informed on site by the FAA that we needed to have 250 ft vertical separation to be consistent with planned FAA regulations
    - For UAS flights at 400 ft the Intruder altitude was changed to 650 ft
    - Need to ensure clarity on approaches for crossing and distance
- Site and personnel logistics
    - Mission support photo board
    - Internet connection at site (used a Hot Spot)
    - Water, coffee, and snacks
    - Provide food/lunch for the flight teams (so they can concentrate on the flight missions)
    - Metal stair railings were hot – wrap in white tape
    - There was an issue with the circuit breaker in the command trailer when the battery charger was plugged in—charger was moved outside near generator under a tent
    - Issue with Air Conditioner (AC) in command trailer
    - Could not run both AC's in the support trailer
    - Let attendees know that the road to the test location is gravel and dirt and that they may want to plan their rental vehicles accordingly
- Part 107 interpretation
    - There was an interpretation difference between operations and the FAA in relation to Part 107
        - Team operated on day 1 with the Pilot In Charge (PIC) inside the command trailer
        - Day 2 the FAA stated that that procedure was not valid and that the PIC had to have eyes directly on the UAS
        - It was noted that the preamble to Part 107 allows for the PIC to "have the ability" and that many others operate this way
        - This is a point for future clarification
        - To not shut operations down over this point, the decision was made to change the PIC to an external pilot for remaining missions
- Intruder altitudes
    - Intruder pilots were instructed to fly at a nominal altitude that was 250 ft above the sUAS altitude. This altitude did not include any margin for the 250 ft vertical

    separation and did not account for other flight variables like wind, updrafts, calibration errors, etc. Targeting a specific vertical separation during encounters needs to include margins and based upon the data gathered, it is recommended that for future testing the nominal vertical separation be at least 350 ft.

- Other
    - Appeared on the first day that the N to S trigger direction was different/better than the S to N direction
    - Appeared with a flight or two that the mission started late on the track – post flight data to assess
    - Question arose regarding how flight is handed off between pilots

A few conclusions can be drawn from the comparisons of the NMSU and Iris data:

- Not all detections in the NMSU processed data would result in an avoidance maneuver
- When detections occurred, the ranges for the minimum, average, and maximum were not much different between the two sets of results
- The average detection distance between the Iris and NMSU data processing was ~14%, with Iris's predicted range being slightly less
- The average detection range was between 1,149.6 and 1,312.3 ft
- The number of false positives with the older Casia software was much higher
- The software revision improved detections and reduced false positives
- The system did not perform as well at the lower altitudes (< 200 ft AGL)—this was noted by both NMSU and Iris
    - The system performed better at higher altitudes (300 to 400 ft AGL)
- The Iris system had no issues identifying the manned Spyder ultralight at ranges beyond 2,500 ft from the DAA system location (this was the first time the Iris system had tried to detect an ultralight)
- During the sUAS versus sUAS flights, detections of the sUAS occurred every encounter even though the system was not tuned specifically for detecting sUAS

3.3 UAF August 2019

A detailed report for this campaign is provided by Remmert and Purdy (2020). The following provides a high-level overview of this campaign.

3.3.1 Objectives

The objectives for this campaign were:

- Further development of a systematic approach to evaluating DAA systems
- Evaluate the efficacy of the Iris Casia EO system

3.3.2 Dates/Schedule

Testing occurred during 19-22 August 2019. The planned daily schedule was similar to that used during the March 2019 UAF ACUASI campaign.

3.3.3 Location

Testing occurred at the same location as used during the March 2019 UAF ACUASI campaign—the Poker Flat Test Range. This testing location is illustrated in Figure 2.

3.3.4 System Tested

The Iris Casia system was used during this campaign. This system had the following characteristics:

- System Software revision 0.19.0.64
- Camera – 1.6 MP FLIR Blackfly S 65° horizontal and 50° vertical FoV
- Camera Lens: Arecont Vision MPL4.0 wide angle

While the analysis utilized data collected with the Iris Casia system, data were also collected using ground-based Echodyne radars.

3.3.5 Test Plan Overview

The test plan consisted of:

- Testing of the detection component of the Iris Casia system
- Encounters that were scenario-inspired but that involved numerous encounter geometries
- Execution of a total of 10 test profiles
- Use of 2 ownship UA
    - The fixed-wing Rightwing Drak
    - The Endurance multi-copter
- Use of 4 intruders
    - The ACUASI S1000 multi-copter [Da-Jiang Innovations (DJI) airframe with Pixhawk II autopilot] UA
    - Fixed-wing Helio Courier 295 CA
    - Fixed-wing Cessna 206 CA
    - Rotary-wing Robinson R44 CA

3.3.6 Sample Test Cards

Details regarding the 10 test scenarios are provided by Remmert and Purdy (2020). Test cards had formatting similar to those used during the March 2019 UAF ACUASI campaign. An example scenario is shown in Figure 23.

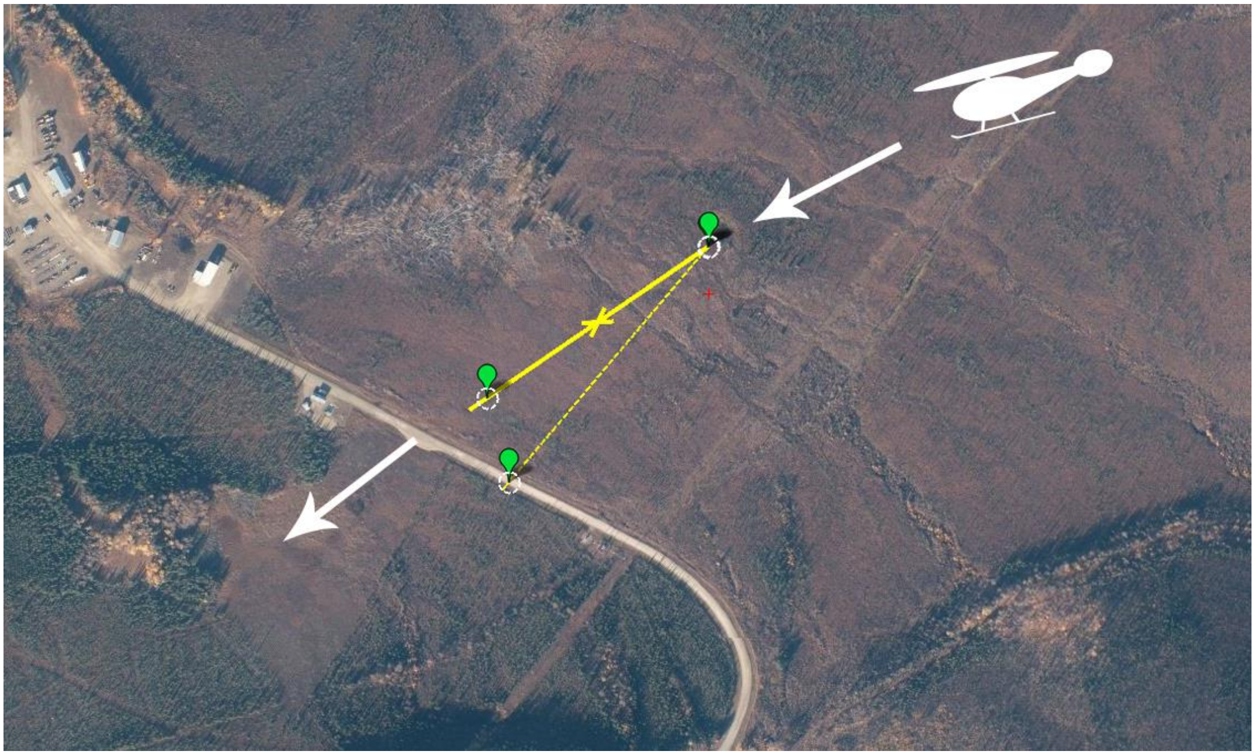


Figure 23. Example scenario (closing head-on scenario) utilized during the August 2019 UAF ACUASI campaign. The solid yellow line indicates the UA flight path, the white figure and arrows indicate the intruder and its flight path, and the dashed yellow line indicates a sight-line for a ground-based Echodyne radar.

3.3.7 Summary of Results

One interesting aspect of this effort was use of VOs to determine when an encounter occurred and the DAA system should have detected an intruder. To assist the VOs, ADS-B data were provided to them. Given this, rough Probability of Detection values could be derived (Table 4). These values are very rough and could depend strongly on the VOs. However, given these results, a few properties of the Casia sensor are apparent. First is the fairly narrow FoV of the sensor; tests heavily dependent upon seeing the aircraft across a wide range of angles like the Hover Perpendicular Crossing and Concentric Circles had poor detection rates. Second is the dwell time before DAA notification during which the aircraft has to remain in the FoV of the sensor. Tests like Timed Circles and Moving Head On show that when the sensor is given an extended period of time facing the aircraft it can reliably detect. Both Moving 10-40 and Hover In Place show the adverse impact of the combination of the narrow FoV and limited dwell time on detection success; the best results for each profile come from the shallow intercept angles of 10° and 15°, respectively. These angles give the sensor an extended period of time with the aircraft in view as well as some relative motion for detection.

Table 4. VO data summary.

	Actual Detections	Viable Encounters	Percentage
Profile 1: Concentric Circles	5	10	
	5	29	
Total	10	39	26%
Profile 3: Timed Circles	2	2	
	1	1	
Total	3	3	100%
Profile 4: Crossing	5	18	28%
Profile 5: Pipeline	12	18	
	2	7	
	12	23	
Total	26	48	54%
Profile 7: Moving Head On	7	7	100%
Profile 8: Moving 10-40	14	15	
	3	8	
	9	18	
	3	12	
Total	29	53	55%
Profile 9: Hover In Place	7	12	
	4	7	
	5	7	
	9	12	
Total	25	38	66%
Profile 10: DAA Hover T-Cross	0	12	0%

Of the encounters with detections, the average time with the intruder within the FoV before triggering was 10.8 s. This value is unexpectedly high, and likely results from the data being skewed by predominantly head-on approaches where the plane is in the FoV but out of range for an extended period of time. Additionally, the average detection distance was determined to be 656 m (2152 ft), which is slightly larger than the 2000 ft horizontal separation recommended for maintaining “well clear” between a manned aircraft and a small UAS (Weinert et al. 2018).

IRIS’s stated detection rate for the tested system was 70% at 390 m when allowed 3 s. This type of encounter is difficult to construct because the of limited FoV of the sensor and the required altitude offset between UAS and intruder trends encounters to distances > 800 m. Despite this, the very limited data acquired does show that IRIS achieved a 67% detection rate for distances < 400 m (Figure 24).

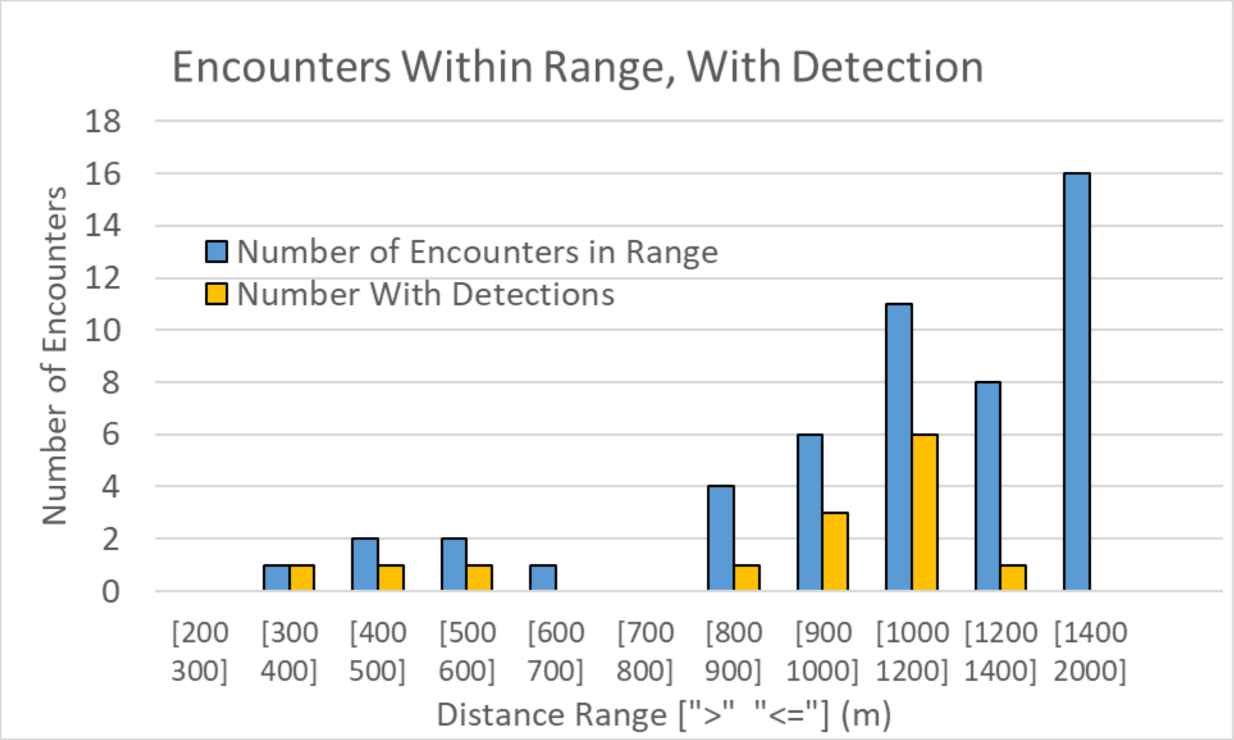


Figure 24. Summary of viable encounters versus detections.

In addition to these results, the following were determined:

- No false positives occurred for the VO-identified expected DAA system detections.
- The system struggles to detect aircraft when facing the sun.

3.3.8 Lessons Learned

Lessons learned during this campaign include:

- Use of a 3D plotting tool helps with visualization of encounters
- Iris Casia performance aligned with vendor specifications
    - Detection range limitations result in this system not generally enabling maintenance of well clear
- Development of a systematic means for testing DAA systems is critical

3.4 UND September 2020

A detailed report for this campaign is provided by Askelson (2022). The following provides a high-level overview of this campaign.

3.4.1 Objectives

The objectives of this test campaign were:

- Collection of enough data to estimate loss of well-clear risk ratio
    - Term is labelled LR_{ch}, with the subscript *c* indicating use of collision geometries in which aircraft would arrive at the same location if a maneuver was not applied (and a vertical safety offset was not used) and the subscript *h* indicating horizontal encounters were used
- Determination if the test methodology allows for maintenance of well clear during encounters
- Determination if the test methodology supports proper testing of the DAA system

3.4.2 Dates/Schedule

Tests were conducted during the week of 20-26 September 2020. 21 September 2020 was a shakedown day, with flights planned for the afternoon if possible. The primary flight tests days were 22-25 September 2020. The schedule for a nominal test day is provided in Figure 25.

Start	End	Day 1 (September 21, 2020)	Day 2 (September 22, 2020)	Day 3 (September 24, 2020)	Day 4 (September 25, 2020)	Day 5 (September 26, 2020)
0600	0630					Weather Day
0630	0700					
0700	0730	Meet at NPUASTS (4201 James Ray Drive)	Meet at NPUASTS (4201 James Ray Drive)	Meet at NPUASTS (4201 James Ray Drive)	Meet at NPUASTS (4201 James Ray Drive)	
0730	0800	Travel to Site	Travel to Site	Travel to Site	Travel to Site	
0800	0830	Morning Briefing	Morning Briefing	Morning Briefing	Morning Briefing	
0830	0900	Site Setup and Preparation	Site Setup and Preparation	Site Setup and Preparation	Site Setup and Preparation	
0900	0930					
0930	1000	Flight Testing	Flight Testing	Flight Testing	Flight Testing	
1000	1030					
1030	1100					
1100	1130					
1130	1200					
1200	1230	Lunch and Aircraft refueling	Lunch and Aircraft refueling	Lunch and Aircraft refueling	Lunch and Aircraft refueling	
1230	1300	Flight Testing	Flight Testing	Flight Testing	Flight Testing	
1300	1330					
1330	1400					
1400	1430					
1430	1500					
1500	1530					
1530	1600					
1600	1630	Site and Equipment tear down	Site and Equipment tear down	Site and Equipment tear down	Site and Equipment tear down	
1630	1700					
1700	1730	Debrief and schedule review	Debrief and schedule review	Debrief and schedule review	Debrief and schedule review	
1730	1800					
1800	1830	Travel to NPUASTS	Travel to NPUASTS	Travel to NPUASTS	Travel to NPUASTS	

Figure 25. Planned daily schedule for the September 2020 UND campaign.

3.4.3 Location

Tests were conducted near Hillsboro, ND. The following provides more details regarding test location.

The Command Center Trailer, from which the tests were directed, was located at the Lovas Farm, at approximately (-97.082223, 47.329763). One UA Launch and Recovery Element (LRE) was at approximately (-97.084370, 47.329733), which is at the Lovas Farm and very near the Command Center Trailer, and the other UA LRE was at approximately (-97.090454, 47.327013). The DAA system, C Speed radar, and Electronic Observer Trailer (location with DAA display system and from which maneuver commands were issued) were located on the ramp of the Hillsboro, ND, airport at (-97.061847, 47.357982). The Hillsboro airport is approximately 1.8 nm northeast of the Lovas Farm. For reference, the Horizontal Encounter Focal Point (HEFP; horizontal location at which aircraft would nominally arrive at the same time if no maneuver was executed) was at (-97.087696, 47.328505).[1] The locations of the Command Center Trailer, one UA LRE, and the Electronic Observer Trailer are illustrated in Figure 26.

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[1] Tests were conducted with aircraft separated by a vertical offset to ensure safety.

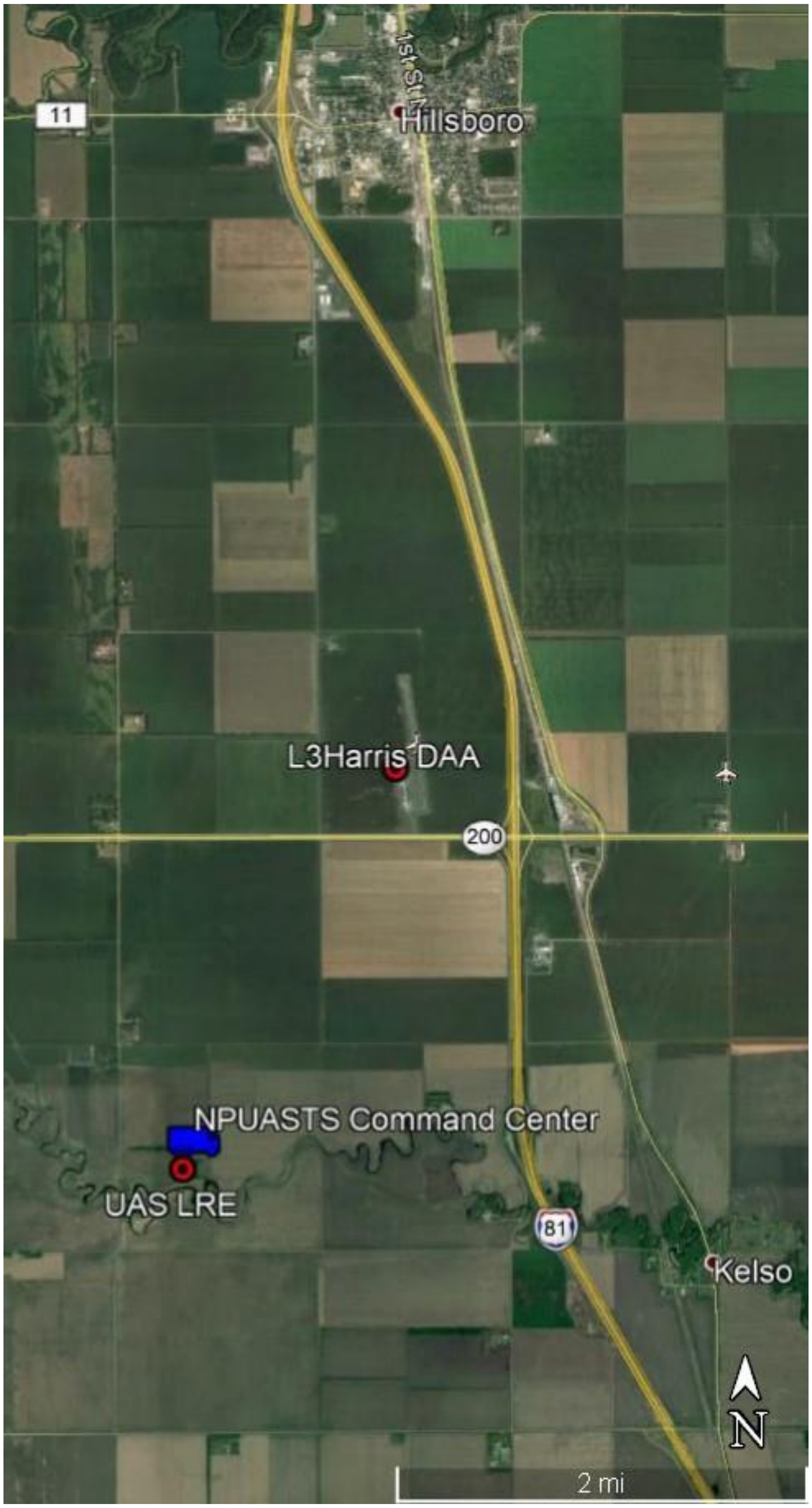

Figure 26. Locations of testing elements during the September 2020 UND campaign.

The UA was flown to the southwest of the Hillsboro airport to avoid any issues with the airport. The manned aircraft launched from the Grand Forks International Airport (KGFK) and refueled at the Hillsboro Airport (3H4) as needed. Figure 27 provides a sectional for the area. The test area is Class G airspace up to 700 ft AGL and Class E airspace above 700 ft AGL (up to Class A airspace).

Figure 27. Sectional centered on the September 2020 flight test area.

Figure 28 provides images from the Lovas Farm, the location of the Command Center Trailer and one UA LRE. That UA LRE was approximately in the location of the large snowbank near the barn shown in the upper-right panel of Figure 28. Flights tests were conducted to the south and west of the Lovas Farm.

Figure 28. Images from the Lovas farm, the location of the Command Center Trailer and one UAS LRE. View is to the north (upper-left), to the east (upper right), to the south (lower left), and to the west (lower right).

3.4.4 System Tested

Testing was conducted using the L3Harris™ Technologies DAA system, which enables multiple approaches for the Evaluate component of DAA.[2] Table 4 provides information regarding the L3Harris™ DAA System and regarding the two options for the Evaluate step.

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[2] Askelson et al. (2017) identified the major steps in DAA as Detect, Track, Evaluate, and Maneuver (DTEM). These are defined as Detect—sense the presence of something that must be avoided through some means; Track—estimate the path of the intruder; Evaluate—determine whether identified intruders pose a threat, prioritize threats, and identify maneuver; Maneuver—execute maneuver. These map to the functions in ASTM (2020) according to: Detect Function DF (Detect and Track), Alert Function A1F (portion of Evaluate wherein hazards are identified and prioritized), and Avoid Function A2F (portion of Evaluate where the maneuver is identified and Maneuver).

Table 4. Information regarding the L3Harris™ DAA system.

DAA Step	DAA Steps	Description
Detect	C-Speed Lightwave Radar and ADS-B SBSSVAS and Xtend	Detect data for non-cooperative targets are provided using a C Speed Lightwave Radar. Data for cooperative targets are provided through the Surveillance and Broadcast Services Subsystem (SBSS) Value Added Service (VAS) and through Xtend ADS-B units.
Track	Best-source selection	Data having the most accurate information regarding intruder locations/tracks are used. Track data are provided through the SBSS VAS or by the C-Speed Lightwave Radar.
Evaluate	EO (Electronic Observer) -or- Alerting and Guidance (A&G) supporting the EO	Either the EO performs all functions in this step or A&G is utilized to help the EO decide upon the maneuver. The display system is RangeVue™ and ownship data are ingested into the system through a telemetry feed from the UAS Ground Control Station (GCS).
Maneuver	Human Pilot	The FX20 flight crew executed maneuvers once received from the EO. This involved setting new waypoints for the FX20.

The L3Harris™ Technologies DAA system obtains intruder detection data from several sources. Non-cooperative data are provided using a C Speed Lightwave Radar (C Speed 2022; Figure 29). This is a low-cost, flexible, “software-defined”, S-Band, 2D (two-dimensional) radar technology platform that can serve a broad range of surveillance missions through reconfiguring of its run-time parameters. Cooperative data are obtained from the L3Harris™ Surveillance and Broadcast Services Subsystem (SBSS) Value Added Service (VAS) and from local Xtend™ ADS-B units (L3Harris 2022) that act as gap-fillers to provide surveillance coverage in areas that may not be effectively covered by the FAA’s system (provided through the SBSS VAS).

Figure 29. The C Speed Lightwave Radar utilized during the September 2020 UND campaign.

Track data are provided by the L3Harris™ SBSS VAS (cooperative intruders) and the C Speed Lightwave Radar system. The L3Harris™ system performs a best source selection. Thus, it selects the surveillance source that provides the best information regarding an intruder and displays those data (locations and tracks). Generally, the source that provides the lowest uncertainty regarding intruder location is considered to be the best source. Thus, these flight tests generally utilized a cooperative DAA system. This, however, had no deleterious impact on test objectives.

As indicated in Table 4, the L3Harris™ system can be used two different ways for the Evaluate step. For the September 2020 flight tests, the A&G capability was not utilized because guidance was not generally provided. This presumably occurred because of the availability of ADS-B surveillance data for the intruder. With those data, the A&G likely recognized the vertical offset between the aircraft (nominally 350 ft).[3] The A&G system was still being developed during these tests, however, and thus the lack of guidance could have occurred for other reasons. Consequently, the EO used the RangeVue™ display to identify conflicts and determine maneuvers. The EO used a Stonecast radio to communicate maneuvers to the UA PIC.

Maneuvers were executed by the UA PIC. Callbacks of commanded maneuvers were commonly used for acknowledgement.

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[3] A 350 ft vertical offset was utilized to enhance safety.

3.4.5 Test Plan Overview

Testing involved the entire of the DTEM chain and were designed by systematically varying factors that affect DAA system performance. Only horizontal encounters were executed, with variations in intruder speeds (nominally 80 and 100 kts) included. Horizontal encounter geometries were separated by 45°, with the CA flying either northwest to southeast or southeast to northwest. The encounter geometries associated with UA origination points for the CA flying northwest to southeast (Figure 30) are:

A. 0°
B. 315°
C. 270°
D. 225°
E. 180°

The encounter geometries associated with UA origination points for the CA flying southeast to northwest (Figure 31) are:

B. 135°
C. 90°
D. 45°

A total of 16 test scenarios/profiles were executed (8 encounter angles x 2 intruder speeds).

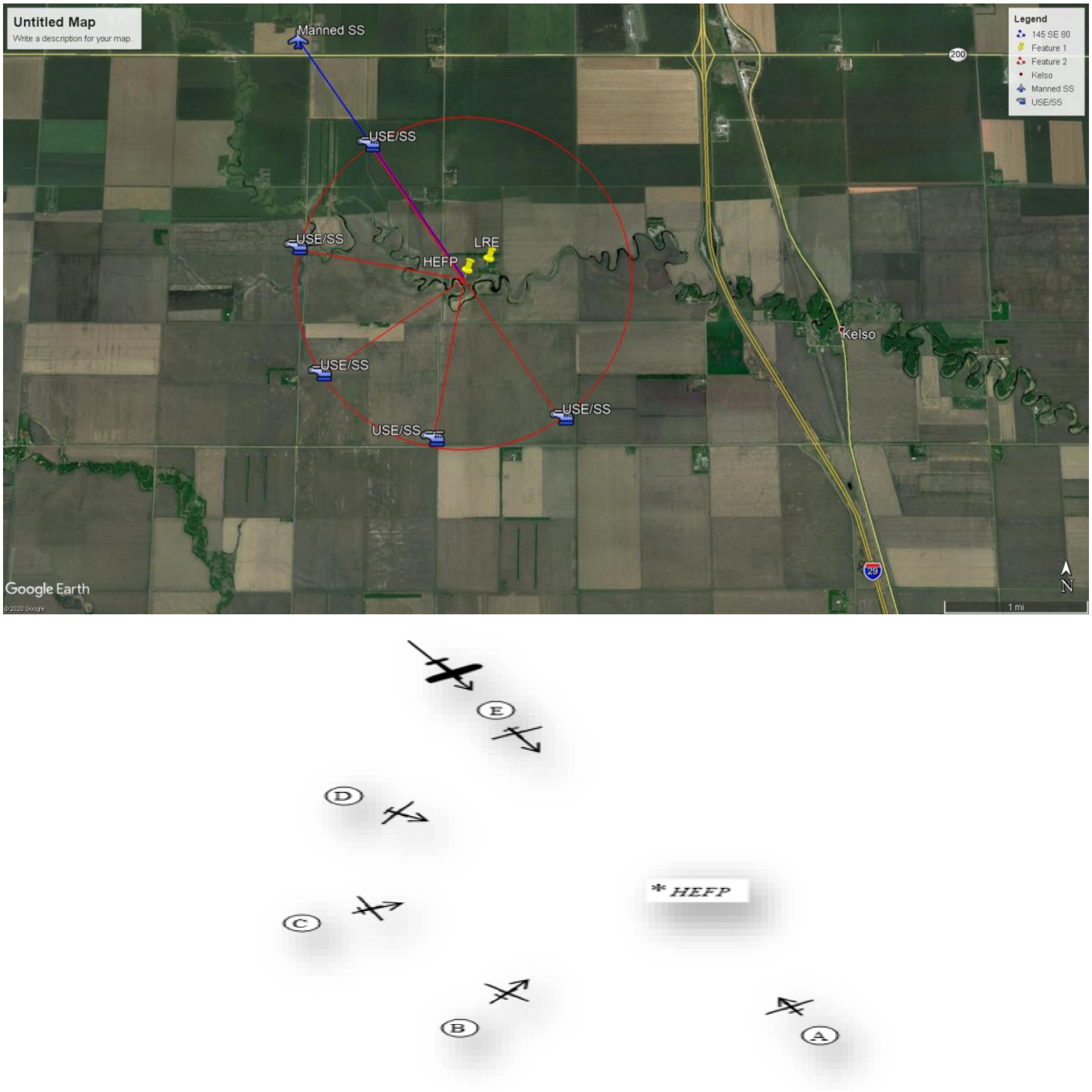


Figure 30. Illustration of encounters associated with the CA flying northwest to southeast. The top image illustrates aircraft paths and origination points. The bottom figure provides labels for UA orignation points.

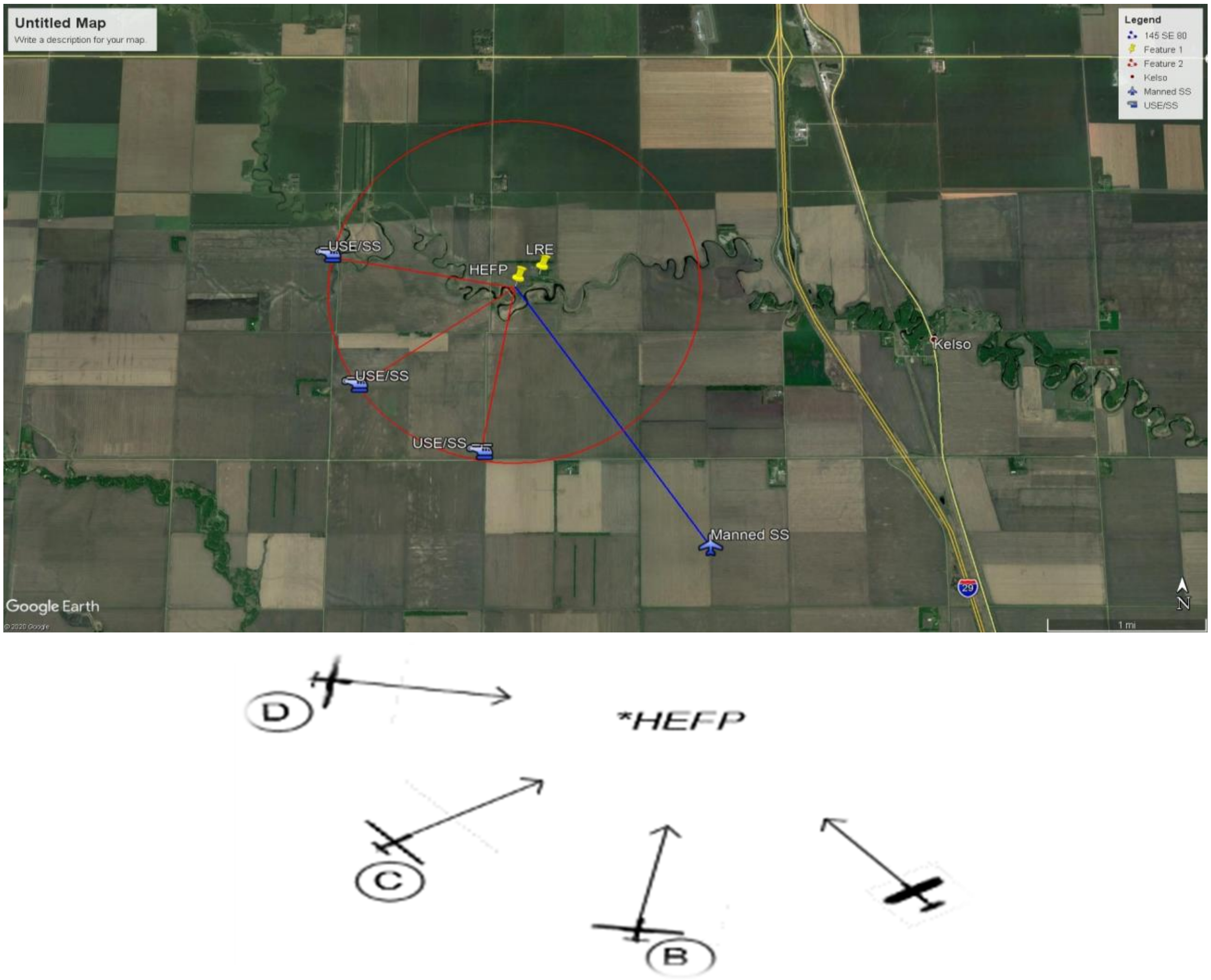


Figure 31. As in Figure 30 but for the CA flying southeast to northwest.

The UA that was flown is SkySkopes' FX20 UAS manufactured by Robot Aviation. Specifications for the FX20 are provided in Table 5. SkySkopes was the UAS operator

The C150 intruder aircraft is owned by UND and was operated by UND during the September 2020 flight tests. Information regarding this aircraft is provided in Table 6.

Table 5. Information regarding the UA used during the September 2020 UND campaign.

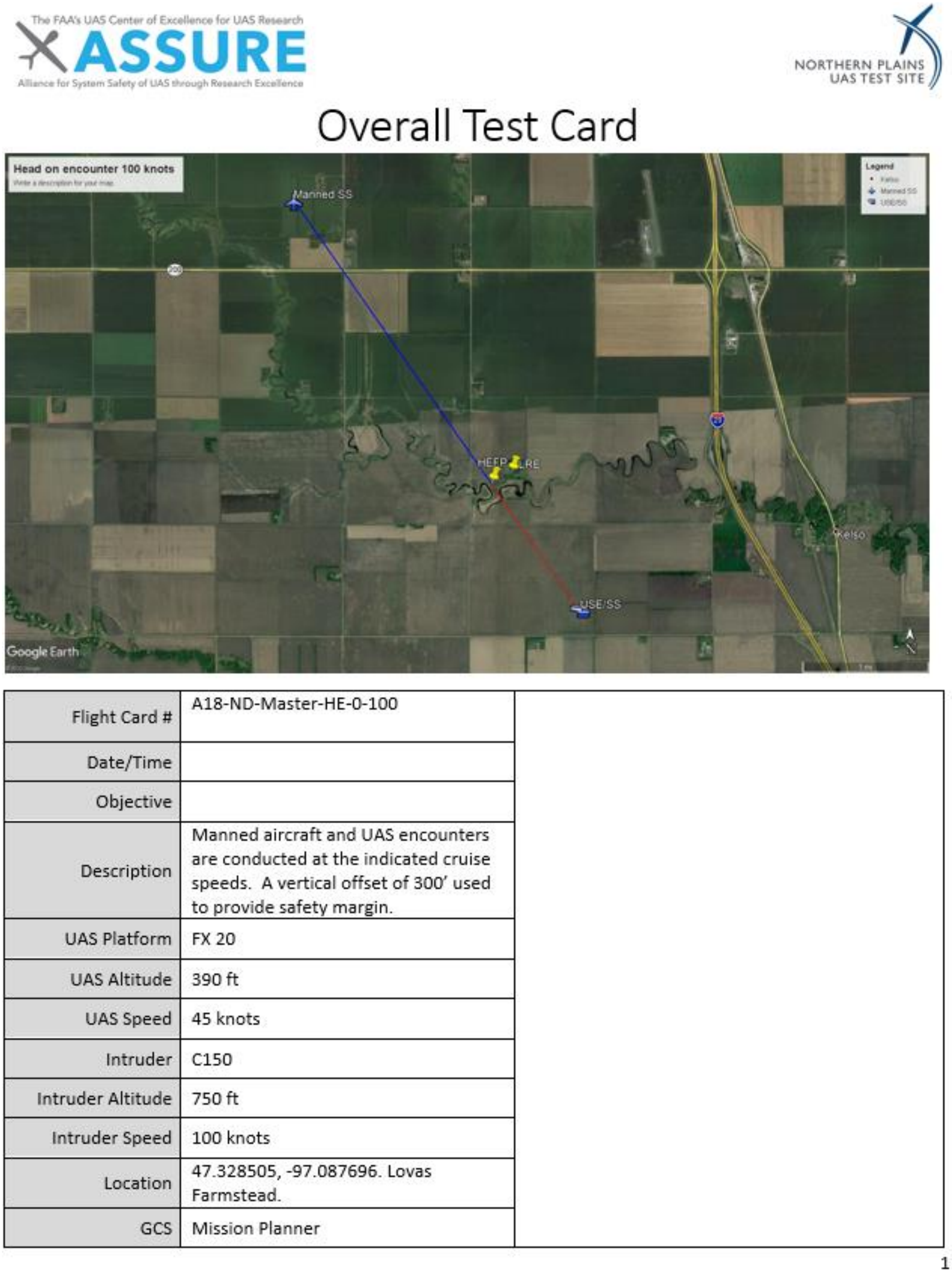
<table>
<tr><td colspan="2"></td><td colspan="2">The FX20 is a high-performance medium-range UAS that can be operated by a crew of two and transported in a small truck or van. Its design results in extremely low energy consumption. As a result, the all-electric flying wing can stay in the air for multiple hours (approaching 4 hrs). A portable launcher allows for runway-independent operation, with recovery conducted using either a net or skids.</td></tr>
<tr><td>Wing Span</td><td>3.0 m</td><td>Cruise Speed</td><td>27 m s^{-1}</td></tr>
<tr><td>Maximum Takeoff Weight</td><td>12 kg</td><td>UAS Operator</td><td>SkySkopes</td></tr>
<tr><td>Endurance</td><td>2 hr</td><td>GCS Type</td><td>Robot Aviation</td></tr>
<tr><td>Autopilot</td><td>Micropilot</td><td></td><td></td></tr>
</table>

Table 6. Information regarding the intruder aircraft used during the September 2020 UND campaign.

<table>
<tr><td colspan="2"></td><td colspan="2">The Cessna 150 is a two-seat, tricycle-gear general aviation airplane that was designed for flight training, touring, and personal use.</td></tr>
<tr><td>Wing Span</td><td>33 ft 2 in</td><td>Cruise Speed</td><td>82 kts</td></tr>
<tr><td>Maximum Takeoff Weight</td><td>1,600 lb</td><td>Operator</td><td>UND</td></tr>
<tr><td>Fuel Capacity</td><td>22.5 US gal</td><td></td><td></td></tr>
</table>

3.4.6 Sample Test Cards

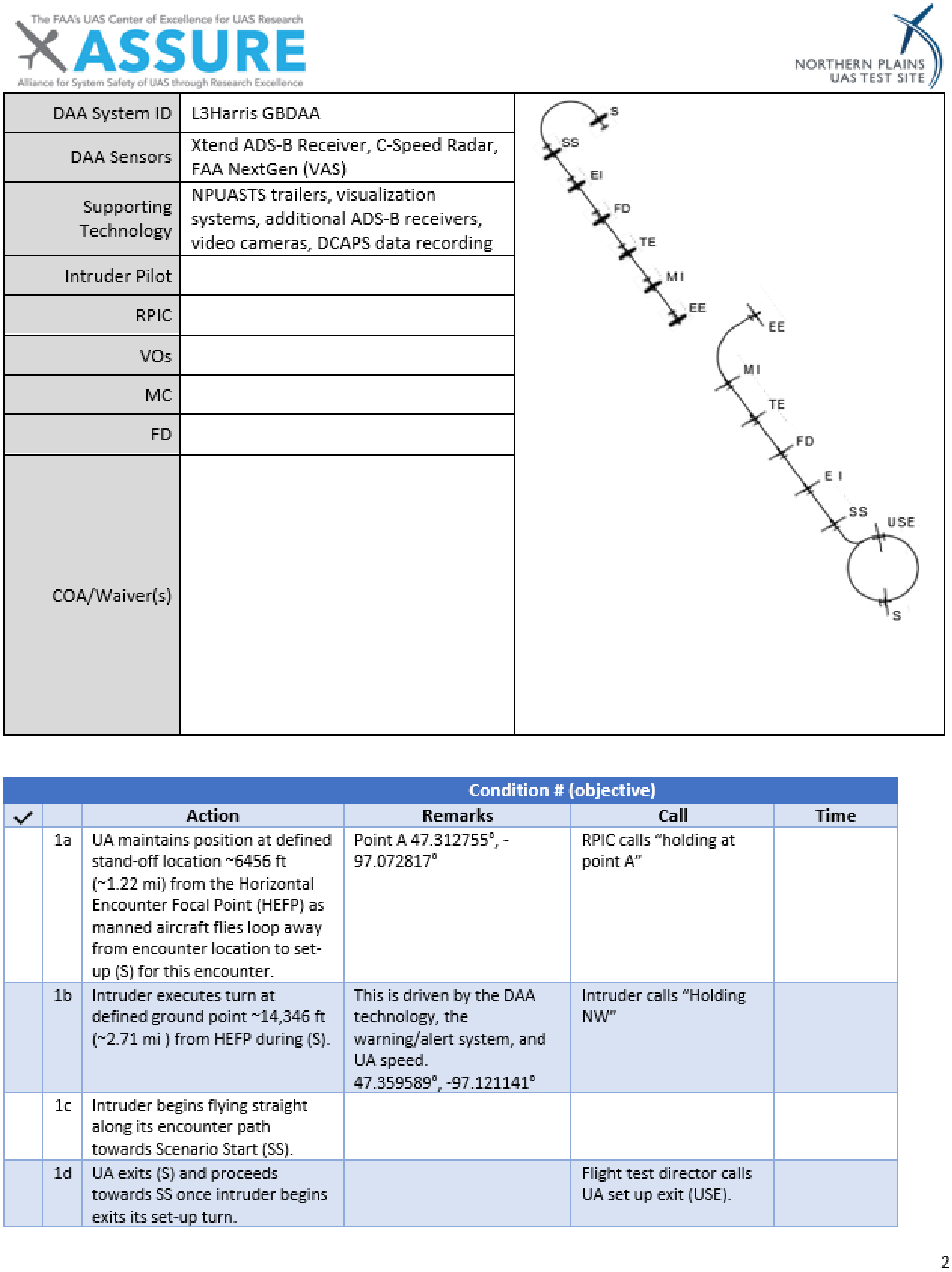
Test cards were developed for three roles: Flight Test Director (FTD), UA pilot, and CA pilot. A total of 48 cards (8 encounter angles x 2 intruder speeds x 3 roles) supported this test campaign. For brevity, the FTD test card for one scenario is provided here (Figure 32).



Overall Test Card

Flight Card #	A18-ND-Master-HE-0-100	
Date/Time		
Objective		
Description	Manned aircraft and UAS encounters are conducted at the indicated cruise speeds. A vertical offset of 300' used to provide safety margin.	
UAS Platform	FX 20	
UAS Altitude	390 ft	
UAS Speed	45 knots	
Intruder	C150	
Intruder Altitude	750 ft	
Intruder Speed	100 knots	
Location	47.328505, -97.087696. Lovas Farmstead.	
GCS	Mission Planner	

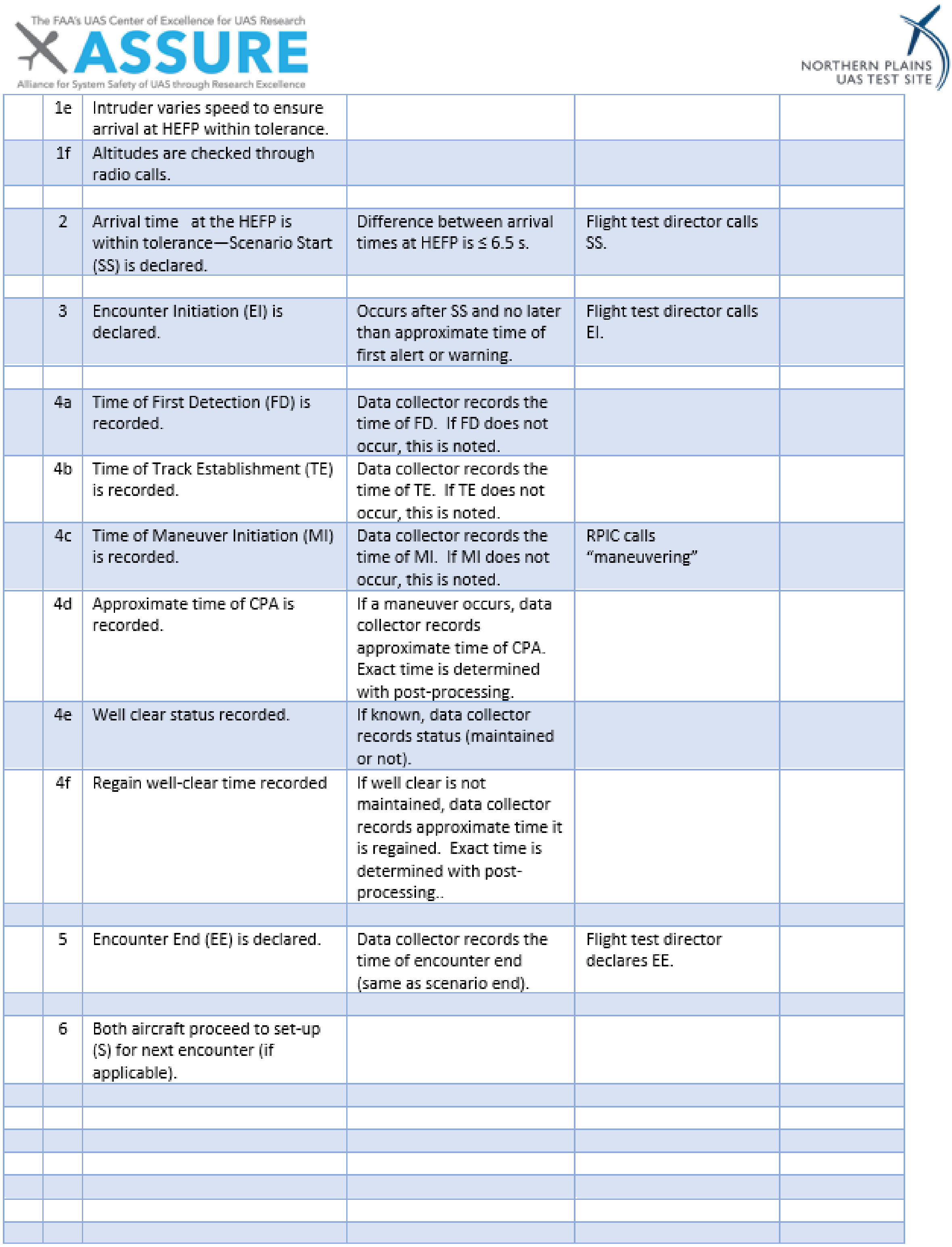
1



DAA System ID	L3Harris GBDAA
DAA Sensors	Xtend ADS-B Receiver, C-Speed Radar, FAA NextGen (VAS)
Supporting Technology	NPUASTS trailers, visualization systems, additional ADS-B receivers, video cameras, DCAPS data recording
Intruder Pilot	
RPIC	
VOs	
MC	
FD	
COA/Waiver(s)	

Condition # (objective)					
✓		Action	Remarks	Call	Time
	1a	UA maintains position at defined stand-off location ~6456 ft (~1.22 mi) from the Horizontal Encounter Focal Point (HEFP) as manned aircraft flies loop away from encounter location to set-up (S) for this encounter.	Point A 47.312755°, -97.072817°	RPIC calls "holding at point A"	
	1b	Intruder executes turn at defined ground point ~14,346 ft (~2.71 mi) from HEFP during (S).	This is driven by the DAA technology, the warning/alert system, and UA speed. 47.359589°, -97.121141°	Intruder calls "Holding NW"	
	1c	Intruder begins flying straight along its encounter path towards Scenario Start (SS).			
	1d	UA exits (S) and proceeds towards SS once intruder begins exits its set-up turn.		Flight test director calls UA set up exit (USE).	

2



	1e	Intruder varies speed to ensure arrival at HEFP within tolerance.			
	1f	Altitudes are checked through radio calls.			
	2	Arrival time at the HEFP is within tolerance—Scenario Start (SS) is declared.	Difference between arrival times at HEFP is ≤ 6.5 s.	Flight test director calls SS.	
	3	Encounter Initiation (EI) is declared.	Occurs after SS and no later than approximate time of first alert or warning.	Flight test director calls EI.	
	4a	Time of First Detection (FD) is recorded.	Data collector records the time of FD. If FD does not occur, this is noted.		
	4b	Time of Track Establishment (TE) is recorded.	Data collector records the time of TE. If TE does not occur, this is noted.		
	4c	Time of Maneuver Initiation (MI) is recorded.	Data collector records the time of MI. If MI does not occur, this is noted.	RPIC calls "maneuvering"	
	4d	Approximate time of CPA is recorded.	If a maneuver occurs, data collector records approximate time of CPA. Exact time is determined with post-processing.		
	4e	Well clear status recorded.	If known, data collector records status (maintained or not).		
	4f	Regain well-clear time recorded	If well clear is not maintained, data collector records approximate time it is regained. Exact time is determined with post-processing..		
	5	Encounter End (EE) is declared.	Data collector records the time of encounter end (same as scenario end).	Flight test director declares EE.	
	6	Both aircraft proceed to set-up (S) for next encounter (if applicable).			

Figure 32. Example FTD test card for the September 2020 UND campaign.

3.4.7 Summary of Results

Numerous metrics for evaluating DAA system performance were evaluated. These include sample risk ratio from ASTM (2020) and sample risk ratio uncertainty, which provides insight into whether the proposed approach (number of encounters) provides a viable basis for evaluation of risk ratio. In addition, the team presented encounter events (well clear/horizontal well clear/vertical well clear violations), evaluated overall encounter metrics such as CPA, and proposed and presented metrics for the DTEM stages of DAA. The team also evaluated maintenance of well clear status during testing, which is a goal during testing.

For test methodology, the team initially used a vertical aircraft altitude safety offset of 350 ft during these tests which generally ensured maintenance of well clear status. Three minor well clear violations occurred, however. Based upon this, the researchers recommend a 400 ft vertical aircraft altitude safety offset for horizontal encounters. Moreover, the team recommends closer monitoring of intruder altitudes during testing to ensure that the intruder is operating at the desired altitude.

For the encounter set that was evaluated, the sample risk ratio uncertainty, evaluated using three different methods, indicates that the set provides viable guidance regarding conformance with the performance standard. An evaluator must place this performance in context with the broader set of encounters, the breadth of which can be evaluated through simulation. Moreover, the metrics that are developed herein for the major stages of DAA, which were developed through the need for information regarding how the system is performing and qualified by pragmatic considerations (e.g., timing challenges associated with data collection), provide useful information regarding these major stages (and are being considered by the ASTM WK62669 DAA Test Methods Task Group). Finally, methods developed for analyzing encounters, including visualization techniques and summary metrics, enable understanding of encounter characteristics. This includes the situation wherein aircraft closure rates increase for a period of time after maneuver initiation.

Example results for an encounter executed during this test campaign are provided in Figure 33. Further details regarding encounters, metrics, estimation of uncertainties, etc., are provided by Askelson (2022).

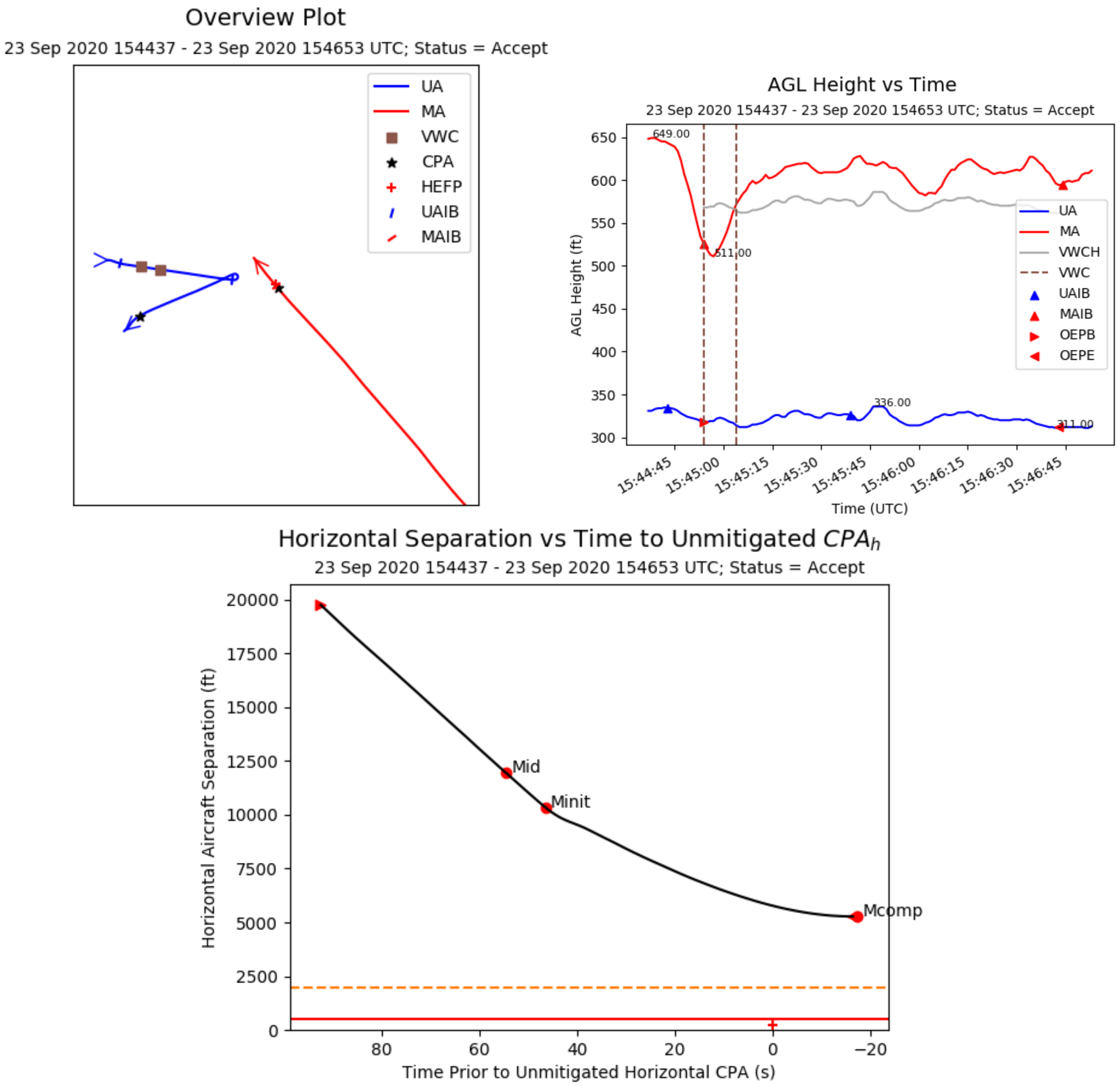


Figure 33. Illustration of the 154437-154653 UTC 23 September 2020 encounter. Upper left provides a plan view, with the UA flight path in blue, CA flight path in red, the period of vertical well clear violation indicated by brown boxes superimposed on the UA flight path (well clear and horizontal well clear are indicated by red and orange boxes, respectively), CPA indicated with a black star symbol, the HEFP indicated with a red plus symbol, and the inbound portions of flight indicated by blue (UA) and red (CA) dashes. Upper right provides a plot of AGL altitudes (relative to HEFP altitude), with the UA altitudes in blue, the CA altitudes in red, the CA altitudes needed to maintain vertical well clear in dark grey, the times of vertical well clear violation indicated by dashed bown lines (well clear and horizontal well clear are indicated by dashed red and orange lines, respectively), the UA inbound portion indicated by blue triangles, the CA inbound portion indicated by red triangles, and the Objective Encounter Period [OEP; see Askelson (2022)] beginning and end indicated by rotated red triangles. Bottom is the separation timeline, with the horizontal well clear boundary indicated by the orange dashed line (colored red if a well clear violation occurs), the horizontal NMAC boundary indicated by the solid red line, unmitigated CPA_h (CPA in horrizontal direction if UA does not maneuver) indicated by the red plus symbol, the time when both aircraft are inbound indicated with a rotated red triangle (left side of plot), the OEP end indicated with a rotated red

triangle (right side of plot), and labels indicating the following: Dfst=First Detection, Testblsh = Track Establishment, Ecaut = Caution, Ewarn = Warning, Mid = Maneuver Identification, Minit = Maneuver Initiation, and Mcomp = Maneuver Completion.

3.4.8 Lessons Learned

Lessons learned from this round of flight tests include:

- Failures associated with testing occur, including ones experienced during this round of flight tests:
    - The wired connection from the radar to the Electronic Observer Trailer failed the week before testing. This was repaired on the Friday prior to testing.
    - The Long Term Evolution connection dropped at the Electronic Observer Trailer. This interrupted communications and connectivity for the Data Collection And Processing System [DCAPS; see Askelson (2022)].
        - Resulted in one encounter being unacceptable.
    - The Command Center Trailer generator ran out of gas.
        - The Uninterruptable Power Supply kicked in.
        - Communications were lost—Zoom™.
- Detection challenges occur
    - ADS-B drop-outs did occur and seemed to be focused on a certain location.
    - Primary tracks (radar) did not always arise for aircraft taking-off and landing at the airport.
        - The clutter filter is believed to be the cause of this.
- Display glitches can occur
    - Occasionally the locations of UA and CA did not (seemingly) update on RangeVue™
        - This resulted in aircraft positions "jumping"

3.5 UAF June 2021

A detailed report for this campaign is provided in the draft report Remmert and Purdy (2021). The following provides a high-level overview of this campaign.

3.5.1 Objectives

The objective of this flight campaign was to evaluate the performance of the Echodyne Echoflight (onboard system) and Echodyne Echoguard (ground-based system). Emphasis was on the detection capabilities of these two systems.

3.5.2 Dates/Schedule

Testing was conducted 2-4 June 2021. The planned daily schedule was similar to previous UAF campaigns.

3.5.3 Location

The first day of flight tests were conducted at the Poker Flat Research Range, which was utilized in previous UAF flight campaigns and is illustrated in Figure 2. The second and third flight test days were conducted at Bradley Sky Ranch Airport located in North Pole, AK, 15 mi southeast of UAF. This airport was selected for this flight test campaign because of light activity, few obstructions, and an unpopulated area to the southwest of the runway. The runway surface is a combination of gravel and natural soil with no surface treatment.

3.5.4 System Tested

The airborne DAA candidate in this report is the Echoflight DAA radar manufactured by Echodyne. Echoflight is an Electronically Scanning Array radar that employs a Metamaterial Electronically Scanning Array (MESA) technology for beam steering. Since the MESA architecture is solid state it does not require moving parts, nor does it require phase shifters typical of phased array antennas. This reduced complexity makes imaging radar solutions accessible to a broad range of applications, including Cost-Size, Weight, and Power constrained applications.

At the time of this campaign a turn-key Echodyne radar-based sense and avoid DAA solution did not exist. The Echoflight radar system is marketed as a sensing solution; it is not a comprehensive or stand-alone DAA system. The radars must be integrated into a DAA or Unmanned Traffic Management (UTM) system. The sensing solution is comprised of the radar hardware, Field Programmable Gate Array logic embedded software and an onboard Inertial Measurement Unit (IMU) for attitude determination. Radar data can be processed onboard the radar with minimal track data transmitted, or raw data can also be output for processing offboard.

In this effort the airborne Echodyne radar was evaluated as a sensor component of a candidate DAA system. Development of a decision algorithm and control system to interpret and react to non-compliant threats was beyond the scope of this effort. As such only the viability of the radar as a sensing platform is considered.

The Echodyne Echoflight radar was integrated onto a heavy-lift hex-copter (ACUASI-owned modified version of the Tarot X6) for testing. Details regarding that integration are provided by Remmert and Purdy (2021).

The second Echodyne system evaluated was a co-located sectoral array comprised of four Echoguard radars. Unlike the Echoflight, which is intended for use in dynamic conditions, the Echoguard is intended to be permanently mounted to a stationary ground support. ACUASI engineering designed and fabricated a portable four sector mount with a collapsible mast that can be transported and rapidly deployed at a given test location. In this case the radars were oriented in 90° quadrants for a full 360° surveillance of the local test area.

Echoguard Security and Surveillance Radar is designed to enable multiple missions such as perimeter security or critical infrastructure applications, counter-UAS detection and tracking of intruders, and Ground-Based Detect and Avoid (GBDAA). It can provide the same level of safe operation for sUAS that are too small to carry their own radar system by providing localized situational pilot awareness of both ownship position, along with cooperative and non-cooperative intruder aircraft. Multiple Echoguard units may be combined into flexible local networks for increased coverage. Echoguard provides 20-30% longer range than the EchoFlight by maximizing transmitter power, waveform processing, and through design of an all-passive cooling system (no forced air cooling) optimized for fixed and portable ground-based use.

3.5.5 Test Plan Overview

The test plan consisted of:

- Testing of the detection component of the two types of Echodyne systems
- Encounters that were geometrically and scenario inspired
    - Horizontal, descend-into (intruder), and climb-into (intruder) encounters
- Execution of a total of 11 test profiles

- Use of a heavy-lift hex-copter ownship UA
- Use of 3 intruders
    - Fixed-wing Helio Courier 295 CA
    - Fixed-wing Cessna 206 CA
    - Trinity 90+ Vertical Take-Off and Landing (VTOL) UA

The intruders are illustrated in Figures 34-36.

Figure 34. Helio Courier 295 CA used as an intruder during the June 2021 UAF campaign.

Figure 35. Cessna 206 CA used as an intruder during the June 2021 UAF campaign.

Figure 36. Trinity F90 VTOL UA used as an intruder during the June 2021 UAF campaign.

Details regarding test profiles are provided by Remmert and Purdy (2021). An example image for a profile in which ownship encounters an intruder (Cessna 206) that is either on final approach (descending) or departing (ascending) is provided in Figure 37. For this profile, horizontal well clear status is maintained through enforcement of a 610 m lateral aircraft offset. It is noted that this campaign incorporated more ascending/descending encounters (in addition to the pop-up encounters executed in the July 2019 NMSU campaign). Doing so for full encounters (i.e., including the TEM steps in DTEM) was accomplished in a later test campaign (June 2021 UND).

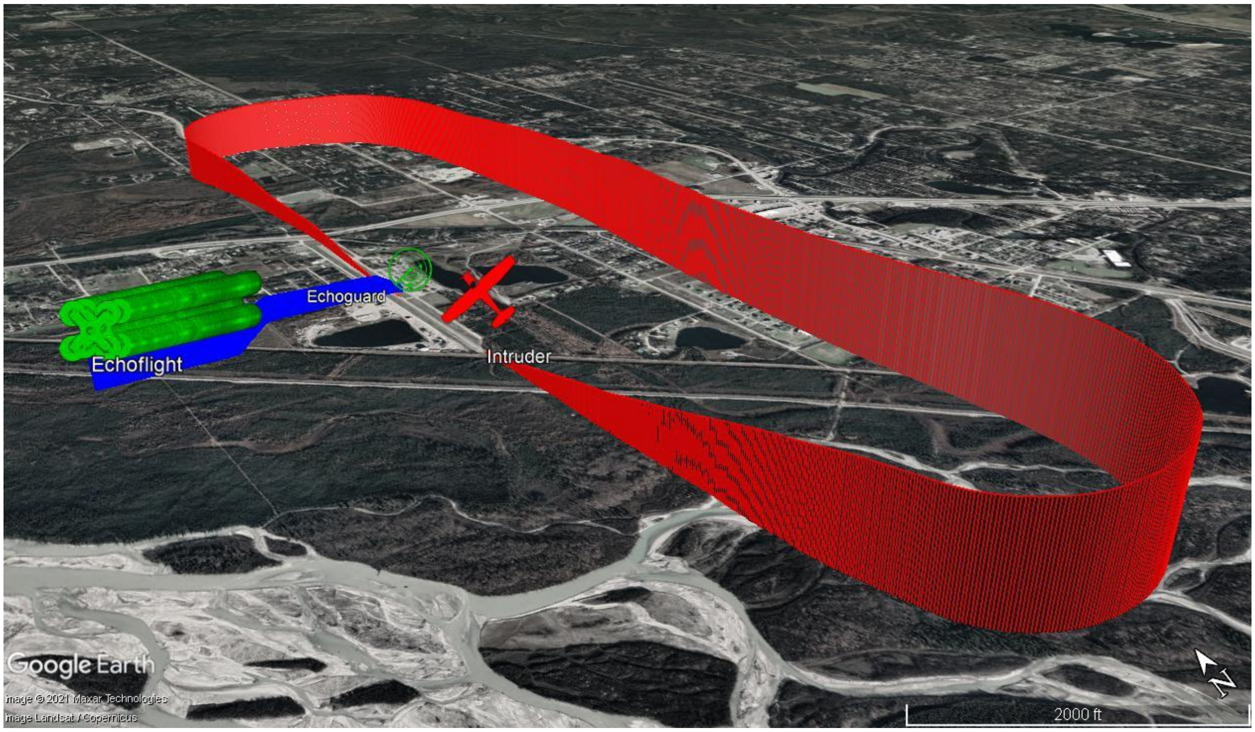
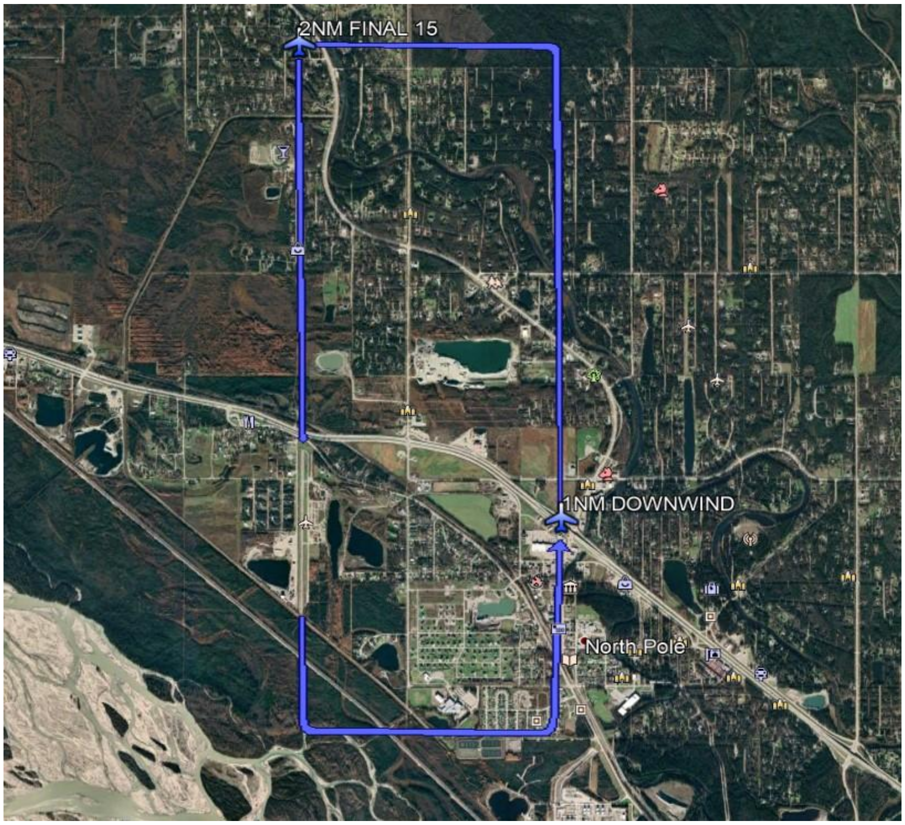


Figure 37. Bradley Ranch encounter profile with intruder in the traffic pattern.

3.5.6 Sample Test Cards

Test cards were developed for the 11 profiles. An example that corresponds to Figure 37 is provided in Figure 38.


2NM FINAL 15
1NM DOWNWIND
North Pole

Flight Card #	ACUASI_AK_95Z_Test Card Mission 2	
Date/Time		
Objective	Primary: Secondary:	
Description	Manned aircraft and UAS encounters are conducted as displayed. A lateral offset of 500m used to provide safety margin.	
UAS Platform	ACUASI X-6	
UAS Altitude	**300' AGL**	
UAS Speed	**6 m/s**	
Intruder	Cessna 206	
Intruder Altitude	(Traffic Pattern Altitude)	
Intruder Speed	(Normal Cruise and landing)	
Location	64.757964, - 147.390461. Bradley Sky Ranch (95Z)	
GCS	Mission Planner	
DAA System ID		
DAA Sensors		
Supporting Technology	Uavionix Ping ADSB, EchoGround Radar, EchoGuard radar, GroundAware GA-9120	
Intruder Pilot		
RPIC		
VOs		
MC		
FD		
COA/Waiver(s)		

		Condition # (objective)			
✓		Action	Remarks	Call	Time
	1	UA executes a E/W oriented flight plan parallel to the runway offset by 500ft from the runway centerline. Crewed aircraft executes standard touch-and-go landings in the FOV of the ground-based radar.	Echodyne radar FOV AZ ±60° EL ±40° EchoGuard radar is oriented 360° FOV	Crewed aircraft to report standard aviation traffic pattern	
	2				
	3				
	4				
	5				
	6				
	7				
	8				
	9				
	10				
	11				
	12				
	END				

Figure 38. Example test card (profile 2) from the June 2021 UAF campaign.

3.5.7 Summary of Results

After initial flight testing of the Echoflight UA platform, it was apparent that the airborne system was adversely affected by ground motion. While some effect was anticipated, the extent to which a dynamic platform would impact radar performance was unknown. While the Echoflight radars do have an integrated IMU for the purpose of tracking self-stabilization, this functionality apparently does not compensate for all platform dynamics. Any relative motion of the ground with respect to the airborne platform induces multiple false tracks. This occurs because ground-based objects appear to move within the Field of Regard (FoR) and stationary objects are interpreted as moving targets. This phenomenon is most pronounced during yaw motion of the UA platform (an example is provided in Figure 39). Unfortunately, for all encounters where the Echoflight platform was in motion, the radar data were rendered useless due to excessive noise. The Echoflight and Echoguard are only capable of tracking 20 simultaneous targets at any given time. Therefore, an excessive number of false tracks effectively saturates the radar. Due to this limitation, only encounters where the Echoflight UA platform is in stationary hover are considered in these test results.

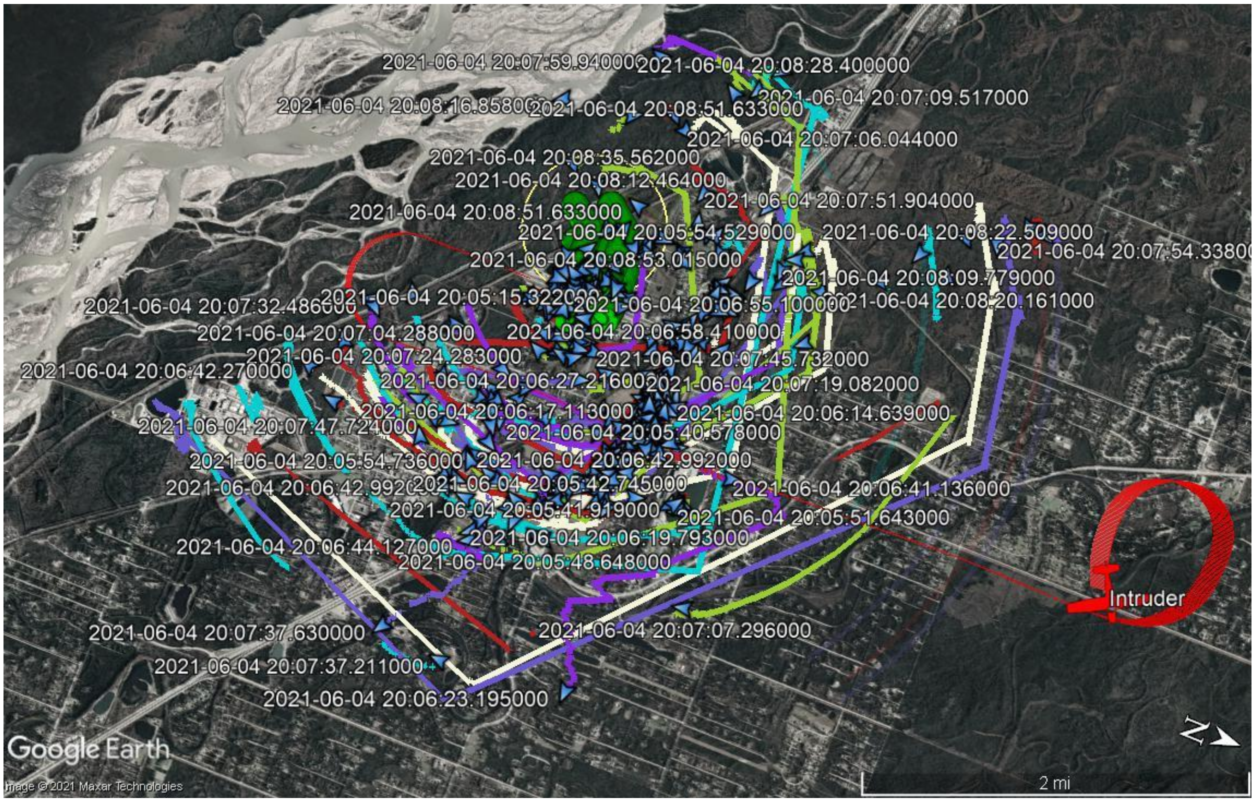


Figure 39. Ground motion induced noise experienced with the Echoflight radar.

For encounters where the airborne UA platform was in a stationary hover, false tracks were attenuated sufficiently to discern a few valid tracks from false positives. In a few encounters an increased maximum detection range was noted as compared to the ground-based Echoguard units. However, there was virtually no consistency; the range of first detection varied dramatically, even between like encounters. It should be noted that this was an issue common to both the Echoflight and Echoguard units.

The tracks generated by the Echoflight radar consistently exhibited erratic variance in altitude as compared to those from the Echoguard units. This altitude variance is a result of vibration and buffeting of the airborne platform. The resulting low amplitude high frequency motion also adversely affects the ability of the Echoflight unit to acquire new targets at extended range. This is a concern for a DAA sensor because it decreases the CPA for intruders.

For the duration of the test campaign, the Echoguard radars demonstrated a markedly improved performance relative to the Echoflight radars. Given that the Echoflight and Echoguard units are virtually identical, it can be inferred that performance is tightly coupled to the use case. Stationary Echodyne units typically have better performance.

During the test campaign it was noted that the range of first detection varied. This characteristic is illustrated in Figure 40, which conveys a significant spread in values. The source of this variability is as of now undetermined. However, given that the conditions of the tests, it can be reasonably inferred that the variability results from the tracking characteristics of the Echoguard.

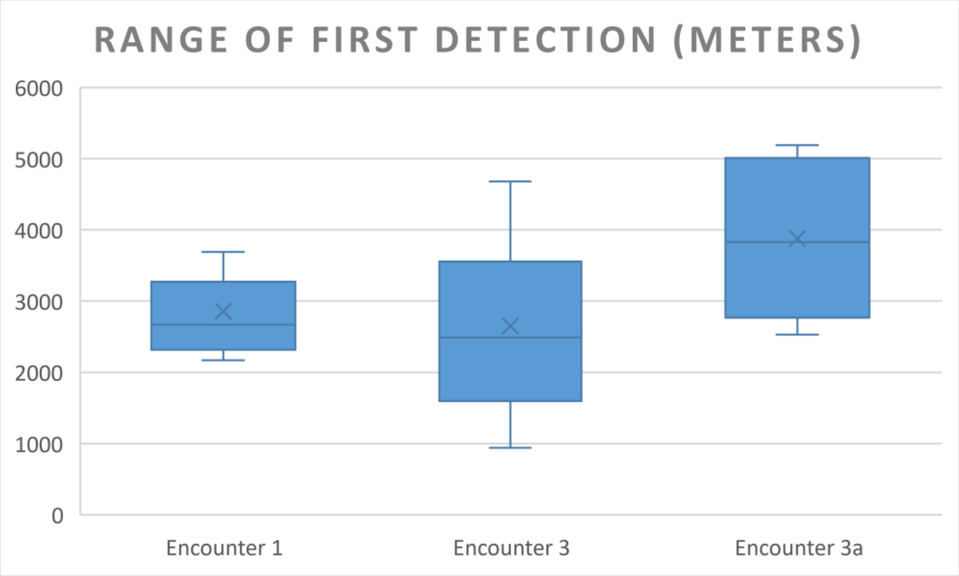


Figure 40. Variability of Echoguard initial detection range.

The data clearly show there were instances during the test where the intruder was detected very late in the encounter. This placed the moment of initial detection just outside the well clear volume. It should also be noted that the Echoguard radars are ground-based DAA sensors and will most likely be utilized as sensors for a UTM system. Therefore, the Echoguard units may not necessarily be co-located with the UA. In order to achieve full coverage a UTM would likely employ a network of Echoguard arrays. If the worst-case detection ranges presented in this report are indicative of the minimum distances required between sensors, such a network may not be practicable.

Another noteworthy attribute that was identified during this test was the effect of intruder aircraft maneuvers on Echoguard tracking. During tight radius turns the radar would consistently lose track of the intruder aircraft. The Echoguard radars employ a probabilistic predictive analysis as part of their detection and tracking algorithm. During maneuvers the radar cross section is dynamic as is the vector of the intruder. The resultant loss of confidence in the track position is likely why the radar loses tracks during tight maneuvers.

3.5.8 Lessons Learned

Lessons learned during this campaign include:

- The dynamic environment associated with the Echoflight system results in significant ground clutter (when flying near the ground)
- Vibration appears to affect altitude estimates of intruders generated using the Echoflight system
- The Echoguard (and presumably Echoflight) system can lose tracks during tight maneuvering of intruders
- Variations in detection range for the Echoguard system can be significant

- Both the Echoflight and Echoguard systems show promise for DAA, although challenges exist

3.6 UND June 2021

A detailed report for this campaign is provided by Askelson and Stephens (2022). The following provides a high-level overview of this campaign.

3.6.1 Objectives

The objectives for this flight test campaign were:

- Determination if the test methodology results in well-clear maintenance during encounters (especially with the increased vertical safety offset and for descend-into encounters)
- Collection of additional samples at selected horizontal encounter geometries and evaluation of impacts on statistical parameters

3.6.2 Dates/Schedule

Tests were conducted during the week of 13-19 June 2021. 14 June 2021 was a planned shakedown day. The team encountered challenges with provision of UA location data to the L3Harris™ system. These issues were resolved on the afternoon of 15 June, resulting in three test days: 16-18 June 2021. The planned schedule for that week is provided in Figure 41.

Start	End	Day 1: 15 June 2021	Day 2: 16 June 2021	Day 3: 17 June 2021	Day 4: 18 June 2021
600	630				
630	700				
700	730	Meet at NPUASTS (4201 James Ray Dr.)	Meet at NPUASTS (4201 James Ray Dr.)	Meet at NPUASTS (4201 James Ray Dr.)	Meet at NPUASTS (4201 James Ray Dr.)
730	800	Travel to Site	Travel to Site	Travel to Site	Travel to Site
800	830	Morning Briefing	Morning Briefing	Morning Briefing	Morning Briefing
830	900	Site Setup and Preparation	Site Setup and Preparation	Site Setup and Preparation	Site Setup and Preparation
900	930				
930	1000	Flight Testing	Flight Testing	Flight Testing	Flight Testing
1000	1030				
1030	1100				
1100	1130				
1130	1200				
1200	1230	Lunch and Aircraft Refueling	Lunch and Aircraft Refueling	Lunch and Aircraft Refueling	Lunch and Aircraft Refueling
1230	1300	Flight Testing	Flight Testing	Flight Testing	Flight Testing
1300	1330				
1330	1400				
1400	1430				
1430	1500				
1500	1530				
1530	1600				
1600	1630	Site and Equipment Tear Down	Site and Equipment Tear Down	Site and Equipment Tear Down	Site and Equipment Tear Down
1630	1700				
1700	1730	Debrief and Schedule Review	Debrief and Schedule Review	Debrief and Schedule Review	Debrief and Schedule Review
1730	1800				
1800	1830	Travel to NPUASTS	Travel to NPUASTS	Travel to NPUASTS	Travel to NPUASTS

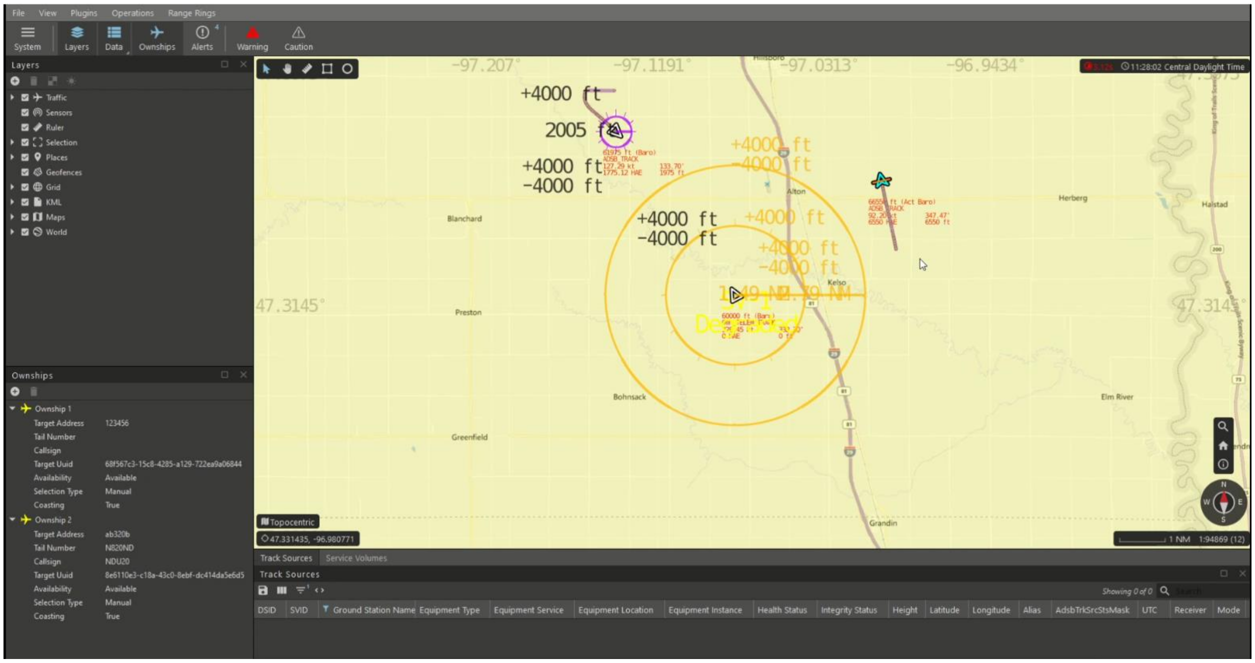
Figure 41. Planned test schedule for June 2021 UND campaign.

3.6.3 Location

Test locations were the same as those used during the September 2020 UND campaign.

3.6.4 System Tested

The system tested was the same as that used during the September 2020 UND campaign except the display system was upgraded to the RangeVue™ Pro display system, which did not provide A&G. For the Evaluate step, the EO used the RangeVue™ Pro display to identify conflicts and identify maneuvers, and a Stonecast radio to communicate maneuvers to the UA PIC. In the absence of an A&G system, distance-based circles were drawn around the UA, as illustrated in Figure 42. The radii of these (outer) circles are generally equal to the horizontal extent of the hazard zone as defined by Radio Technical Commission for Aeronautics (RTCA) (2017; §2.2.4.3.2), which vary with horizontal encounter geometry to account for changes in closure rates and depends upon the alert threshold. For these tests, a late (60 s) alert threshold was used to limit the distance between UA origin points and the Encounter Focal Point (EFP), which simplified Part 107 operations in that daisy-chained ground observers were not required and sped up the testing process by decreasing the amount of time required for set-up between encounters. For simplicity, distances for 0° and 180° horizontal encounter angles were computed, and distances for intervening angles were linearly interpolated from those values. In addition, a buffer of 0.17 mi was added for 180° encounters, which provides an additional 5 s. This was based upon computations of the amount of time required for the UA to travel 2000 ft [the horizontal well-clear distance used in ASTM (2020)] from the line adjoining the aircraft tracks for a 180° encounter, the estimated amount of time required for initiating a maneuver (~15 s), and the distance the intruder travels in that amount of time.



Ownship 1

Target Address	123456
Tail Number	
Callsign	
Target Uuid	68f567c3-15c8-4285-a129-722ea9a06844
Availability	Available
Selection Type	Manual
Coasting	True

Ownship 2

Target Address	ab320b
Tail Number	N820ND
Callsign	NDU20
Target Uuid	8e6110e3-c18a-43c0-8ebf-dc414da5e6d5
Availability	Available
Selection Type	Manual
Coasting	True

Figure 42. Example of the RangeVue™ Pro display. The UA is indicated by the triangle symbol located near the center of the display, with concentric rings drawn around it. The intruder is indicated by the triangle symbol surrounded by a magenta-colored circle. The outer ring around the UA serves as the alert for the EO to identify and communicate a maneuver to the UA PIC.

3.6.5 Test Plan Overview

Testing involved the entire of the DTEM chain and encounters were geometrically based. During the prior set of flight tests conducted by the UND and NPUASTS in September 2020 (Askelson 2022), horizontal encounters including the full range of possible encounter angles (0°-360°) and using a 45° increment (0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°) were conducted. Analysis of those tests indicated an interesting pattern in which the horizontal component of CPA (CPA_h) appeared to depend upon the encounter angle, with smaller CPA_h values associated with overtaking encounters (encounter geometries of 180° and 225°) and larger values associated with head-on encounters such as 0° and 45° [cf. Figure 22 of Askelson (2022)]. To explore whether the differences observed during the September 2020 flight tests consistently occur, the June 2021 tests utilized a selected subset of horizontal encounter angles (0°, 45°, 180°, 225°). In addition, for the horizontal encounters and these encounter angles, 10 tests at each angle were incorporated into the encounter test script (as opposed to 5 in the September 2020 test). Executing more tests at each angle produces greater confidence in observed differences and also enables exploration of dependence of statistical properties (e.g., variance) on the number of samples through comparison with previous test results. These horizontal encounters followed collision trajectories, wherein the aircraft were flown towards an EFP using a vertical safety offset. This follows Askelson (2022), with the exception of a larger vertical safety offset of 400 ft [vs 350 ft with Askelson (2022)] used for this round of flight tests. Collision trajectories were used because they result in the strictest timing requirements for DAA for each encounter angle.

In addition to horizontal encounters, tests also included descend-into encounters, as shown in Figure 43. For these, horizontal origination points were the same as in horizontal encounters for the corresponding horizontal encounter angles, which were 0° and 135° for the June 2021 descend-into encounters. In these encounters, the intruder descended at a rate of 500 ft min^{-1} (a typical descent rate for the Piper Archer intruder aircraft used in this set of tests). Initial intruder altitude was set such that the intruder and UAS would fly to the same location, horizontally and vertically, without the use of the vertical safety offset (described subsequently). Thus, a collision-type geometry was employed and applied to the point of enacting the vertical safety offset. Given the horizontal 120 kt speed and 500 ft min^{-1} descent rate of the intruder, the vertical encounter angle is +2°.

Because ground features that could be used to ensure horizontal aircraft safety offsets were either not present or not aligned with horizontal encounter geometries, safety was maintained by having the intruder halt descent by the time 800 ft AGL was reached. Given that the UAS was operated at 390 ft AGL, this provided ~400 ft of vertical safety offset, which is 50 ft greater than that used in the September 2020 tests. With this design, at 900 ft AGL the intruder is ~250 ft from the vertical well clear boundary of the UA and, at a descent rate of 500 ft min^{-1}, ~30 s from the vertical well clear boundary. This produced a trend prior to activating the vertical safety offset that required a maneuver to maintain well clear in the vertical direction. In the horizontal direction, the trend is constant (before and after activation of the vertical safety offset) and required a maneuver to maintain well clear in the horizontal direction. Thus, the descend-into encounter design resulted in a trend to a well clear violation prior to activation of the vertical safety offset that required a maneuver for maintenance of well clear.

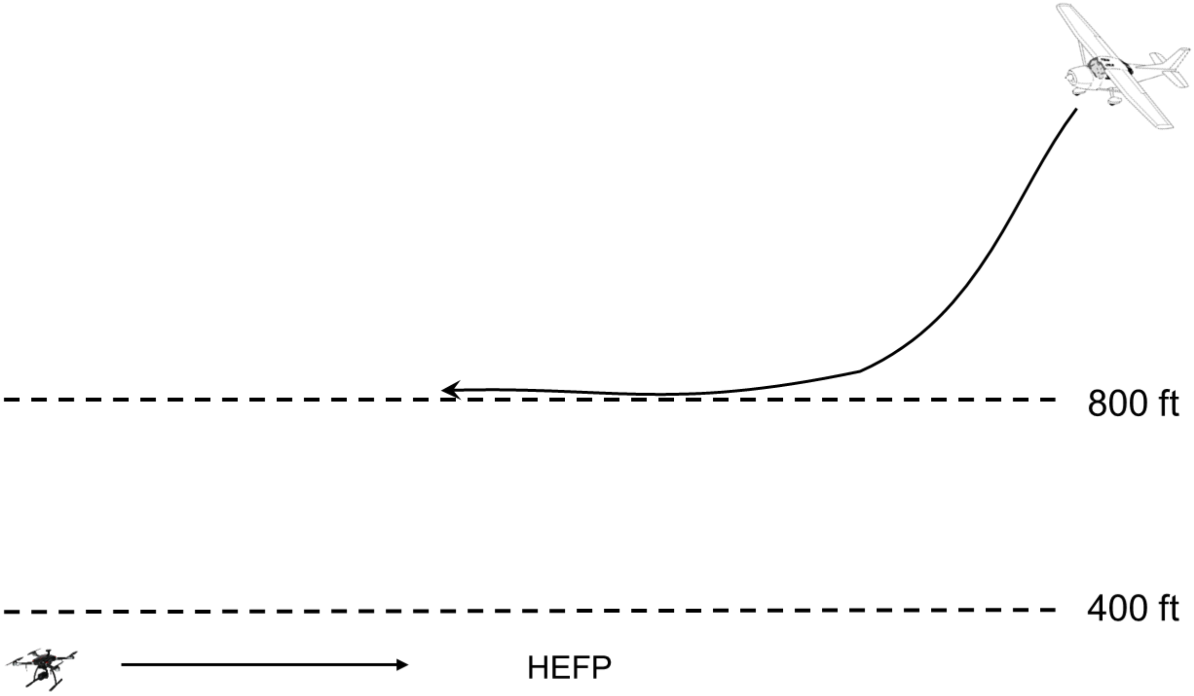


Figure 43. Illustration of descend-into encounters used during the June 2021 UND campaign.

Speed variations (beyond those driven by environmental winds) were not included. A total of 6 scenarios were tested [(4 horizontal scenarios + 2 descend-into scenarios) x 1 intruder speed].

The UA that was flown is Isight Drone Services' SuperVolo UAS. Specifications for the SuperVolo are provided in Table 7. Isight Drone Services operated the SuperVolo.

The Piper Archer intruder aircraft is owned by UND and was operated by UND during the June 2021 flight tests. Information regarding this aircraft is provided in Table 8.

Table 7. Information regarding the UA used during the June 2021 UND campaign.

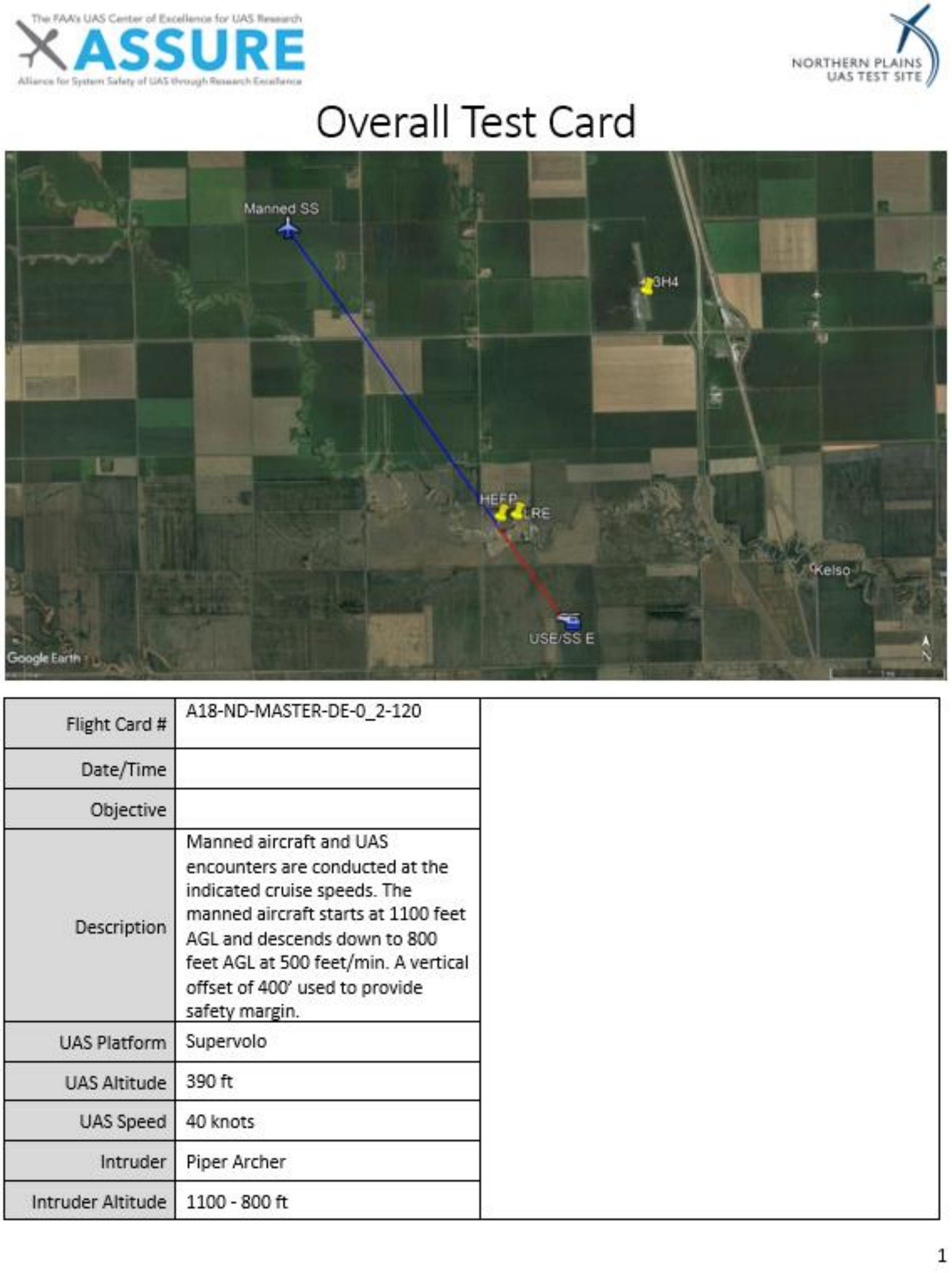
	The SuperVolo is a long range, Vertical Take-Off and Landing (VTOL) UAS designed for simplified deployment/ease of use. It utilizes a hybrid gas/electric power plant. The SuperVolo enables quick refueling for successive flights and requires very little ground infrastructure for operations. It also features a modular airframe that enables diverse payload configurations and cost-effective maintenance.		
Wing Span	3.0 m	**Cruise Speed**	18-34 m s^{-1}
Maximum Takeoff Weight	18.2 kg	**UAS Operator**	ISight Drone Services
Endurance	8 hrs	**GCS Type**	ACER computer with Swift GCS
Autopilot	CUAV PixHawk – Mavlink		

Table 8. Information regarding the intruder aircraft used during the June 2021 UND campaign.

	The Piper Archer is a two-seat, tricycle-gear general aviation airplane that is used heavily in UND's aviation education and training programs.		
Wing Span	35 ft 6 in	**Cruise Speed**	128 kts
Maximum Takeoff Weight	2,550 lb	**Operator**	UND
Fuel Capacity	50 US gal		

3.6.6 Sample Test Cards

Test cards were developed for three roles: FTD, UA pilot, and CA pilot. A total of 18 cards [(4 horizontal scenarios + 2 descend-into scenarios) x 1 intruder speed x 3 roles] supported this test campaign. For brevity, the FTD test card for one scenario is provided here (Figure 44).

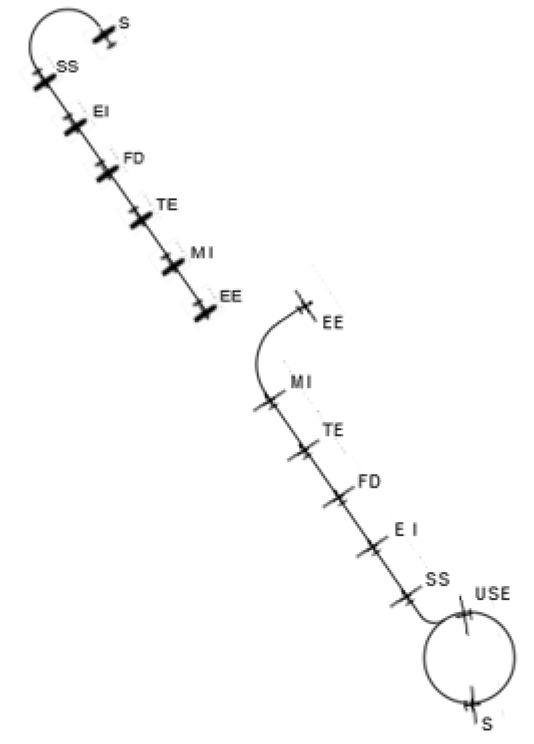


Overall Test Card

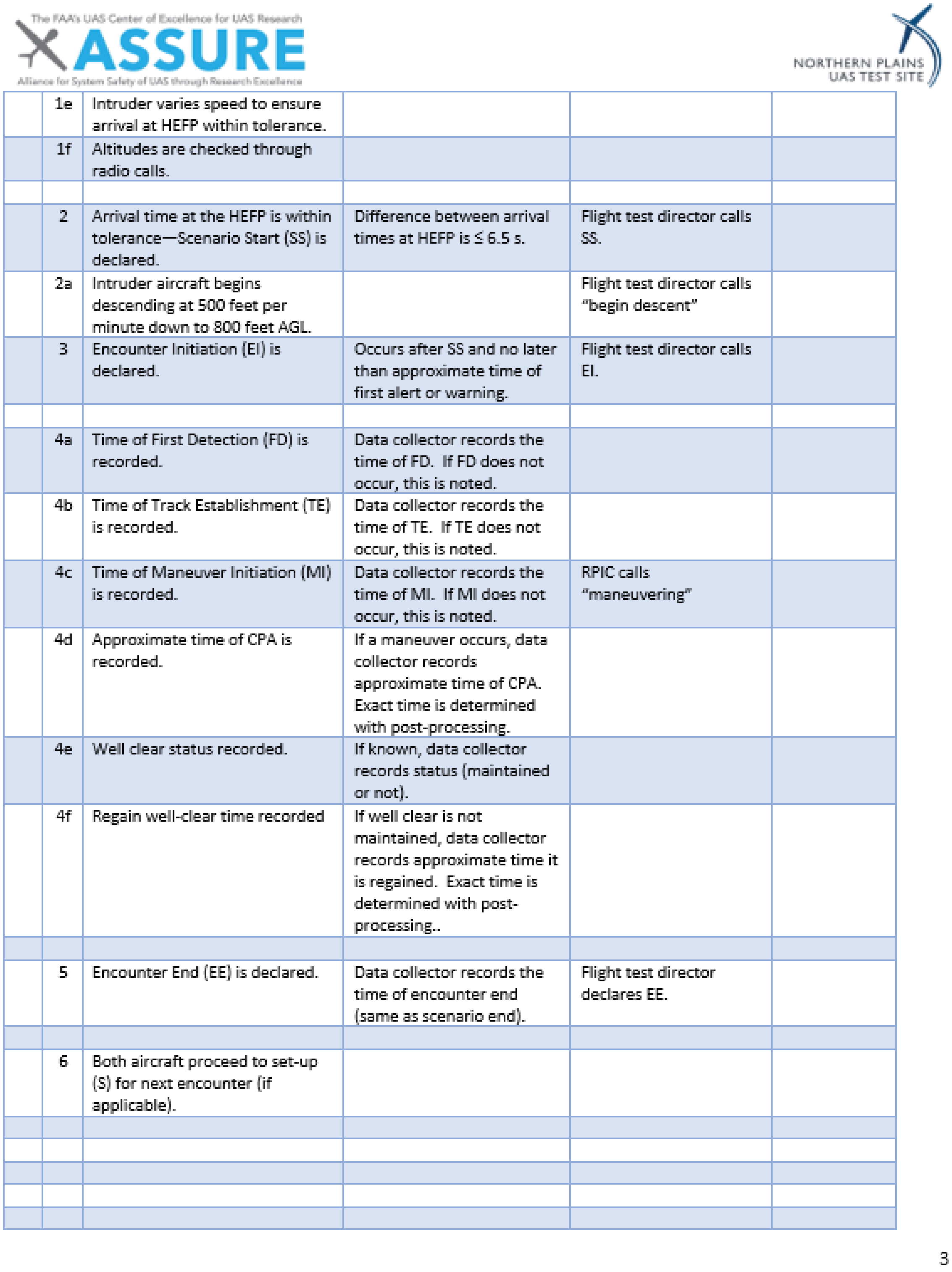
Flight Card #	A18-ND-MASTER-DE-0_2-120
Date/Time	
Objective	
Description	Manned aircraft and UAS encounters are conducted at the indicated cruise speeds. The manned aircraft starts at 1100 feet AGL and descends down to 800 feet AGL at 500 feet/min. A vertical offset of 400' used to provide safety margin.
UAS Platform	Supervolo
UAS Altitude	390 ft
UAS Speed	40 knots
Intruder	Piper Archer
Intruder Altitude	1100 - 800 ft

1

Intruder Speed	120 knots
Location	47.328505, -97.087696. Lovas Farmstead.
GCS	Mission Planner
DAA System ID	L3Harris GBDAA
DAA Sensors	Xtend ADS-B Receiver, C-Speed Radar, FAA NextGen (VAS)
Supporting Technology	NPUASTS trailers, visualization systems, additional ADS-B receivers, video cameras, DCAPS data recording
Intruder Pilot	
RPIC	
VOs	
MC	
FD	
COA/Waiver(s)	



Condition # (objective)					
✓		Action	Remarks	Call	Time
	1a	UA maintains position at defined stand-off location ~5649 ft (~1.07 mi) from the Horizontal Encounter Focal Point (HEFP) as manned aircraft flies loop away from encounter location to set-up (S) for this encounter.	Point E 47.315149°, -97.075449°	RPIC calls "holding at point E"	
	1b	Intruder executes turn at defined ground point ~17,160 ft (~3.25 mi) from HEFP during (S) at 1100 feet AGL.	This is driven by the DAA technology, the warning/alert system, and UA speed. 47.365509°, -97.126405°	Intruder calls "Holding NW"	
	1c	Intruder begins flying straight along its encounter path towards Scenario Start (SS).			
	1d	UA exits (S) and proceeds towards SS once intruder begins exits its set-up turn.		Flight test director calls UA set up exit (USE).	



	1e	Intruder varies speed to ensure arrival at HEFP within tolerance.			
	1f	Altitudes are checked through radio calls.			
	2	Arrival time at the HEFP is within tolerance—Scenario Start (SS) is declared.	Difference between arrival times at HEFP is ≤ 6.5 s.	Flight test director calls SS.	
	2a	Intruder aircraft begins descending at 500 feet per minute down to 800 feet AGL.		Flight test director calls “begin descent”	
	3	Encounter Initiation (EI) is declared.	Occurs after SS and no later than approximate time of first alert or warning.	Flight test director calls EI.	
	4a	Time of First Detection (FD) is recorded.	Data collector records the time of FD. If FD does not occur, this is noted.		
	4b	Time of Track Establishment (TE) is recorded.	Data collector records the time of TE. If TE does not occur, this is noted.		
	4c	Time of Maneuver Initiation (MI) is recorded.	Data collector records the time of MI. If MI does not occur, this is noted.	RPIC calls “maneuvering”	
	4d	Approximate time of CPA is recorded.	If a maneuver occurs, data collector records approximate time of CPA. Exact time is determined with post-processing.		
	4e	Well clear status recorded.	If known, data collector records status (maintained or not).		
	4f	Regain well-clear time recorded	If well clear is not maintained, data collector records approximate time it is regained. Exact time is determined with post-processing..		
	5	Encounter End (EE) is declared.	Data collector records the time of encounter end (same as scenario end).	Flight test director declares EE.	
	6	Both aircraft proceed to set-up (S) for next encounter (if applicable).			

3

Figure 44. Example FTD test card for the June 2021 UND campaign.

3.6.7 Summary of Results

The vertical aircraft safety offset was increased 50 ft relative to that used by Askelson (2022) to 400 ft. This helped ensure desired aircraft separation. The biggest enabler for ensuring maintenance of vertical well clear during testing, however, was CA altitude monitoring in which CA altitudes were adjusted if they were deemed to be too low. These resulted in no vertical well clear violations occurring during the June 2021 test campaign. For descend-into encounters, CA descent was halted to preserve a 400 ft vertical safety offset between aircraft. The pilots were successful at halting their descent as planned, as the minimum vertical offset for the 10 descend-into encounters was 403 ft.

In addition to metrics developed by Askelson (2022), an encounter descriptor/metric labelled coast period was added. This is needed because of flight of the UA under Part 107 rules, without the use of daisy-chained observers, and the speed of the UA resulting in it reaching the visual range limit associated with Part 107 prior to the time when aircraft separation was minimized. When that limit was reached, the aircraft was directed to station-keep (fly circles around a defined location). To obtain results consistent with a BVLOS type of operation in which such station-keeping would not generally occur, the straight-line portion of the UA path associated with its maneuver was extrapolated forward/coasted.

Execution of more encounters for given scenarios did not consistently reduce the standard deviation of the aircraft separation metric analyzed herein. It did, however, reduce uncertainty in both the mean and standard deviations of that metric.

No horizontal well clear violations occurred during this test campaign, resulting in a loss of well clear risk ratio for this subset of encounter scenarios of 0.0. Uncertainty windows for this subset of encounters ranged from 0.0-0.01 to 0.0-0.02. The exceptional performance of the SuperVolo UA that was used in these tests—especially its cruising speed (up to ~66 kts), significantly enabled maintenance of horizontal well clear.

3.6.8 Lessons Learned

Lessons learned from this round of flight tests include:

- Failures associated with testing occur, including ones experienced during this round of flight tests:
    - Ingestion of UA telemetry into the DAA system can be a major challenge. It resulted in a significant delay in data collection during the June 2021 tests.
- Detection challenges occur
    - ADS-B drop-outs did occur and seemed to be focused on a certain location.
    - Primary tracks (radar) did not always arise for aircraft taking-off and landing at the airport.
- Display glitches can occur
    - Occasionally the locations of UA and CA did not update on RangeVue™ Pro
        - This resulted in aircraft positions "jumping"

3.7 NMSU Fall 2021

The NMSU UASTS planned to execute an equivalent of 5 days of flight testing in the Fall of 2021. Each flight set had multiple encounters profiles. Each profile was planned to be flown a minimum of 5 times with data collected during each event. Both ground based and airborne systems have been tested as part of the A18 research arc. Each has advantages and challenges. The A18 team tested a number of different systems in UA to CA encounters, and UA to UA encounters that have been completed with safe separation distances. Areas identified as challenges are the climb-into and descend-into encounters. These might be experienced with crop dusters or other CA flying specific low-altitude missions/operations. This testing addressed these climb-into and descend-into types of encounters.

3.7.1 Objectives

This effort was designed to evaluate methods for testing DAA technologies by looking at types of operations, defining collected data parameters, and defining data processing required for validation of DAA technologies. The test methodology for DAA systems generally follows a phased approach wherein the first phase is to understand what the system can do in simulation space before advancing to flight test phases. For flight tests, the simplest encounters were executed using an altitude offset. Subsequent testing was executed where encounters become co-altitude by including descend/climb-into encounters. Encounter profiles were planned to allow for the Iris CasiaX system to detect an intruder aircraft from multiple angles and altitudes.

In previous DAA testing the A18 team tested a number of different systems UA to CA and UA to UA encounters. For the planned climb-into and descend-into encounters, safe vertical offsets could not be maintained with a UAS by the very nature of the test profiles. Once the vertical offset is violated, the question of what lateral offset is required arises. To address this paradox and to ensure safe flights, the DAA system was installed on a CA that served as a proxy UAS. This allowed two CA with VOs onboard to safely and legally execute the planned encounters. Vertical and lateral offsets were incorporated into the test cards for safety. The planned number encounters for the planned scenarios for this campaign are provided in Table 9.

Table 9. Planned number of encounters for encounter scenarios for the Fall 2021 NMSU campaign.

Test Card	Test Card Description	Planned Number of encounters
1	Compass rose encounter(s)	20
2	Intruder descends behind UAS	5 x 2 = 10
3	Intruder climbs behind of UAS	5 x 2 = 10
4	Intruder descends in front of UAS	5 x 2 = 10
5	Intruder climbs in front of UAS	5 x 2 = 10
6	UAS climbs in front of Intruder *	5
7	UAS descends in front of Intruder *	5
	Total Encounters	70

3.7.2 Dates/Schedule

The flight testing was scheduled to occur during several periods to allow for testing of like encounters on specific days to ensure safety. The team felt that it was safer to not mix different types of encounters within a single day, but to do all encounters of the same type one day, and then reset for the next configuration on subsequent days. This allowed the pilots and onboard VOs to only concentrate on one type of flight profile for consistency and safety.

The Compass Rose encounters were competed on 21 October 2021 during two rounds of flights. Initial data processing was completed after these flights to ensure system capture of the information and as a check on the flight planning and procedures. The Intruder Climb/Descend Behind encounters were executed on 16 November 2021 during two rounds of flights. The Intruder Climb/Descend In Front encounters were executed on 17 November 2021 during two rounds of flights. A short fueling and "leg stretching" break was inserted between the flights each day.

3.7.3 Location

Both aircraft launched from the Las Cruces International Airport (KLRU). Generally, most of the flight maneuvers took place away from the airport so as to minimize impact on general aviation operations. The area is sparsely populated and all maneuvering was performed at or below 6500 ft MSL. To maintain safety, both aircraft involved in the operation had ADS-B in/out installed so that pilots had a high level of situational awareness and to allow for smoother setup for encounters. Figure 45 provides a plan view of the test area for this campaign.

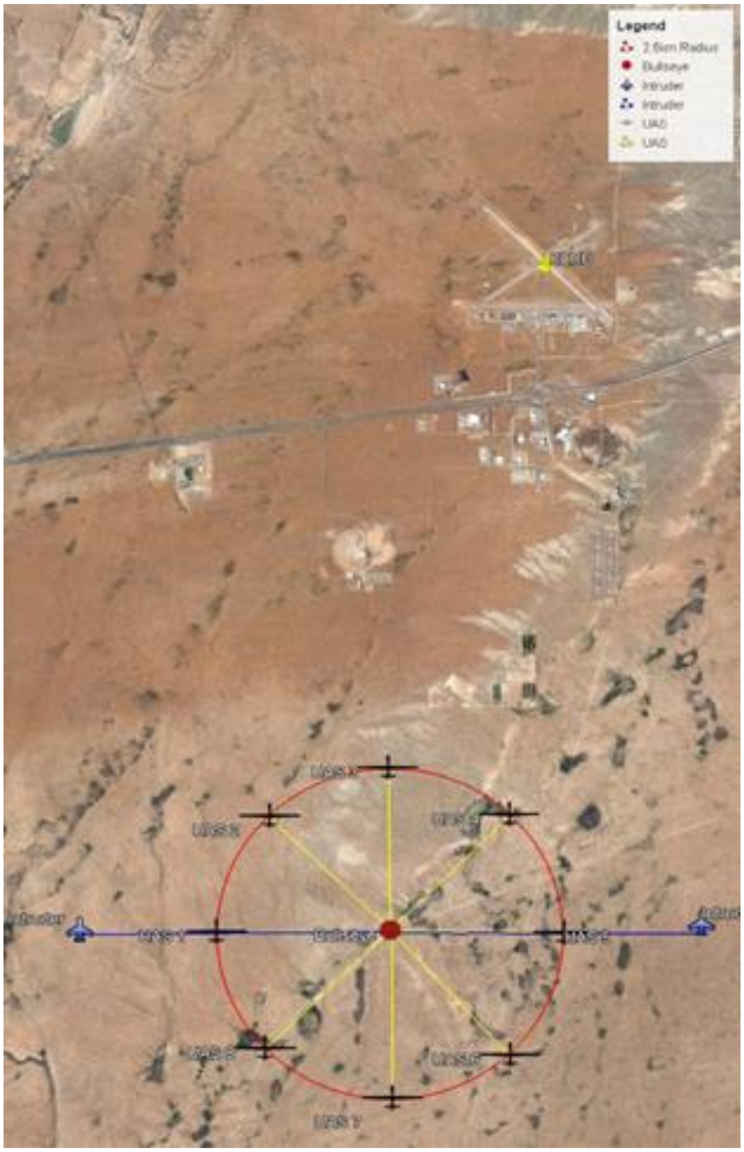


Figure 45. Plan view of the test area for the Fall 2021 NMSU campaign.

3.7.4 System Tested

Testing was conducted using the Iris Automation CasiaX DAA system, which is a multi-camera vision-based DAA system. Differences from previous testing are that this system used 5 cameras for a 360° view (versus one camera used in previous tests) and how the system as integrated. Table 10 outlines the technologies used.

Table 10. DAA system used in the Fall 2021 NMSU campaign.

Iris Automation, CasiaX	Sensor: Vision Based DAA	Casia X is the first commercially available 50° Vertical and 360° radial computer vision DAA system for UAS. It also has a viewing range of 1.5 km. As an integrated

		onboard hardware and software solution, Casia systems are small, light and low power.

The Iris CasiaX system was designed pursuant to the emerging ASTM standards for performance risk-ratios. All Casia systems combine ultra-lightweight and compact hardware with software that integrates with most industrial drones (Figure 46). Figures 47-49 illustrate how the CasiaX cameras were mounted for this test campaign.

Figure 46. The Iris CasiaX system.

Figure 47. CasiaX cameras mounted on the left wing of ownship.

Figure 48. CasiaX cameras mounted on the right wing of ownship.

Figure 49. CasiaX camera mounted on the front of ownship.

3.7.5 Test Plan Overview

The NMSU UASTS utilized a Flight Star E-LSA as a UAS surrogate. The CasiaX system was integrated onto this aircraft. This was used for an increased level of safety during the climb-into and descend-into flight encounters. The Flight Star E-LSA is a small 2 seat ultralight. The intruder was a Flight Design CTLS owned and operated by NMSU.

The configuration for horizontal encounters is provided in Figure 50. The CasiaX DAA system has a nominal range of 1.5 km and a FoV of 360º horizontal x 50º vertical. With this information the encounters were designed around the compass rose. Encounters begin at a distance beyond the range of the vision system. The intruder either approaches from the east or the west with the UA surrogate flying toward the center bullseye. The UA surrogate and the intruder will be separated by 500 ft vertically during this phase of testing. Both the UA surrogate and intruder are CA with dedicated pilots and VOs to help ensure safety.

The configurations of climb- and descend-into encounters are provided in Figure 51. For these encounters, the ascent/descent rate of 500 ft min^{-1} was used based on previous tests.

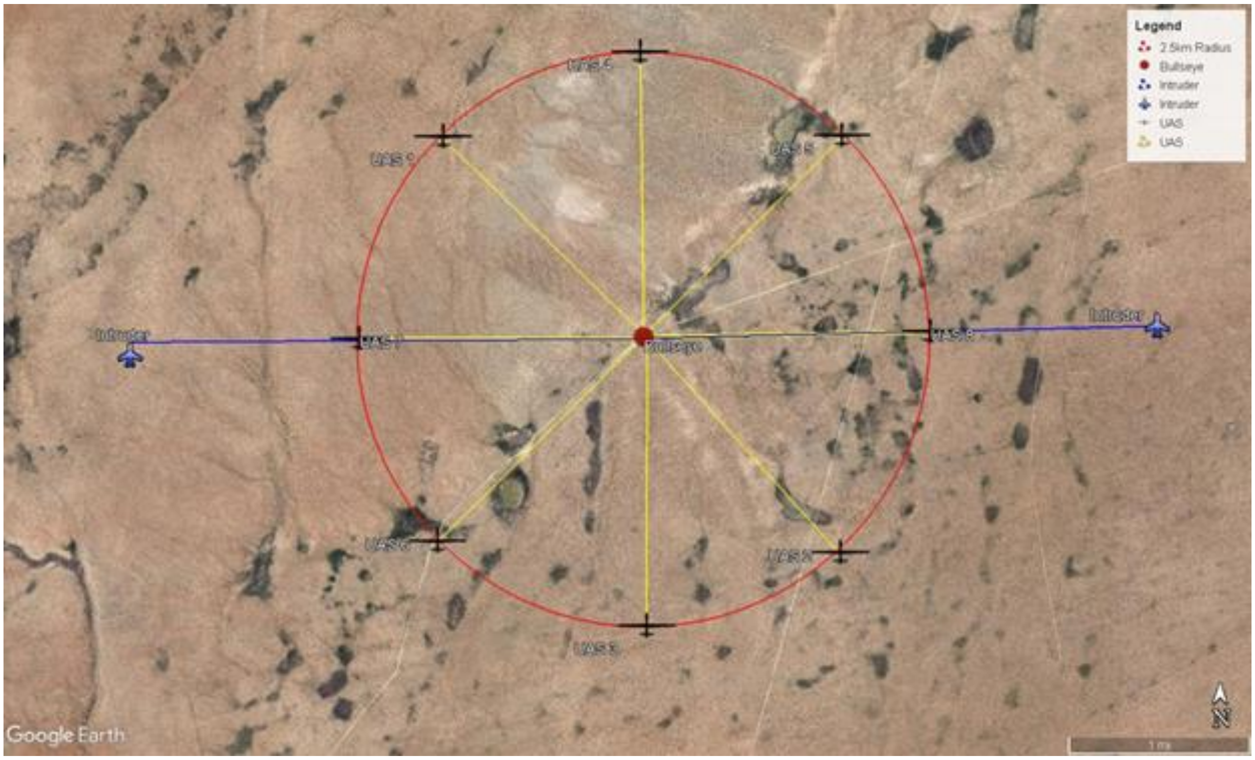


Figure 50. Configuration of horizontal encounters executed during the Fall 2021 NMSU campaign.

Intruder Descends Behind UAS

Intruder Climbs Behind UAS

Intruder Climbs Ahead of UAS

Intruder Descends Ahead of UAS

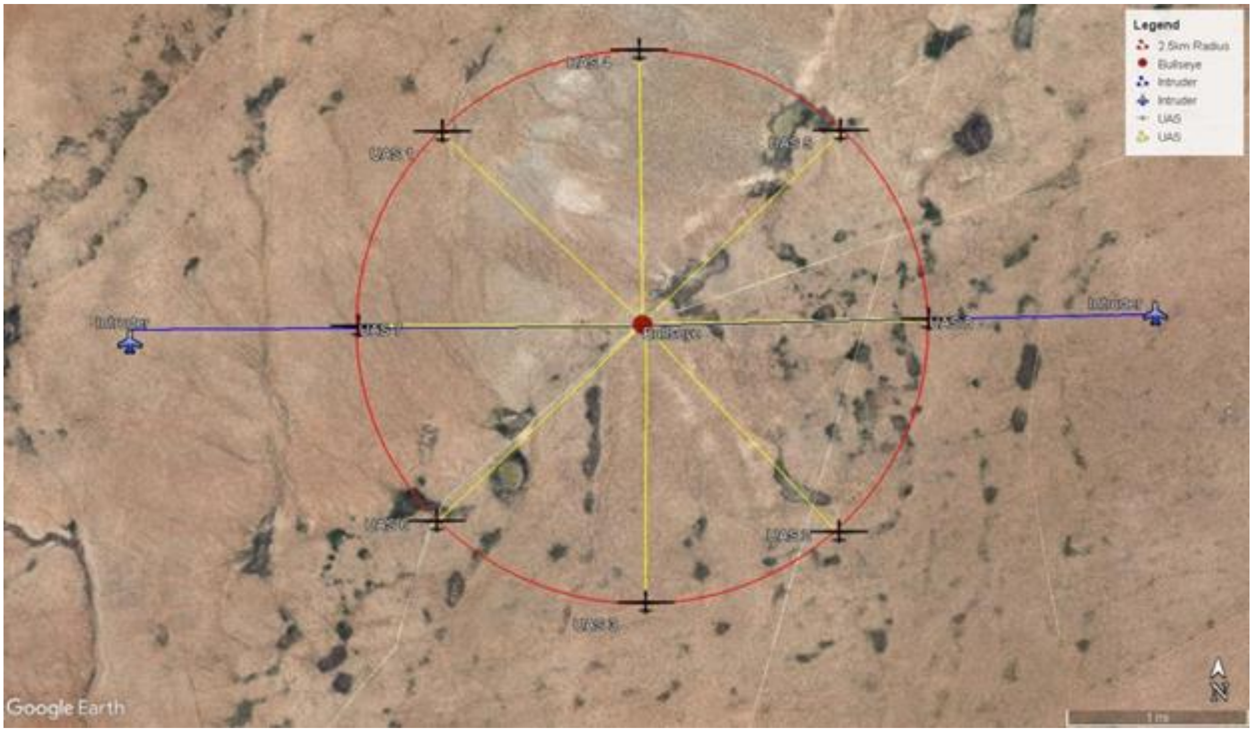
UAS Climbs Ahead of Intruder

UAS Descends Ahead of Intruder

Figure 51. Configuration of climb- and descend-into encounters executed during the Fall 2021 NMSU campaign.

3.7.6 Sample Test Cards

Encounters can be organized into two groups: the “compass rose” and the various climb-into and descend-into encounters. Figure 52 provides the compass rose test card, while Figure 53 provides a sample of the climb-into and descend-into encounters.

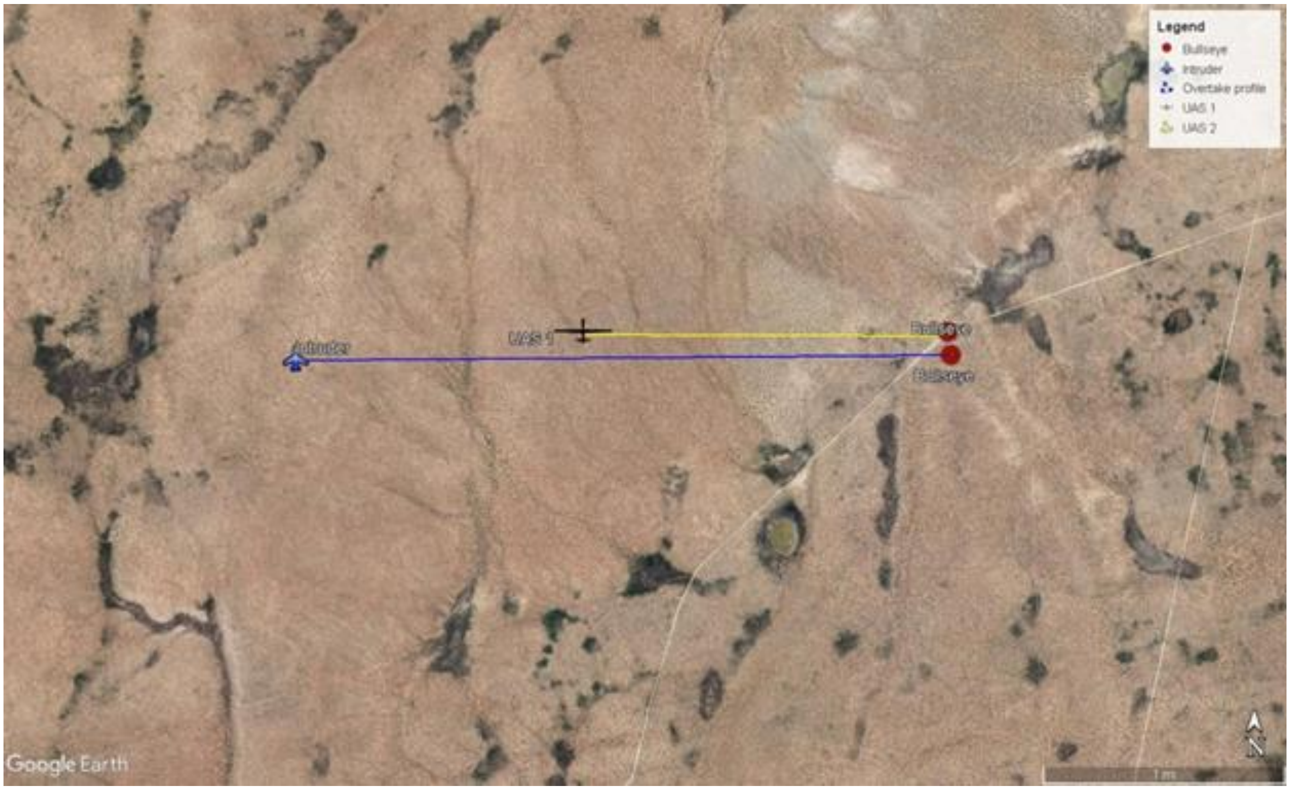


Flight Card #	NMSU_NM_DAA_Iris Test 1	The Intruder will fly both directions east to west and then west to east. The intruder will maintain an altitude of 7000' MSL at all times during the encounters. The UAS will start at WP 1 and fly the lines in sequential order crossing over the bullseye each time. This includes three encounter angles plus head on and following. The UAS will maintain 6000'MSL at all times during the encounters. This this portion will be repeated 5 times (20 total encounters).
Date/Time	TBD	
Objective	**Primary:** This will test the FOV of the Iris DAA while an intruder is crossing the path from right to left. **Secondary:**	
Description	Descending behind UAS	
UAS Platform	Flight Star SCII (UAS Surrogate)	
UAS Altitude	6000' MSL descending 500 fpm	
UAS Speed	60 mph (52 kts)	
Intruder	CTLS Light Sport	
Intruder Altitude	7000' MSL	
Intruder Speed	80 mph (70 kts)	
Location	Las Cruces, 5 NM from airport	

GCS	N/A
DAA System ID	CasiaX (360)
DAA Sensors	5 Cameras
Supporting Technology	(Vision Base)
Intruder PIC	
Intruder VO	
Surrogate UAS PIC	
Surrogate UAS VO	

Condition # (objective)					
		Action	**Remarks**	**Call**	**Time**
	1	Get to Starting altitudes UAS 6000’ MSL / Intruder 7000’MSL			
	2	Line up with initial WP			
	3	Fly to bulls eye			
	4	Reset-for total of 5 encounters			
	5				
	6				
	7				

Figure 52. Compass rose test card used during the Fall 2021 NMSU campaign.



Flight Card #	NMSU_NM_DAA_Iris Test 2	The Intruder will start at 8000’ MSL and 2 km behind the UAS. Once the Intruder and the UAS are at the designated waypoints, the intruder will start a 500fpm decent until an altitude of 6000’ MSL The Profile will keep the UAS and Intruder 1000’ horizontal separation. The UAS will Maintain an altitude of 7000’MSL and fly to bullseye. This Card will be repeated 5 times.
Date/Time	TBD	
Objective	**Primary:** This will test the FOV of the Iris DAA while an intruder is crossing the path from above and to the rear of the UAS. **Secondary:**	
Description	Descending behind UAS	
UAS Platform	Flight Star SCII (UAS Surrogate)	
UAS Altitude	7000’ MSL	
UAS Speed	60 mph (52 kts)	
Intruder	CTLS Light Sport	
Intruder Altitude	8000’ MSL descending 500 fpm	
Intruder Speed	80 mph (70 kts)	

Location	Las Cruces, 5 NM from airport
GCS	N/A
DAA System ID	CasiaX (360)
DAA Sensors	5 Cameras
Supporting Technology	(Vision Base)
Intruder PIC	
Intruder VO	
Surrogate UAS PIC	
Surrogate UAS VO	

Condition # (objective)					
		Action	**Remarks**	**Call**	**Time**
	1	Get to Starting altitudes UAS 7000’ MSL / Intruder 8000’MSL			
	2	Line up with initial WP			
	3	Once waypoint is met, intruder will begin 500 fpm decent			
	4	Fly to bulls eye			
	5	Reset for total of 10 encounters			
	6				
	7				

Figure 53. Intruder descend behind test card used during the Fall 2021 NMSU campaign.

3.7.7 Summary of Results

Testing took place over two different time periods in the Fall of 2021. The “compass rose” encounters were flown on 21 October 2021. The “rise into” and “descend into” encounters were flown over two days on 16 and 17 November 2021. The full test report with details are included in Cathey et al. (2022) which covers the test planning, setup, encounter geometries, test cards, and results. It should be noted that the DAA system also had ADS-B as part of the detection filters. It was able to identify aircraft via ADS-B as well as the visual system. During testing, the intruder aircraft as well as commercial aircraft in the area (for example, American Airlines flights passing over at > 20,000 ft) were detected. For these analyses, the ADS-B detections were filtered out and just the visual system detections were analyzed to better simulate non-cooperative aircraft.

The compass rose encounters were also used as an initial test of the five-camera system to assess the effectiveness of the integration of the system and to collect data for what was considered the more straight-forward test patterns. The surrogate UAS performed basically East-West passes and the intruder crossed this path from different encounter angles. As noted, a built-in vertical aircraft offset was used during these runs.

Challenges with the timing of encounters arose in which it was difficult to make both aircraft cross the approximate center point of the planned testing geometry at/around the same time. This was not as difficult with the compass rose encounters. Overall, the detections and tracking of aircraft throughout the compass rose encounters was as expected. The five-camera system detected the intruder aircraft at all encounter geometries. Detections were where the aircraft were actually located and at ranges comparable to the published detection ranges. Simply put, there were no real surprises or issues with the operation of the system. Post testing review of the data showed some slight tuning of the elevation and overlapping of the cameras was required. Overall this was very minor.

The “climb into” and “descend into” runs were completed over two days. As noted previously, timing challenges affected these encounters. These were exacerbated by the additional timing element related to climbing or descending in front of or behind the other aircraft. These encounter geometries were easy to design on paper and were much more difficult to implement in flight with the added time dimension. It is easy to make an aircraft climb or descend along a desired path, but more difficult to do this when it has to be perfectly timed with another aircraft also moving across the test space. The aircraft are always in motion so they have pre-test-event timing that has to consider the flight time and patterns to get both aircraft into the desired start positions when they begin a run. This was a challenge.

The first day of these tests was 16 November 2021. The testing was divided into two sets of sorties. This was mainly due to the flight time of the Spyder. This aircraft was flown for a period of time, landed, refueled, and then flown again. The Spyder, with the DAA system installed, flew a basically level flight and the intruder CTLS performed the climb-into and descend-into encounters. The challenge of test timing noted above is clearly apparent in Figure 54.

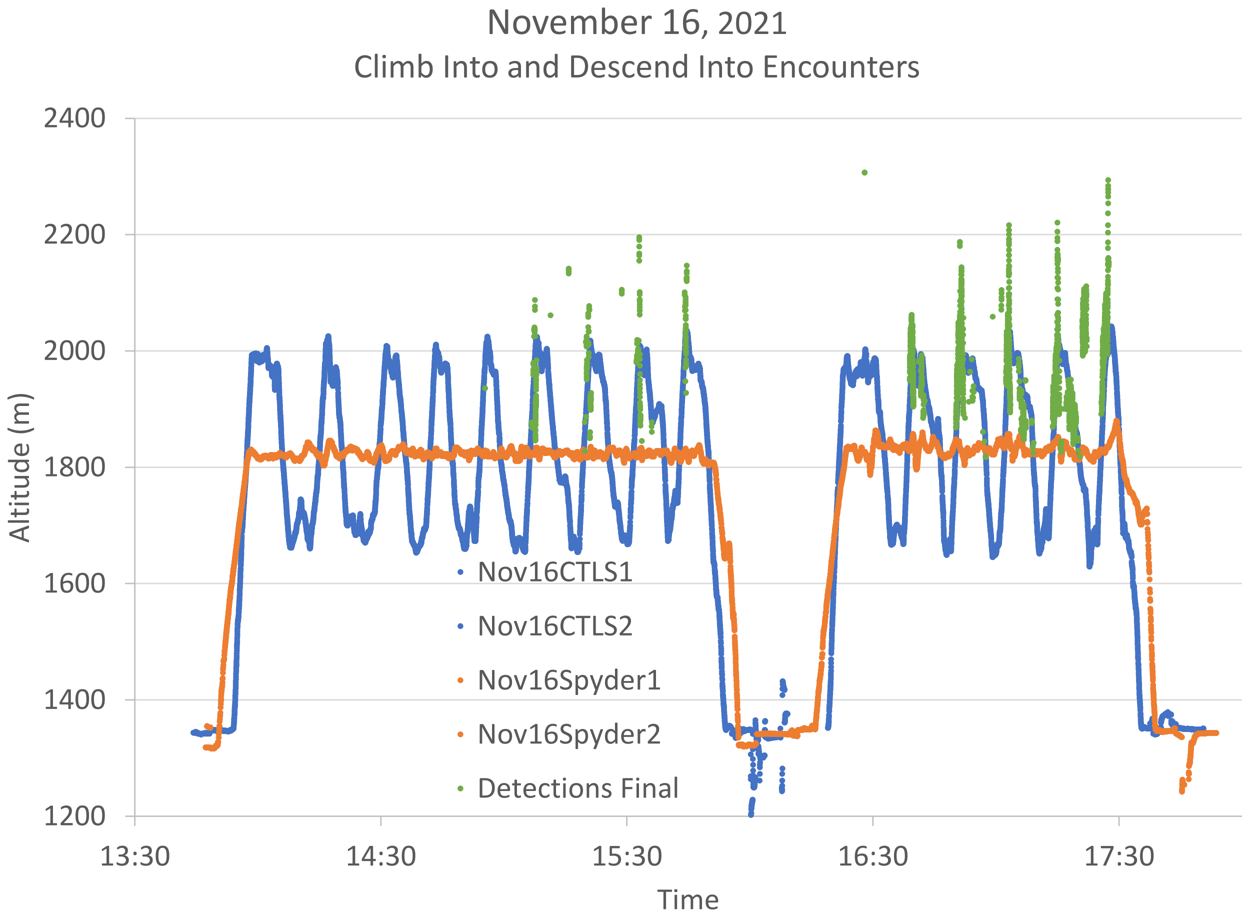


Figure 54. 16 November 2021 flight profiles and detections. Orange dots represent the altitude of the Spyder (with DAA system), blue dots are CTLS intruder altitudes, and green dots are detections.

The first half of the first round of sorties showed zero detections. This was not a reflection of the performance of the DAA system, but resulted from the challenge with setting up the timing of the encounters to put the aircraft into the right places at the right times with the ascent or descent profiles. The first four passes did not result in any detections, and the fifth one had a single detection at one point. The flight team realized they were not positioning the aircraft as desired and adjusted the start timing and positioning for subsequent runs. The detections for the balance of the runs were much more consistent. The same plot as above with revised scales is shown in Figure 55.

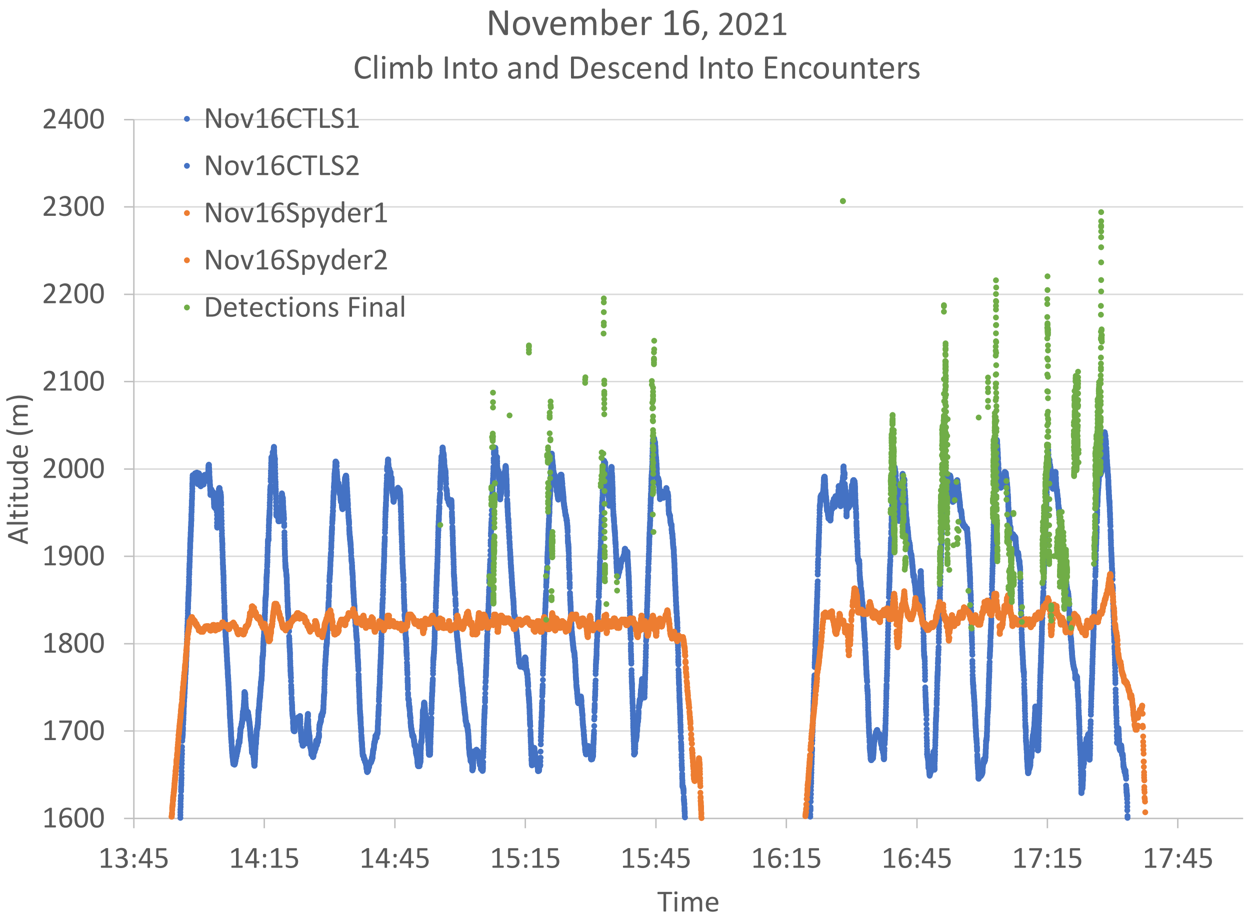


Figure 55. As in Figure 54, but with revised scales.

The test flights revealed a challenge with completing all of the planned test cards. The UAS climb-into and descend-into cards were problematic given the aircraft used for that role. The Spyder has a hard time climbing within the test encounter area (timing and geometry challenge) and it is likely that these encounters will have to be omitted in future testing. The Spyder Ultralight is really slow at climbing, meaning that modifications to the profiles are needed to enable transitions from one encounter the another.

The second day of testing was completed on 17 November 2021. Similar plots for the flight altitudes and detections are provided in Figures 56 and 57.

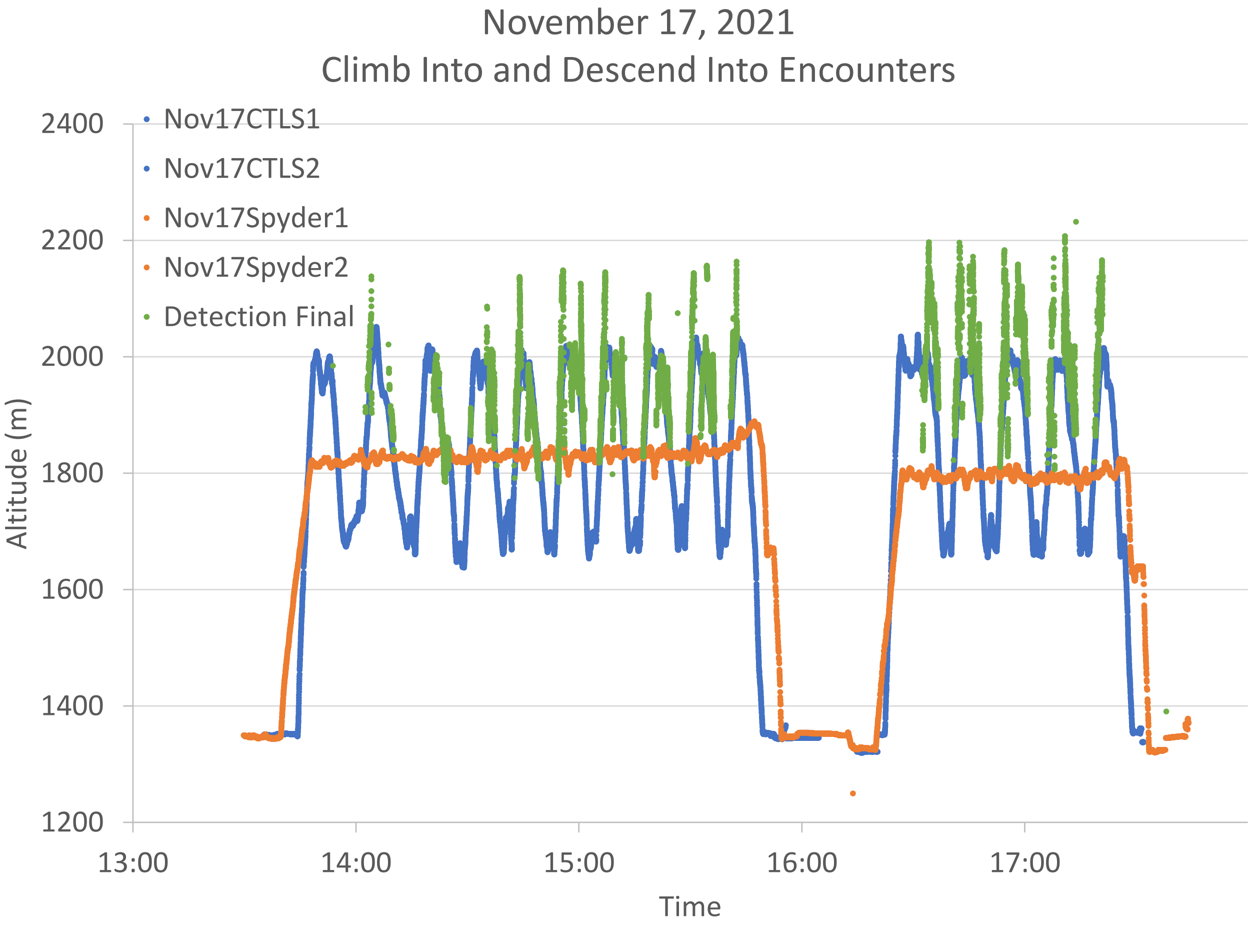


Figure 56. As in Figure 54 but for 17 November 2021 flight profiles and detections.

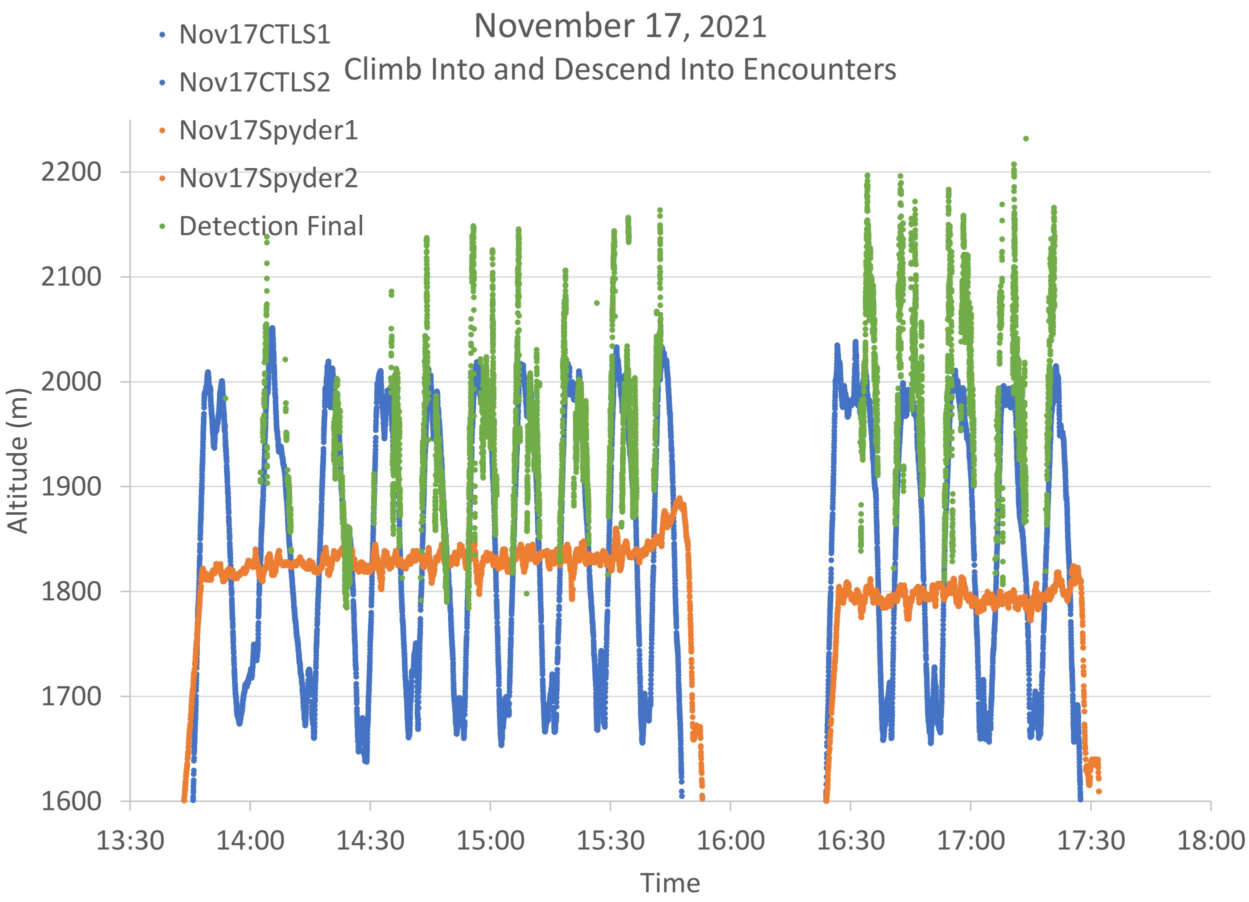


Figure 57. As in Figure 56, but with revised scales.

A closer look at the first set of flights on 17 November 2021 is provided in Figure 58. This figure best illustrates what was observed during the testing.

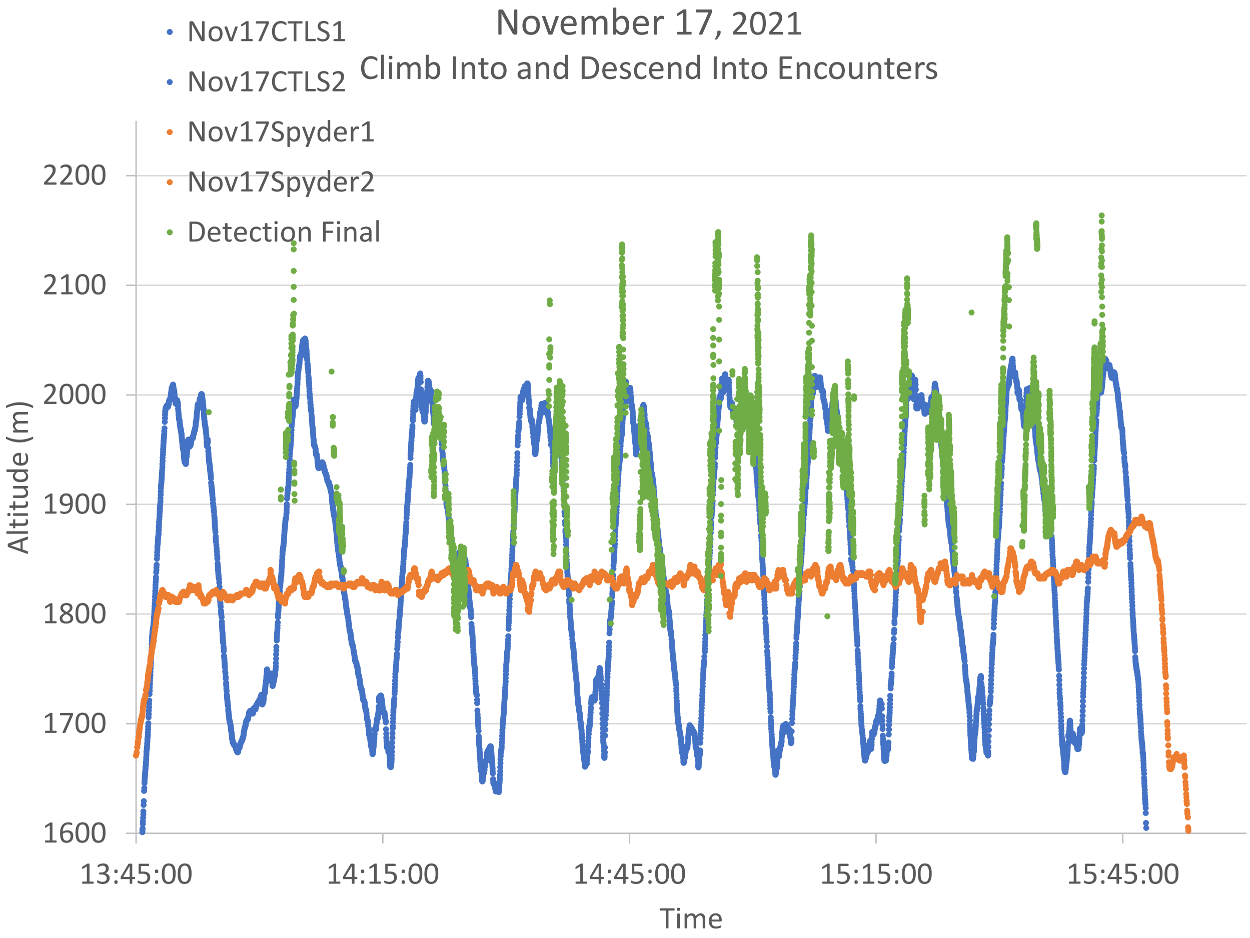


Figure 58. As in Figure 56, but with a change of scales (zoomed-in).

A number of conclusions can be drawn from these data. Detections are apparent during ascend-into encounters when the intruder aircraft is ascending. The same is true for similar descend-into encounters. Both are indicated in Figures 54-58 where the 'green' detections are overlaid with the intruder altitude. Run 3 in Figure 58 is a clear example of a descend-into encounter. The last run in Figure 58 is a clear example of an ascend-into encounter. For many of the encounters, the aircraft was detected visually for much of the ascent and descent trajectories when the aircraft were in visual range and the detections were at or above the simulated UAS's altitude.

The major finding from these tests is that almost all of the detections occurred when the intruder aircraft was at or above the simulated UAS flight altitude. This occurs for a number of potential reasons. The system design and tuning are the first considerations. The DAA system was not designed/tuned to look below the horizon for aircraft so the ascent portion of the ascend-into encounters (before reaching approximate co-altitude) had limited detections. The system is tuned using thousands of images of aircraft. These are generally with sky as the background to the intruder aircraft.

Testing geometry is the second consideration and is related to the first consideration. The intruder aircraft flying below the UAS altitude generally put the intruder aircraft into a position where it had the ground and ground clutter as background. This is a much more challenging visual detection, not only for the systems as configured, but also in reality with the background.

Detections were best when the intruder was above the plane of the simulated UAS. Detections above the DAA system's altitude were quite good. The detections where the system was looking downward from horizontal were not as good. The detections of the intruder aircraft were good when the aircraft was above the simulated UAS altitude, but were limited after the descent portion of the descend-into encounters. The aircraft were tracked for longer periods when above the DAA system's altitude.

The detection locations and altitudes are very close to the actual intruder location. The further away the two aircraft are, the greater the uncertainty, but the estimated altitudes were generally within 100-150 m.

3.7.8 Lessons Learned

A number of specific lessons learned that covered the initial system integration through testing and performance arose from this effort. These are noted below. The lessons learned from the test planning and integration are as follows:

- Close encounter testing of a UAS and a manned aircraft is difficult. Testing of these types of systems proposed for UAS operations cannot be easily safely or legally tested where very close encounters with CA are required. Surrogate or proxy tests using two CA was used to replicate this.
- Two aircraft with pilots onboard can be employed to safely replicate a CA intruder with UAS encounters.
- This particular DAA system was generally designed to be used on a UAS at lower altitudes. Planning for the encounters required an adjustment of the crossing altitudes needed to perform these tests safely.

Lessons learned related to the integration of this specific system into the aircraft include:

- Time to integrate and test the Iris system was more time-consuming than anticipated. Planning more time for this type of integration and flight testing prior to the research flight is suggested.
- Adapting a sUAS autopilot into the Spyder for data recording presented some challenges with extensions and placement of the GPS to prevent GPS glitches.
- Initial flight testing was required after integration to adjust the camera elevation and overlap. This was very minor, but a step to be included in planning.

Flight testing reveled some additional lessons learned:

- Having 2 pilots in each aircraft provided an extra set of eyes looking for the intruder/surrogate UAS as well as additional aircraft operating in the area.
- The Spyder Ultralight is really slow at climbing. Modifications to the profiles are needed to enable effective transitions from one encounter another.
- UAS climb-into and descend-into encounters are problematic. The Spyder has a hard time climbing within the test encounter area (timing and geometry challenge) and it is likely that these encounters will be omitted in future testing.
- The uAvionic telemetry system allowed for ideal connectivity during long-range operations. Tracking and monitoring of both the Spyder (telemetry) and CTLS (ADS-B)

were effective. Constant contact with both aircraft allowed for enhanced situational awareness.

- During some of the descend behind the UAS encounters, relatively poor visibility down and in front of the CTLS made it hard to maintain visibility of the Spyder. Use of ADS-B and iPads allowed for maintenance of situational awareness.

Lessons learned related to post flight operations and the DAA system performance include:

- The DAA system tested was designed for operational use and the encounter data were not easy to extract for analysis. It is quite easy to assess an individual encounter or series of encounters using the vendor's post flight tools, but more difficult to actually use the raw extracted encounter data. To be fair, the raw data formats from the vendor were not set up for the type of post-flight assessment performed by the team.
- The DAA system produced very good estimates of intruder aircraft altitude.
- Detections above the DAA system's altitude were quite good. The detections where the system was looking downward from horizontal were not as good. Again, it should be noted that the system was not designed/tuned to look below the horizon for aircraft so the ascent portion of the ascend-into encounters (before reaching approximate co-altitude) had limited detections. The detections of the intruder aircraft were good when the aircraft was above the simulated UAS altitude, but were limited after the descent portion of the descend-into encounters.

4 OTHER TASKS/ADDITIONAL MATERIAL

4.1 OSU Radar System Development and Testing

In addition to the flight testing described in Section 3, the Ohio State University (OSU) developed and tested a passive radar system that could be utilized, with further development, for DAA. This system leverages reflections from aircraft of existing terrestrial television broadcasts. During A18, this system was matured from a prototype system with non-real-time data processing of detections to a system with real-time detection and tracking having a 2 s update rate. The system leverages a passive detection array that enables estimation of target location (Figure 59). One of the advantages of such a system is it does not require a transmitter (since it is passive), which decreases cost and size, weight, and power requirements.

Figure 59. Image of the OSU passive radar system.

The OSU team obtained promising results with their system, as illustrated in Figure 60. Given the cost and SWaP benefits of such a system, this approach is promising for GBDAA. Future work would include further evaluation in a DAA context, further evaluation of system characteristics (e.g., track accuracy), clutter susceptibility, etc.

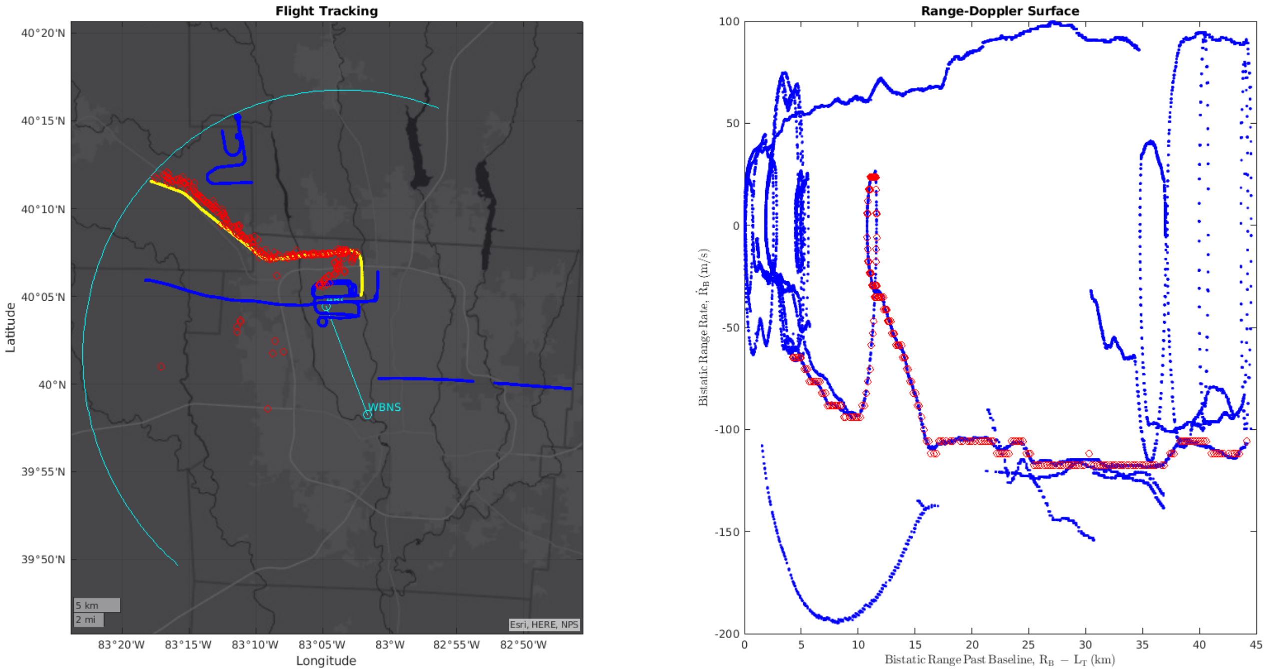


Figure 60. Results obtained with the OSU passive radar system. The figure on the left shows a track developed with the radar (yellow) and associated ADS-B detections (red diamonds) for that aircraft. The figure on the right shows range-rate versus range for tracked objects with ADS-B detections for a tracked aircraft (red diamonds).

5 CONCLUSIONS

This effort addressed critical questions associated with sUAS DAA, including:

- What are the use cases requiring DAA for BVLOS operations?
- What DAA systems are available, what are their capabilities and limitations, and are they mature enough to support BVLOS operations?
- What characteristics of DAA systems and UASs must be considered to ensure maintenance of well clear status?
- How should sUAS DAA systems be evaluated to ensure they provide safe separation services in the NAS?
- What is the recommended test method(s) to evaluate different DAA systems?

These were addressed through execution of the following tasks:

1. Development of an Operational Framework for sUAS BVLOS Operations—New Use Cases, Industry Focus, and Framework Expansion
2. Update of sUAS DAA Solutions Inventory
3. Coordination with Standards Agency to Establish Framework
4. Development of Separation Framework
5. Development of a Testing Plan
6. Testing of a) the recommended DAA testing plan and b) candidate DAA systems
7. Final Report

Given the broad set of tasks, multiple methods were applied to execute them. These include review of previous efforts (Tasks 1, 3-4, and 5), analysis and synthesis (Tasks 1-3 and 5-6), simulation (Task 4), and testing and validation (Task 6).

Results for Tasks 1 and 4-6 are provided in separate reports. The interested reader is directed to those for a detailed description of results (citations are provided throughout this report). A high-level summary of results is provided herein.

The Operational Framework effort resulted in a slight expansion of the previously-developed use case taxonomy (Cathey and Hottman 2017) and identification of technologies that are now being operationally utilized. Minimal additional information regarding expansion of the operational framework based on RLOS coverage was identified. In addition, environments, conditions, assumptions, and limitations that will enable BVLOS operations are discussed.

Results of Task 2 (DAA Solutions Inventory) indicated that the characterization of DAA systems provided by Askelson et al. (2017) still applies. This includes strengths and limitations of on/off board systems identified by Askelson et al. (2017). Some of the most promising systems identified in this task were utilized during evaluation of DAA test methods.

Through Task 3 (Coordination with Standards Agency), the team worked with others in the industry to stand up two ASTM groups focused on sUAS DAA. The team has contributed significantly to both groups, with support of the test methods group arguably being the most significant. Important contributions have been provided by the team in the areas of test methods, test artifacts, and the interplay of testing and simulation for evaluating DAA system performance.

Task 4 (Separation Framework) involved a significant simulation effort to evaluate DAA system and UAS characteristics that impact maintenance of well clear. The DAA characteristics that had the greatest impact are range and FoV. Update rate and latency impacts were not as dramatic, while horizontal and vertical resolution were the least impactful. UAS characteristics that strongly impact maintenance of well clear are response time (i.e., the time required to initiate a maneuver) and UAS speed.

An overarching test plan (Task 5) was developed. This test plan describes test locations/performers, dates of testing, DAA systems used in tests, overarching test objectives, individual test plan structure, methods for maintenance of safety during testing, data collection approaches, the structure of test reports, and test metrics/artifacts.

Seven rounds of flight tests were completed. Important outcomes from these tests include:

- A systematic approach for evaluating DAA systems
- Identification of test metrics/artifacts
- Test data collection methods/best practices
- Methods for enabling flight test safety
- Methods for executing both horizontal and climb- and descend-into encounters
- Evaluation of DAA systems (especially the detection component of DAA systems)
    - Evaluation of performance—especially detection range and FoV
    - Identification of challenges (clutter, etc.)
- Utilization of results in ASTM committees to support standards development

This effort involved a broad set of tasks designed to inform FAA regulations and industry standards regarding sUAS DAA systems. Through execution of these tasks and application of the numerous methods required to do so, the A18 team has significantly advanced sUAS DAA, which will enable more rapid integration of sUAS into the NAS—especially for BVLOS operations.

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