Demonstration and Validation of Remote ID Detect and Avoid

Timothy M. Bagnall[1] (tbagnall@mosaicatm.com)
Mosaic ATM, Leesburg, VA, 20176, United States of America

Andrew Kriz[2] (akriz@vt.edu), Robert Briggs[3] (rcbriggs@vt.edu)
Virginia Tech Mid-Atlantic Aviation Partnership, Blacksburg, VA, 24061, United States Of America

and
Ko Takamizawa[4] (ko.takamizawa@wrc-nc.org)
Wireless Research Center of North Carolina, Wake Forest, NC, 27587, United States of America

Executive Summary: This technical report details a twelve-month joint effort conducted by Mosaic ATM, the Virginia Tech Mid-Atlantic Aviation Partnership (VT MAAP), and the Wireless Research Center of North Carolina (WRC) to demonstrate and validate a prototype Detect and Avoid (DAA) system for small uncrewed aircraft systems (sUAS) using Remote Identification (RID). The prototype system was specifically designed for sUAS encounters against other sUAS and excluded encounters against (large) UAS or crewed aircraft. The team performed the work for the Federal Aviation Administration's (FAA) Unmanned Aircraft Systems Integration Office (UASIO). UASIO awarded the work through the FAA's Broad Agency Announcement 692M15-19-R-00020-03, a federal program supporting work the FAA considers essential to the safe integration of UAS in the National Airspace (NAS). In the effort, the team fulfilled two primary objectives: 1) Demonstration and validation of RID DAA, and 2) Providing the FAA with evidence-based small Well Clear (sWC) recommendations. ("sWC," a relatively new and yet to be adopted DAA term, in the context of this report, is intended for sUAS-only encounters (i.e., drone vs. drone). It should not be confused with the well clear (WC) definition intended for (large) UAS and crewed aircraft.) To fulfill the first objective, the team conducted a six-day flight test at the FAA-designated UAS test site in Virginia. To fulfill the second objective, the team ran a high-fidelity, fast-time encounter simulation. The significance of the work and how it furthers the FAA's mission of integrating UAS into the NAS is multifaceted. Firstly, it proves the validity and feasibility of RID-based DAA, a feat the research team believes had not been accomplished previously. Secondly, it helps support the FAA's drive to expand Beyond Visual Line of Sight (BVLOS) operations by providing evidence-based sWC recommendations that consider the target operational environment and that balance integration safety with sUAS performance capabilities. sWC recommendations are conveyed through a mid-air collision risk ratio contour map which shows the relationship between RID detection range, sWC volume, and estimated mid-air collision risk. The contour map allows the FAA to size the sWC according to the level of risk it is willing to assume for the operational area.

[1] Principal Analyst, Research and Development.
[2] Senior Engineer, Engineering.
[3] Chief Engineer, Engineering.
[4] Technical Manager, Research and Technology.

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I. Background

This technical report details a twelve-month joint research and development effort conducted by Mosaic ATM, the Virginia Tech Mid-Atlantic Aviation Partnership (VT MAAP), and the Wireless Research Center of North Carolina (WRC) to demonstrate and validate a prototype Detect and Avoid (DAA) system for small uncrewed aircraft systems (sUAS) using Remote Identification (RID). The team performed the work for the Federal Aviation Administration's (FAA) Unmanned Aircraft Systems Integration Office (UASIO). UASIO awarded the work through the FAA's Broad Agency Announcement 692M15-19-R-00020-03 (Call 04), a federal research initiative that supports research and technology the FAA considers essential to the safe integration of UAS in the National Airspace (NAS).

A. Primer on Detect and Avoid and Remote Identification

Detect and Avoid (DAA) systems equip UAS with a capability to mitigate collision risk and avoid other air traffic. Originally designed for the integration of large UAS into the NAS, fulfilling the pilot's duties to "see and avoid" other traffic as codified in federal regulations (14 CFR Part 91, §91.111(a), §91.113, and §91.181), DAA systems have also been shown to have value for small UAS (sUAS). A fundamental requirement for their operation, however, is a real-time, near continuous data stream of nearby aircraft traffic positions (to avoid something you need to know its location, direction, and velocity, as well as your own). Though there are alternative means of acquiring aircraft position data (e.g., radar), the relatively new FAA RID rule (14 CFR Part 89), which requires most sUAS operators to continuously and publicly broadcast position and velocity messages through an RID Radio Frequency (RF) transmitter, may satisfy this DAA requirement for sUAS. The roll out of RID by the FAA opens the door to a potentially effective and inexpensive DAA solution for sUAS. The work here is an initial investigation on that potential, assessing the feasibility of RID-based DAA.

B. Impetus

The primary impetus for the work is to support the FAA in its multipronged pursuit of technology solutions that help integrate UAS into the NAS safely and economically. A secondary impetus for the work revolves around the general notion that DAA will reduce sUAS mid-air collision risk, most significantly for encounters with sUAS operating outside the UAS Traffic Management (UTM) system. Whereas UTM operations will be strategically deconflicted through a common airspace reservation system, non-UTM operations will remain hidden until discovery by an RID receiver. This mid-air collision risk posed by non-UTM operations to UTM operations is an impediment to the adoption of large-scale Beyond Visual Line of Sight (BVLOS) operations. Today, UAS operators wishing to perform BVLOS operations must obtain permission from the FAA in the form of a waiver, an application process which can be time-consuming and expensive. Reducing mid-air collision risk posed by non-UTM operations will help improve UAS-NAS aviation safety and help support the expansion of BVLOS operations, benefiting industry and the public alike through the myriad number of proposed sUAS operational use cases.

C. A Note on small Well Clear (sWC)

This report uses a relatively new term yet to be fully adopted by the broader DAA community: small Well Clear (sWC). Whereas WC is an established term for encounters against (large) UAS and crewed aircraft, the term sWC, in the context of this report and investigation, is for sUAS-only encounters (i.e., drone vs. drone). Other than this nuance that drives the focus to **small** UAS, the term's general meaning as volumes of airspace to avoid, remains consistent.

Whether this term eventually takes root in the DAA lexicon remains to be seen, as no determination has been made whether to officially pursue sWC regulations.

D. Document Organization

The outline for this document follows the one prescribed by the underlying FAA contract. To help the reader, Table 1 provides a short summary of each section.

Table 1. Document Organization.

Section	Content
I. Background	The background section includes a brief overview of two fundamental technological concepts underscoring the project – DAA and RID – and a discussion on the rationale behind and importance of the work.
II. Project Objectives	Section II discusses the project's two primary objectives: **1)** To demonstrate and validate Remote ID (RID) Detect and Avoid (DAA), and **2)** To provide evidence-based small UAS Well Clear (sWC) recommendations.
III. Demonstration / Verification Results	Section III covers how the team fulfilled the first project objective of demonstrating and validating RID DAA. The first subsection covers demonstration activities, and the second subsection covers verification activities. (The second project objective is covered later, in Section V and Section VI.)
IV. Integrated Data Tables	Section IV includes a discussion on the Integrated Data Tables (IDTs) the team produced from data captured during flight testing. An IDT time-synchronizes data collected from several disparate data sensors and collectors into one data table (AKA

	spreadsheet or data frame). The intent behind an IDT is to support data analysis by collocating all pertinent data within a single object.
V. Approach	Section V discusses the approach the team took to fulfill the second project objective of providing evidence-based sWC recommendations. (The first project objective is covered earlier, in Section III.)
VI. Data Analysis	Section VI, Data Analysis, continues the discussion begun in Section V, elaborating on how the team analyzed data to provide recommendations for a sWC definition. (The first project objective is covered earlier, in Section III.)
VII. Challenges	The challenges section details the significant technical challenges the team faced and overcame throughout the project.
VIII. Lessons Learned	The lessons learned section takes a critical review of the project and discusses important lessons the team learned about the concept and underlying technology.
IX. Conclusions	The conclusions section highlights the major takeaways resulting from the project. This includes a discussion on the two primary threats facing the concept: subpar RID transmitter performance and RF desense.
X. Recommendations	Section X provides a discussion on recommended next steps that the FAA can pursue to continue to mature the concept.

II. Project Objectives

The effort focused around two primary objectives:

1) **To demonstrate and validate Remote ID (RID) Detect and Avoid (DAA), and**

2) **To provide evidence-based small UAS Well Clear (sWC) recommendations.**

To fulfill the first objective, the team designed and implemented a prototype DAA software capability – Mosaic ATM's small UAS Collision Avoidance System (sUCAS) – and conducted a six-day flight test at VT MAAP's FAA-designated UAS test site. Flight testing entailed 55 individual flights and successfully showcased a variety of advanced DAA capabilities and concepts, including: suggestive guidance to maintain and regain well clear; air-based and ground-based Remote ID message receivers; both ACAS sXu and DO-365 DAA logic; automated resolution advisories (Auto RAs); automated returns to course (Auto RTCs); and pilot on the loop (POTL) supervision. By the end of the six-day flight test, the team had successfully demonstrated and validated RID DAA multiple times through 36 pairwise encounters. Section III, Demonstration / Verification, elaborates on how the team fulfilled this first objective.

To fulfill the second objective, the team used VT MAAP's high-fidelity, fast-time DAA encounter simulation capability (hereafter also referred to as the DAA encounter simulation). This capability predicts key DAA performance metrics (i.e., risk ratios, severity, loss of well clear, near mid-air collision, mid-air collision, horizontal miss distance, vertical miss distance, time to closest point of approach, closest point of approach, and time to co-altitude) based on several independent variables (e.g., DAA logic, ownship and intruder performance and configuration, and background electromagnetic interference). WRC implemented an RID sensor model that is used to predict RID broadcast reception between small uncrewed aircraft within VT MAAP's high-fidelity encounter simulation. WRC designed the sensor model using RID performance data collected by the team during a sensor characterization flight test that preceded the demonstration and validation flight test. WRC then validated the sensor model against RID performance data collected during the latter demonstration and validation flight test. Section VI, Data Analysis, elaborates on how the team fulfilled the second objective. This section also includes the evidence-based sWC recommendations.

III. Demonstration / Verification Results

This section documents the efforts the team undertook to fulfill the first objective: to demonstrate and verify the RID DAA prototype and related concepts. The first subsection covers demonstration activities. The second subsection covers verification activities.

A. Demonstration

1. Location

Demonstration flight testing of RID DAA took place at Virginia Tech's Kentland Farms, an FAA-designated UAS test site 10 miles west of Blacksburg, Va (see Figure 1). The 1800-acre site is flanked by the New river on two sides and, with sterile ground risk, offers an ideal site for testing close sUAS encounters.

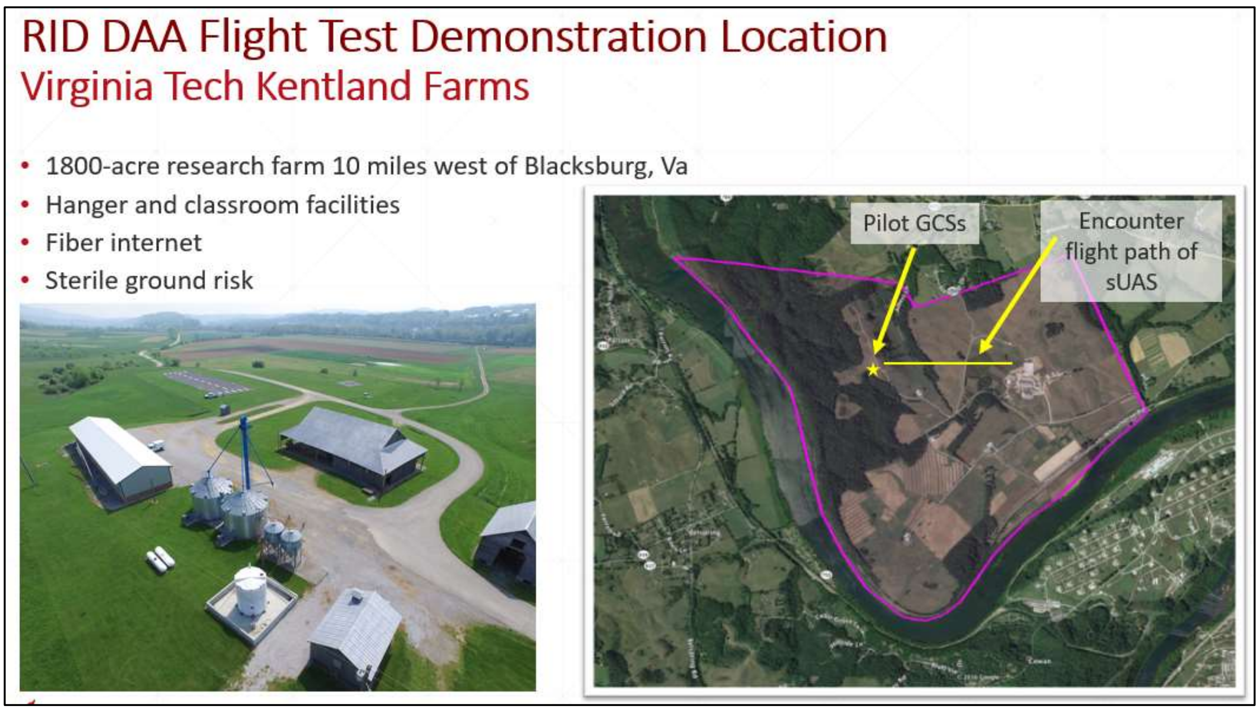


Figure 1. Flight Test Location Overview.

2. Flight Test Infrastructure

RID DAA Testbed

Figure 2 shares the RID DAA encounter testbed the team designed and implemented for live flight demonstration. The testbed facilitates the efficient demonstration and testing of many DAA concepts and capabilities. Beyond Visual Line of Sight (BVLOS) operators can face an array of encounters against one or more intruders with varying degrees of technological capabilities and performance characteristics (e.g., a BVLOS vs. VLOS encounter using exclusively

BT-based RID). BVLOS operators were equipped with the prototype sUCAS DAA system that includes suggestive guidance for avoiding loss of well clear and that interfaces with RID and Airborne Collision Avoidance System (ACAS) sXu and the DO-365 DAIDALUS DAA system. RID transmitters and receivers, available in both Bluetooth and Wi-Fi formats, provided the position and velocity data that underpins DAA. A ground-based RID receiver serving as an RID Supplementary Data Service Provider (SDSP) was available for the assessment of networked RID data streams. All combined, the versatile and robust testbed allowed for the testing of a substantial number of alternate mixed-equipage configurations. Telemetry recording devices and other instrumentation captured a full array of aircraft and system performance parameters and metrics for an objective assessment of the prototype RID DAA solution's feasibility, performance, interoperability, and efficacy.

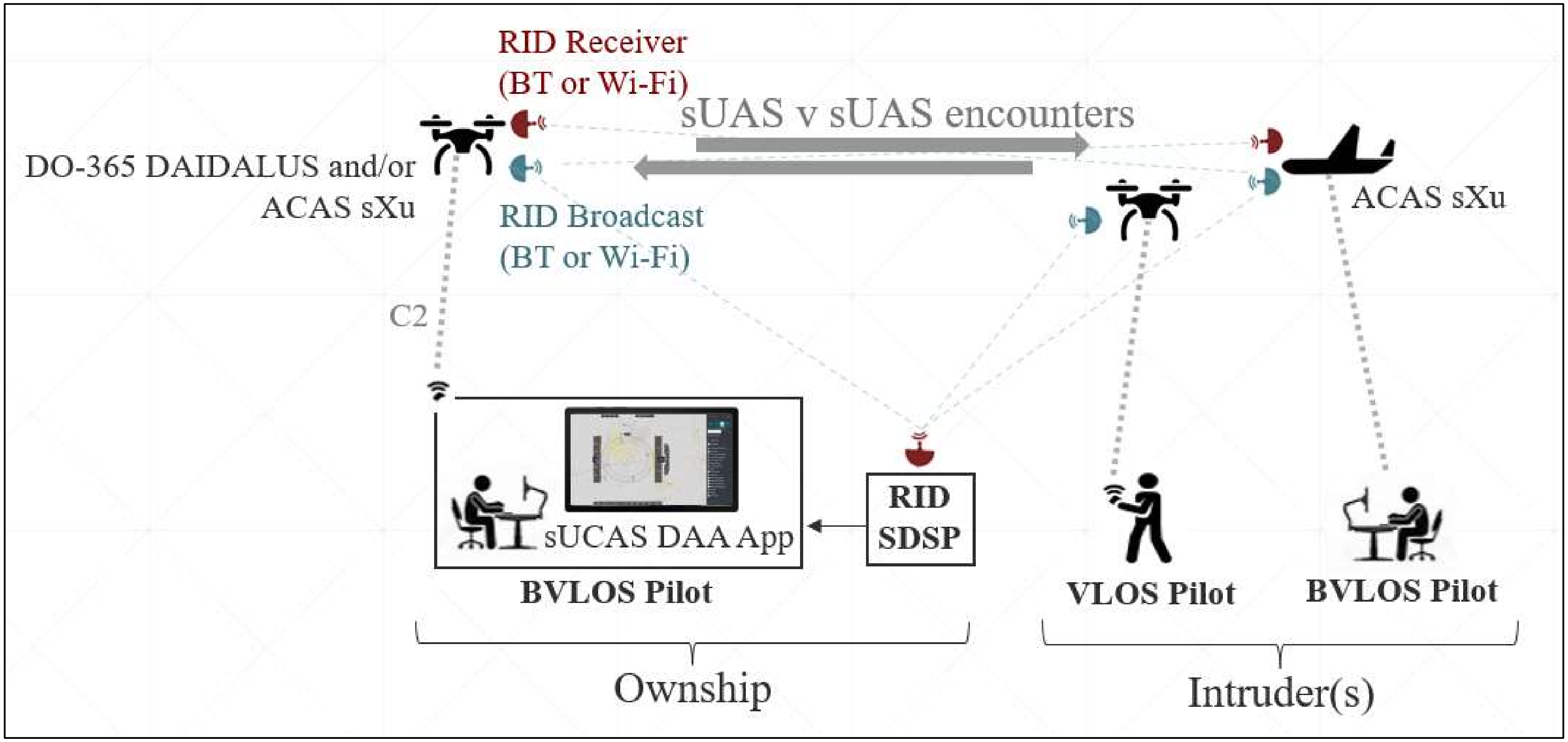


Figure 2. RID DAA Testbed.

sUCAS RID DAA Prototype Software Architecture

Figure 3 shares the sUCAS prototype architecture. There are five major subsystems:

A) Ground Control System (GCS)
B) small Uncrewed Aircraft (sUA)
C) Intruder RID DAA Peer - BVLOS
D) Remote ID Supplementary Data Service Provider (RID SDSP)
E) Intruder No CA – VLOS

The sUCAS prototype is comprised of Subsystem **A** (GCS), and Subsystem **B**, (sUA).

Subsystem **C** represents an intruder aircraft, which is a peer to and equally equipped as ownship. In this sense, Subsystem C can also be thought of as an additional sUCAS prototype. The testbed had multiple instances of Subsystem C (i.e., more than one sUCAS prototypes operating simultaneously).

Subsystem **D** is a Supplemental Data Service Provider (SDSP) that provides RID surveillance data to subscribers over the internet. All sUCAS prototypes in the testbed could conceivably subscribe to RID surveillance from Subsystem D.

Subsystem **E** represents an sUA intruder equipped with a broadcast-only RID module and lacks collision avoidance capabilities.

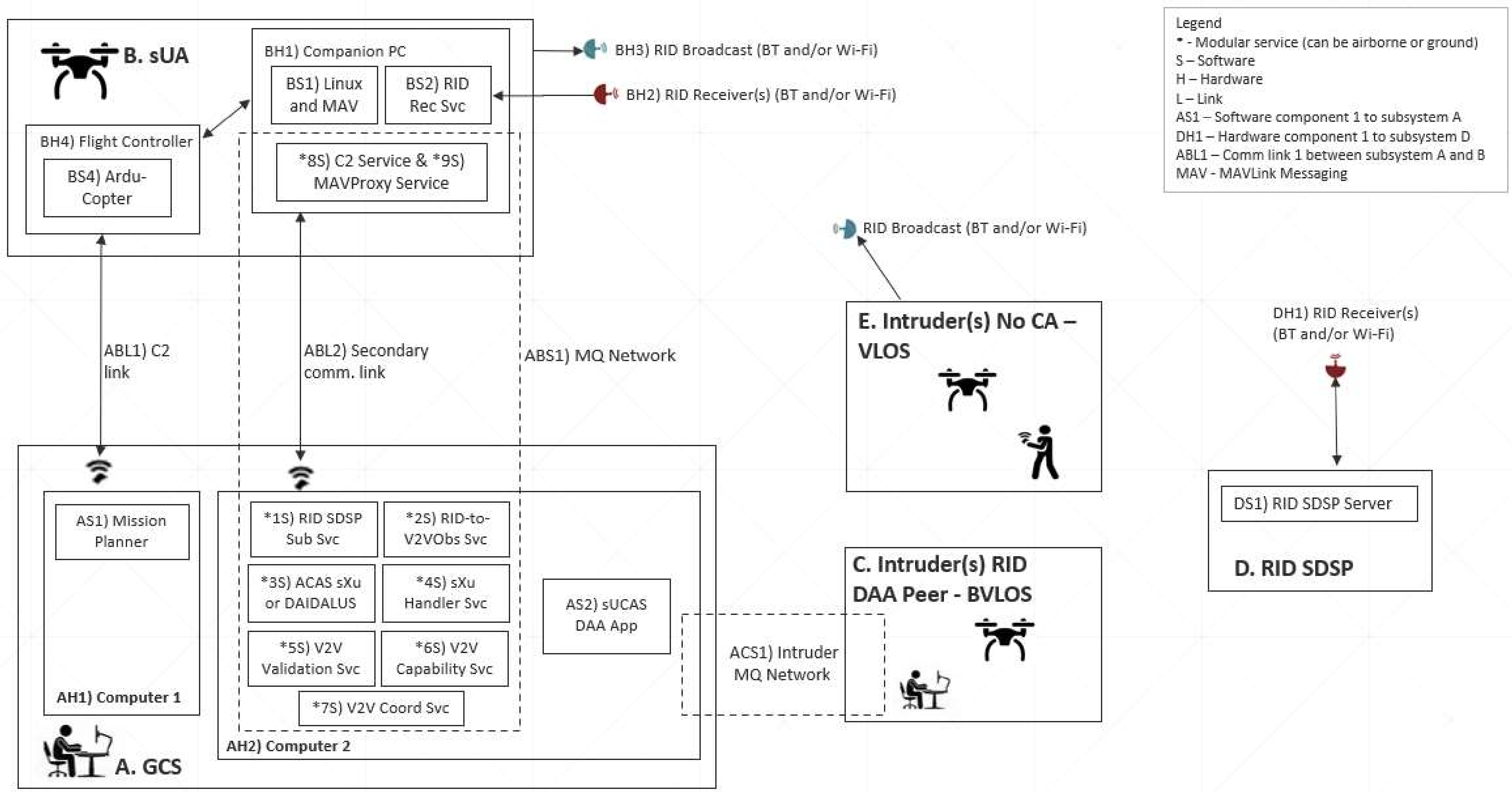


Figure 3. sUCAS RID DAA Prototype Software Architecture.

Aircraft

Flight testing featured three types of quadcopters: a VT MAAP custom build, a DJI Inspire 2, and a DJI Mini 3 Pro (see Figure 4). The VT MAAP custom build quadcopter played the role of the Beyond Visual Line of Sight (BVLOS) aircraft equipped with the prototype RID DAA system (Mosaic ATM's sUCAS). The Inspire 2 and Mini 3 Pro played the role of intruder aircraft, broadcasting RID. Mini 3 Pro encounters used the native DJI RID implementation (AKA standard RID). The Inspire 2, without a native RID implementation, could carry several various RID transmitters (AKA RID broadcast modules).

Figure 4. sUAS Aircraft.

Figure 5 shares the antenna installation location on the VT MAAP custom quadcopter. Please note that only one RID receiver – a Wifi receiver - is shown in this figure. Not shown is a Bluetooth RID receiver.

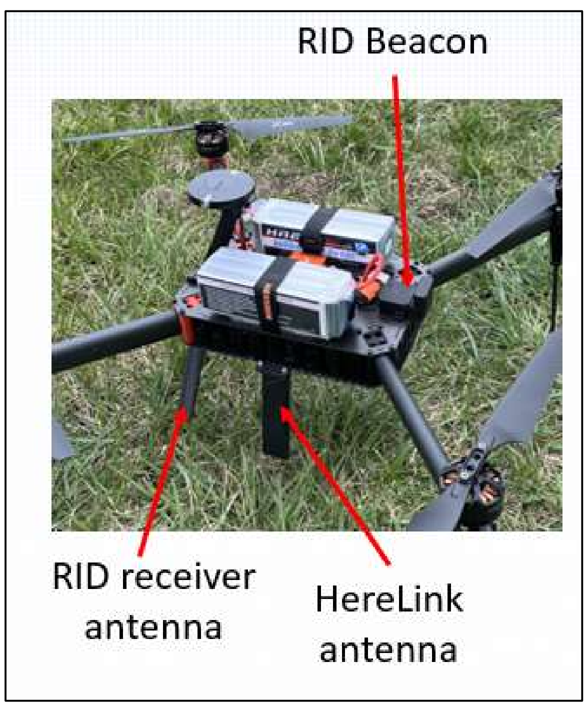


Figure 5. VT MAAP Quadcopter Antenna Mounting.

RID Transmitters

Table 2 lists the five types of RID transmitters the team used during flight testing. These five provided a decent representation of commercially available products and allowed for testing of both Bluetooth and WiFi RID protocols. All RID transmitters used during testing have an FAA accepted declaration of compliance (DOC).

Table 2. Demonstration (Flight Test 2) RID Transmitters.

Remote ID	Type	Protocol	Application
DJI Mini 3 Pro 	Standard	WiFi	VLOS Intruder
BlueMark db120 	Module	WiFi and Bluetooth	VLOS Intruder & BVLOS Intruder
BlueMark db121 	Module	WiFi and Bluetooth	BVLOS Ownship
Pierce Aerospace B1 	Module	Bluetooth	VLOS Intruder
DroneTag Mini 	Module	Bluetooth	VLOS Intruder

RID Receivers

Figure 6 shows the four Bluetooth and WiFi adapters the team used as RID receivers during demonstration flight testing. All four adapters are commercially available. The team used the ground-based RID receiving stations as part of a UAS Traffic Management (UTM) Supplementary Data Service Provider (SDSP) RID subscription service concept. In this concept, ownship's DAA system can receive intruder position data from the SDSP RID service, as supplementary, early warning, or sole-source input.

Figure 6. Demonstration (Flight Test 2) RID Receivers.

Data Collection Instrumentation

Figure 7 shares the instrumentation the team used during flight testing to capture key demonstration and performance data. Ground Control Station (GCS) software recorded aircraft state data for all participating aircraft. Personal computers with wireless signal packet analyzer software captured RID performance parameters. The air-based computer, mounted on the VT MAAP custom quadcopter, was an UDOO x86 II Advance Plus. Mosaic ATM's sUCAS DAA prototype software captured the key DAA metrics of each encounter.

#	System	Description
1	Ground Control Station Flight Software	• Capture of aircraft state data (3D location, roll, pitch, and true heading)
2	Air and ground PCs with wireless packet analyzers	• Capture of RID performance parameters (RID receipt, RID receipt rate, RSSI, RF receipt channel)
3	sUCAS DAA Prototype	• Capture of DAA metrics (Horizontal miss distance (HMD), vertical miss distance (VMD), time to closest point of approach (TCPA), time to co-altitude (TCOA), taumod, severity, loss of well clear (LOWC), near midair collision (NMAC)

Figure 7. Demonstration (Flight Test 2) Data Collection Instrumentation.

sUCAS RID DAA Prototype Graphical User Interface

The sUCAS DAA application provides the pilot with a situational awareness display, suggestive guidance for maintaining and regaining well clear, and directive guidance (AKA RAs) to avoid mid-air collision. It also provides supervisory modes for execution of avoidance maneuvers and return to course functions where the pilot is on the loop (tacitly monitoring imminent maneuvers) or in the loop (must approve maneuvers prior to execution). Figure 8 shares a screenshot captured during the demonstration of the sUCAS DAA prototype graphical user interface (GUI). The test run was of a pairwise, head-on encounter with both aircraft traveling at 20 knots. ACAS sXu is the DAA logic. The pilot has enabled Auto RA and Auto RTC functionality. There is no POTL supervision enabled, meaning Ownship will immediately engage an RA and, once clear of the intruder, immediately engage a return to course. The screenshot captures Ownship amidst an active turn to a target heading of 140 degrees. The green dashed line extending from the blue chevron (Ownship) to the 14 on the heading compass conveys the target heading. The red arc around the heading compass suggests headings undesirable for the collision avoidance scenario.

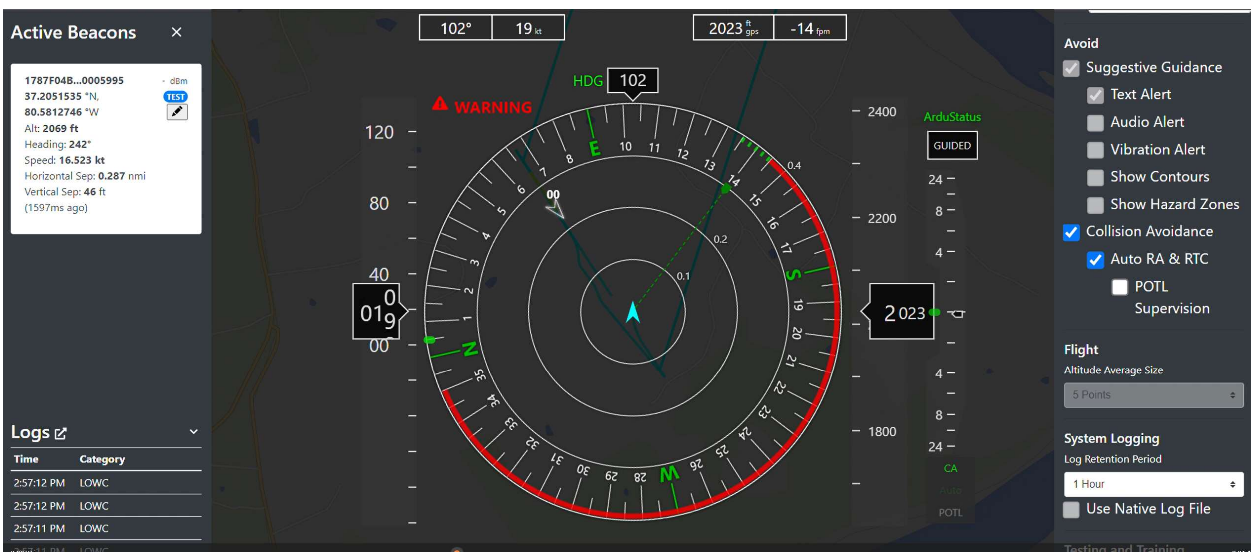


Figure 8. sUCAS DAA Prototype GUI.

The text below is an example of DAA metrics captured by the sUCAS DAA prototype throughout an encounter.

{"aircraftId":"1787F04BM23100005995","daaConfig":"sUCAS_RID_DAA_Config_ACASsXuOrBoth_V2-60v320h","beaconOffsetAlt":0,"separation":{"horizontal":{"val":"1511.77","units":"ft","internal":"460.79","internal_units":"m"},"vertical":{"val":"45.52","units":"ft","internal":"13.87","internal_units":"m"}},"missdistance":{"horizontal":{"val":"597.24","units":"ft","internal":"182.04","internal_units":"m"},"vertical":{"val":"45.52","units":"ft","internal":"13.87","internal_units":"m"}},"closurerate":{"horizontal":{"val":"33.61","units":"knot","internal":"17.29","internal_units":"m/s"},"vertical":{"val":"13.78","units":"fpm","internal":"0.07","internal_units":"m/s"}},"tcpa":{"val":"24.48","units":"s"},"tcoa":{"val":"-198.2","units":"s"},"taumod":{"val":"27.71","units":"s"},"lowc":false,"nmac":false,"severity":0}

Figure 9 shares another screen capture of Mosaic ATM's sUCAS DAA prototype. This example provides a glimpse of the prototype's POTL supervision capability. In this instance, the pilot has three of five seconds remaining to confirm the execution of an RA. This test run was of another head-on, pairwise encounter with both aircraft traveling at 20 knots. The RA is directing a target heading of 105 degrees. NASA's LaRC DAIDALUS, a reference implementation of DO-365, is serving as the DAA logic.

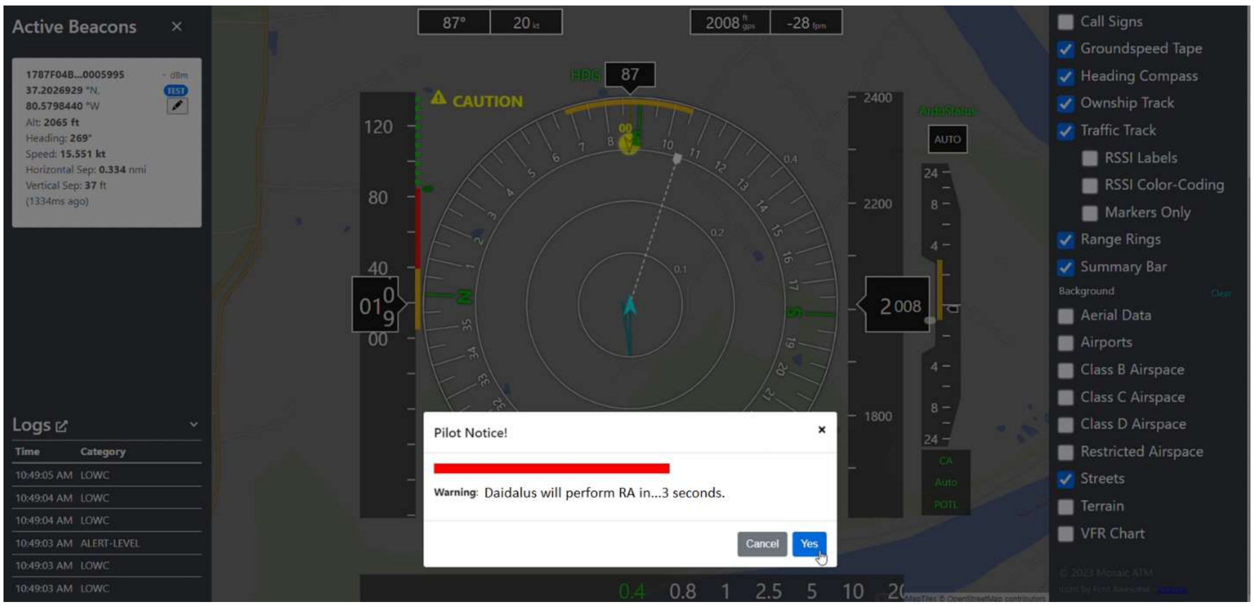


Figure 9. sUCAS DAA Prototype GUI: POTL Supervision.

Operational Configuration

Figure 10 depicts the operational configuration of Mosaic ATM's sUCAS DAA prototype. The pilot remained in positive control of the aircraft through a manual sUA controller. Mission Planner on one computer workstation provided mission planning capabilities. Another workstation hosted the sUCAS DAA prototype software system and related DAA software services required for executing the DAA logic. A HereLink command and control (C2) system provided C2 between the GCS and aircraft, and a high-speed air-to-ground datalink for communicating RID messages, DAA instructions, and aircraft telemetry. Depending on the flight test point, a third and fourth computer workstation served as a ground-based RID receiver. When applicable, these workstations were strategically placed within the flight test operational area on Kentland Farm to expand the total surveillance volume.

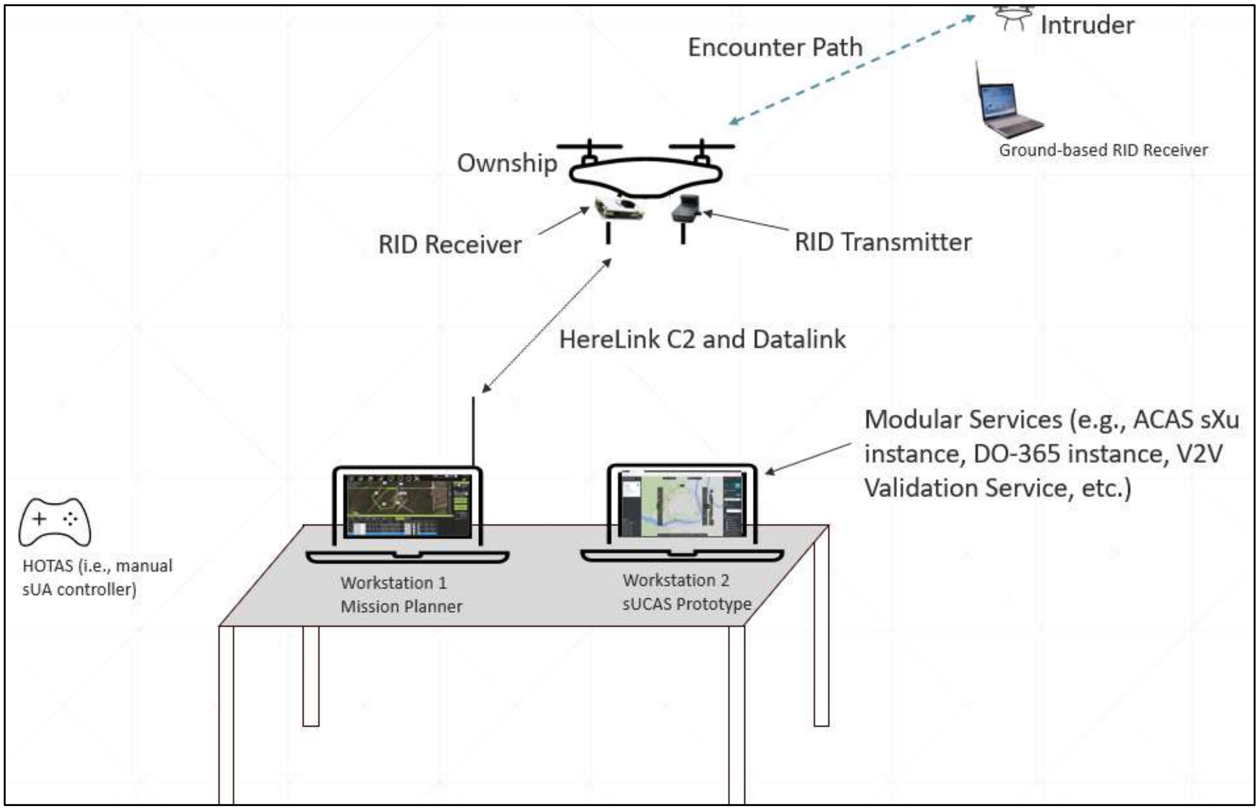


Figure 10. Demonstration (Flight Test 2) Operational Configuration.

Encounter Geometries

Figure 11 shares the encounter geometries the team planned for the flight test: head-on, 90-degree crossing, and 45-degree crossing. Only the head-on encounter was used during demonstration flights. Relative to the crossing geometries, the head-on encounter represents a worst-case encounter as well as being easier to initiate. This yielded operational efficiency, allowing the team to focus on testing and demonstrating a fuller gamut of DAA concepts and capabilities.

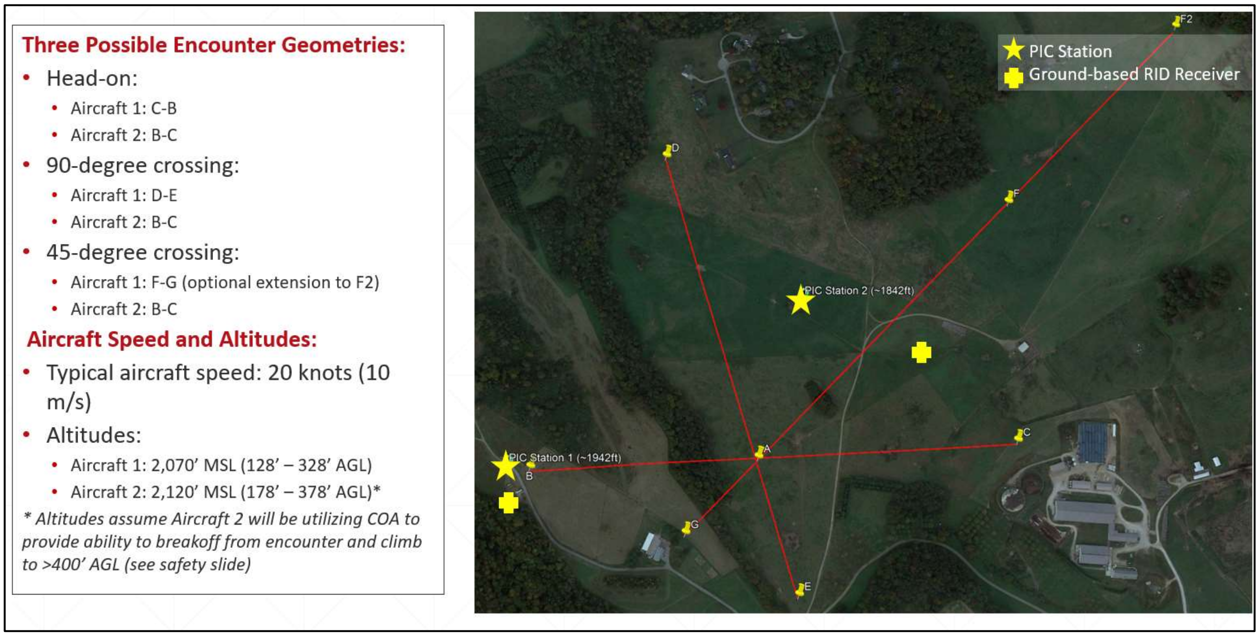


Figure 11. Demonstration (Flight Test 2) Encounter Geometries.

Safety Considerations

Figure 12 bulletizes the safety precautions the team enacted for the flight test demonstration. Of note are the authorities by which aircraft flew, Part 107 and a test site certificate of authorization (COA), geofences to maintain altitude separation and separation from terrain, and the 50-foot vertical separation between aircraft. The COA was utilized to ensure the second aircraft could fly above 400’ AGL in case of a need to abort an encounter.

- Flight Authorizations:
  - Aircraft 1 (equipped aircraft for entire test) will be flown Part 107
  - Aircraft 2 (non-equipped and equipped intruder) will be flown under the test site COA to allow for flights above 400’ AGL in case aircraft needs to break away from encounter
- Mid-Air Collision Mitigations:
  - Aircraft encounters will be vertically separated by 50’
  - Pilots will be in radio communications with each other, the test director and the Aviation Safety Officer (ASO) during the encounter
  - Altitudes verified with pilots prior to encounter
  - Geofences utilized to maintain altitude separation
  - At any time, a knock it off command can be given. Once knock it off command is issued, both aircraft break right, top aircraft will climb, and bottom aircraft will descend.

Figure 12. Demonstration (Flight Test 2) Safety Considerations.

3. *Flight Test 2 Test Matrix*

Appendix B shares the flight test matrix followed by the team during the demonstration test flight. (The demonstration test flight was the second flight test of the project and so is also referred to as Flight Test 2.) The matrix details each of the 55 flight tests the team conducted during the RID DAA demonstration.

4. *Demonstrated DAA Concepts and Capabilities*

Over the course of six days of flight testing (24 – 28 June and 2 July), the team not only met but exceeded contract requirements regarding RID DAA demonstration. The flight testing featured 55 total runs/test points. Four of these test points, held at the beginning of the campaign, involved testing the ground-based RID equipment prior to starting the encounters. The following 51 test points were all focused on encounters, demonstrating or testing DAA concepts and capabilities. The project team marked 36 of the 51 encounters as successful DAA events. That is, encounters where ownship executed an avoidance maneuver on time and reasonable for the encounter profile. Fifteen of the 51 encounters the team marked as unsuccessful. There were several causes of these unsuccessful encounters. One primary cause that the team mitigated early in testing had to do with improper implementation of asynchronous software programming code and improper application of Active MQ messaging programming code. Another primary cause was faulty Remote ID transmitter performance. One RID transmitter was not broadcasting heading. Another RID transmitter was broadcasting orthometric altitude instead of geometric. Knowing that the demonstration was using a prototype DAA system, and knowing that RID transmitter products are relatively inchoate, rather than looking at these unsuccessful encounters as disappointments, the team turned them into opportunities to improve the prototype and to reflect on how RID standards may be improved going forward. Table 3 lists the DAA concepts and capabilities demonstrated by the team during flight testing.

Table 3. DAA Concepts Demonstrated and Validated.

DAA Concept Demonstrated	DAA Concept Description
Following maneuver guidance to maintain and regain well-clear	Pilot DAA displays may include both suggestive and directive guidance. Suggestive guidance provides a suggested course of action (e.g., change of heading or altitude) to the pilot so that the pilot can maintain or regain a safe separation from other traffic. Directive guidance is more obligatory and provides specific guidance on how the pilot can maintain or regain a safe separation from other traffic. Typically, urgent

	conditions involve directive guidance, while concerning but not yet urgent conditions involve suggestive guidance. **During the demonstration flight test, the pilot followed the suggestive guidance presented by the sUCAS display to maintain and/or regain well clear with the intruder.**
ACAS sXu DAA logic	Within the DAA field, known to the authors of the report, there are two prevailing DAA schools of thought: DO-365 and ACAS sXu. Both provide collision avoidance guidance based on ownship and intruder position and velocity data. ACAS sXu Version 3.0, the version implemented by the team for the project, only includes a small Near Mid-air Collision (sNMAC) definition - 50 feet horizontal and 15 feet vertical - and does not include an sWC definition. ACAS sXu V3.0 does not include suggestive guidance, like that of the DO-365 DAA, but does include directive guidance in the form of a Resolution Advisory (RA). **During the demonstration flight test, several encounters featured the ACAS sXu DAA logic where Ownship executed the RA issued by ACAS sXu.**
DO-365 DAA logic	The team used the NASA Langley Research Center's (LaRC) DAIDALUS software for its implementation of DO-365 DAA logic. DAIDALUS is a reference implementation of DO-365. A DAIDALUS configuration file allows users to define NMAC and WC volumes. This is the file the team modified to assess various sNMAC and sWC volumes, using DAIDALUS' NMAC and WC as proxies for sNMAC and sWC, respectively. DO-365 includes both suggestive and directive guidance. **During the demonstration flight test, several encounters featured the DO-365 DAA logic. This included instances where the pilot followed suggestive guidance issued by DO-365 and instances where**

	Ownship executed the directive guidance (AKA RA) issued by DO-365.
ACAS sXu & DO-365 DAA logic	To push forward advanced DAA concepts, one variation of DAA logic tested by the team combined the two logics together where DO-365, because it includes a definition for sWC, provided suggestive guidance to maintain and regain well clear, and where ACAS sXu provided directive guidance to avoid sNMAC. In this conglomeration, to avoid conflicting guidance, the sUCAS prototype system prioritized ACAS sXu guidance over DO-365. During encounters, DO-365 suggestive guidance would be shown until an ACAS sXu RA materialized. **During the demonstration flight test, several encounters featured a combined ACAS sXu and DO-365 DAA logic.**
Uncoordinated DAA maneuvers	The two DAA logics – ACAS sXu and DO-365 DAIDALUS - include a capability to coordinate avoidance maneuvers which help improve safety outcomes. For example, in a pairwise head-on encounter, both aircraft may coordinate their maneuvers by agreeing to turn right. Coordination requires not only the sharing of real-time position and velocity information but the maneuver intent in a sort of negotiation. In uncoordinated maneuvers, the aircraft involved act independently and do not coordinate the maneuver. **During the demonstration flight test, all encounters were uncoordinated. On the last day of flight testing, 2 July, several attempts to run coordinated encounters failed. This was due to a misconfigured peer aircraft.**
Air-based RID Message Receipt	To receive RID messages, the team implemented two solutions, one for receiving RID messages in the air and a second for receiving RID messages on the ground. Both methods supported the various Bluetooth and WiFi adapters listed in Section III.A.2. Flight Test Infrastructure.

	The air-based RID message receiver software ran on the UDOO x86 II Advance Plus single board computer mounted on Ownship. An advantage of air-based RID message receipt over ground-based RID message receipt is that the DAA logic, if hosted on the aircraft, receives the RID message sooner than ground-based RID messages. The prototype sUCAS DAA system designed by the team was modular, meaning that software services could be hosted in the air or ground. For flight testing, the DAA logic module was hosted on a ground workstation. **During the demonstration flight test, several runs featured air-based RID message receipt.**
Ground-based RID message receipt	Please see the description of air-based RID message receipt to understand ground-based RID message receipt. One advantage of ground-based RID message receipt relative to air-based RID message receipt is, assuming an array of ground-RID sensors strategically positioned to optimize a surveillance volume, access to RID messages outside the Ownship's surveillance volume and potentially ones inside Ownship's surveillance volume missed by Ownship. **During the demonstration flight test, several runs featured ground-based RID message receipt.**
RID SDSP Software Service	To explore how RID-based DAA may benefit from the UTM ecosystem the team designed and implemented an RID Supplementary Data Service Provider (SDSP) software service. (The team chose a REpresentational State Transfer – i.e., REST - software architecture.) Ground-based RID message receivers source the RID SDSP with RID messages. RID SDSP clients then subscribe to the RID SDSP service to receive pertinent RID messages. The client subscription query allows the client to request RID messages filtered by 3D location and volume.

	During the demonstration flight test, several runs featured the RID SDSP software service. Ground-based RID receivers forwarded intruder RID messages to the RID SDSP software service. Ownship subscribed to the RID SDSP software service to receive intruder RID messages.
Automated Resolution Advisories (Auto RAs)	Automated Resolution Advisories (AKA Auto RAs) is a concept where Ownship immediately executes the directive guidance issued by the DAA logic. Immediately executing an RA often leads to better collision avoidance outcomes. **During the demonstration flight test, several runs featured Auto RAs, some of those runs following ACAS sXu RAs and some of those runs following DO-365 RAs.**
Automated Returns to Course (RTCs)	Automated Returns to Course (AKA Auto RTCs) is a concept where Ownship immediately returns to its mission plan once clearing a collision risk. Auto RTCs can be challenging to implement depending on the geometry of the encounter, where returning to course can inadvertently place Ownship back into a collision risk scenario. **During the demonstration flight test, several runs featured Auto RTCs. None of the executed Auto RTCs put Ownship back in risk with the Intruder.**
Pilot-on-the-Loop (POTL) Supervision	Pilot-on-the-loop (POTL) supervision is a DAA concept that gives the pilot a more active role in deciding whether Ownship should follow an RA or RTC. In POTL supervision, the display gives the pilot a certain amount of time to review the proposed RA or RTC and either approve it or cancel it. If the timer expires before the pilot approves the RA or RTC, Ownship will typically execute the RA or RTC. On the one hand, delaying the time until Ownship initiates a maneuver may adversely

	impact safety outcomes or mission efficiency. On the other hand, the pilot is often aware of extraneous factors unknown to the DAA system (e.g., that an intruder aircraft is not a threat or that returning to course may place the aircraft back in harm's way). A POTL supervision capability can provide flexibility within the DAA decision chain. **During the demonstration flight test, several runs featured POTL supervision for both RAs and RTCs. In all demonstration cases, the pilot accepted the proposed RA and RTC.**

B. Verification

Owing to a lack of project time, there were only two DAA concepts that the team was unable to demonstrate during flight testing: multiple intruder encounters and coordinated DAA maneuvers. The team believes it could have demonstrated both with one more day of flight testing. At any rate, the team was able to verify both concepts in a virtual DAA simulation environment.

1. Multiple Intruder Encounters and Coordinated Maneuvers

Though admittedly a contrived scenario unlikely to ever occur, the Google Earth snapshot in Figure 13 below illustrates a multiple intruder encounter between peer aircraft. Peer aircraft means that all aircraft are equally equipped with DAA logic and capable of coordinating DAA maneuvers. The scenario is a four-way, head-on, co-altitude, co-speed encounter. A careful inspection of the figure, which is easier to do within the native Google Earth application, reveals multiple coordinated maneuvers taken by each aircraft. The team did not pursue any such encounter during its flight testing but did verify through several simulations the sUCAS DAA prototype's capability to support multiple intruder encounters and coordinated maneuvers.

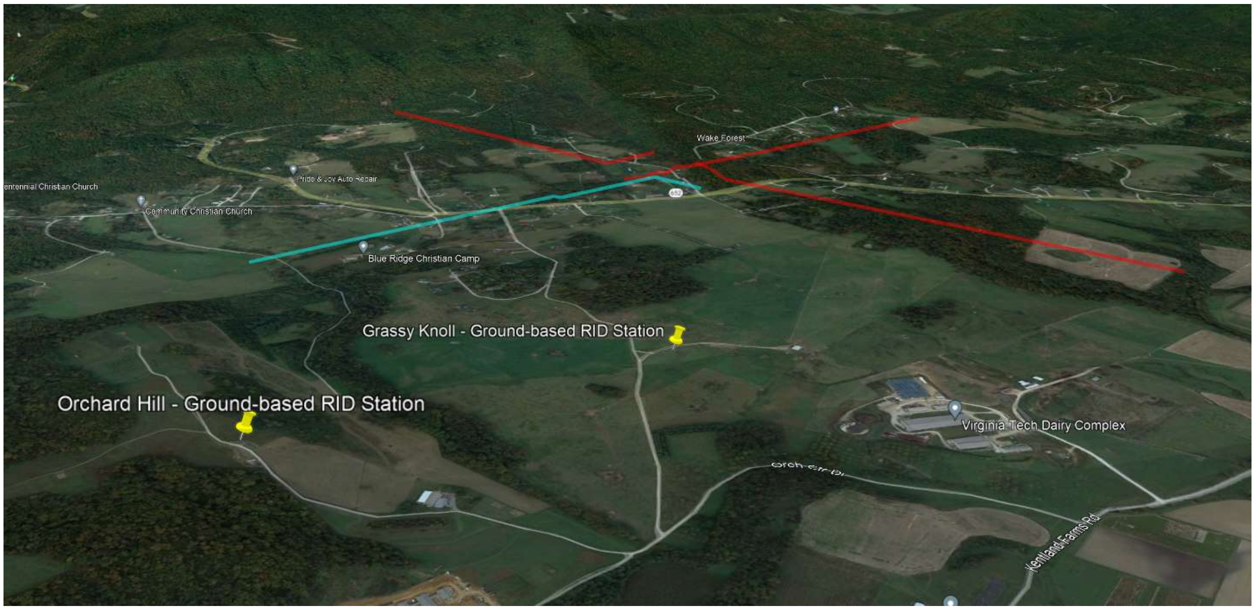


Figure 13. Snapshot of a Four-way, Head-on, Co-altitude, Co-speed, ACAS sXu Coordinated Peer Encounter.

2. *Pilot HFE Surveys*

As part of the effort, the research team had the flight test pilots take a human factors engineering (HFE) survey regarding the Mosaic ATM's sUCAS DAA prototype. The survey covered a variety of topics on usability and mental workload. It followed the NASA-TLX workload scale. The responses from the survey can be found in Appendix A. In general, the pilots found the sUCAS app intuitive, easy to follow, and not taxing with respect to mental workload. The pilots provided good feedback on how the application could be improved to help reduce perceived uncertainties.

IV. Integrated Data Tables

One problem inhibiting analysis of the data collected during flight tests is that it exists across multiple files and file types. It is not necessarily easy or straightforward, for example, to compare the location of the intruder as reported by its own telemetry and the location of the intruder as reported by received RID messages. One useful technique to address this analysis issue is to create an integrated data table that combines and time-synchronizes all data. Table 4 shares an example of an integrated data table (IDT) from a previous effort the team supported for NASA (own = ownship; int = intruder; cpRec = cockpit receiver; chnl = Bluetooth channel). The table reveals received signal strength indicator (RSSI), RID receive channel, and slant range between ownship and intruder during one run of a flight test.

Table 4. Example of an Integrated Data Table.

time	own_lat_cpRec	own_lon_cpRec	own_alt_cpRec	int_lat_cpRec	int_lon_cpRec	int_alt_cpRec	int_rssi_cpRec	int_chnl_cpRec	slantRng_own_int_nmi
2023-05-17T16:32:24.002127Z	37.226799	-80.4550552	2749.343832	37.2053527	-80.5813293	1911.089239	-94	1	6.189044664
2023-05-17T16:32:27.802128Z	37.2264633	-80.4573516	2754.265092	37.2053489	-80.5813369	1911.089239	-91	12	6.077660906
2023-05-17T16:32:31.002128Z	37.2261848	-80.4590454	2754.265092	37.2053489	-80.5813369	1911.089239	-94	36	5.994810514
2023-05-17T16:32:31.202128Z	37.2260818	-80.4596023	2754.265092	37.2053489	-80.5813369	1911.089239	-92	32	5.967428154

The IDTs the team generated from the demonstration include well over 400 individual fields. The team has shared all 55 IDTs, one for each flight point, with the FAA to support future research endeavors. The IDTs are available as both Python pickle files and comma separated value files. The sheer size of the IDTs makes them unwieldy to include here in the final report. Please contact the FAA's UASIO office for more information regarding the IDTs.

V. Approach

This section details the methodology the team followed to fulfill the second project objective: to provide evidence-based sWC recommendations. This section includes two subsections. The first subsection details the approach the team followed to design and implement the RID sensor model, an integral component used by the DAA encounter simulation to properly model RID reception between two aircraft. The second subsection details the approach the team followed to design and apply VT MAAP's high-fidelity, fast-time DAA encounter simulation.

Following the mandated FAA report outline, this section is limited to the *approach* the team followed for designing and building the RID sensor model DAA encounter simulation. The following section – *Data Analysis* – continues the discussion and presents the data collected, produced, and applied from executing the approach.

A. Remote ID Sensor Model - Approach

1. Overview

An available input to the encounter simulation is a realistic RID sensor model. The model estimates the probability of detection between specific RID broadcast modules (AKA transmitters) and RID receivers. VT MAAP's DAA encounter simulation uses the sensor model to determine whether an aircraft can "see" other aircraft. VT MAAP's encounter model can call the RID probability of detection model at each time step, passing the state of the environment as parameters (or independent variables) to receive a prediction on whether the ownship sUAS can receive intruder RID broadcasts. WRC used the Python programming language to implement the RID sensor model. WRC's model uses the International Telecommunication Union (ITU) P.528 propagation model. ITU-P.528 is a propagation model for aeronautical mobile and radio navigation services in the VHF, UHF, and SHF bands [1]. Figure 14 shares the model design, listing the independent variables and the sole dependent variable.

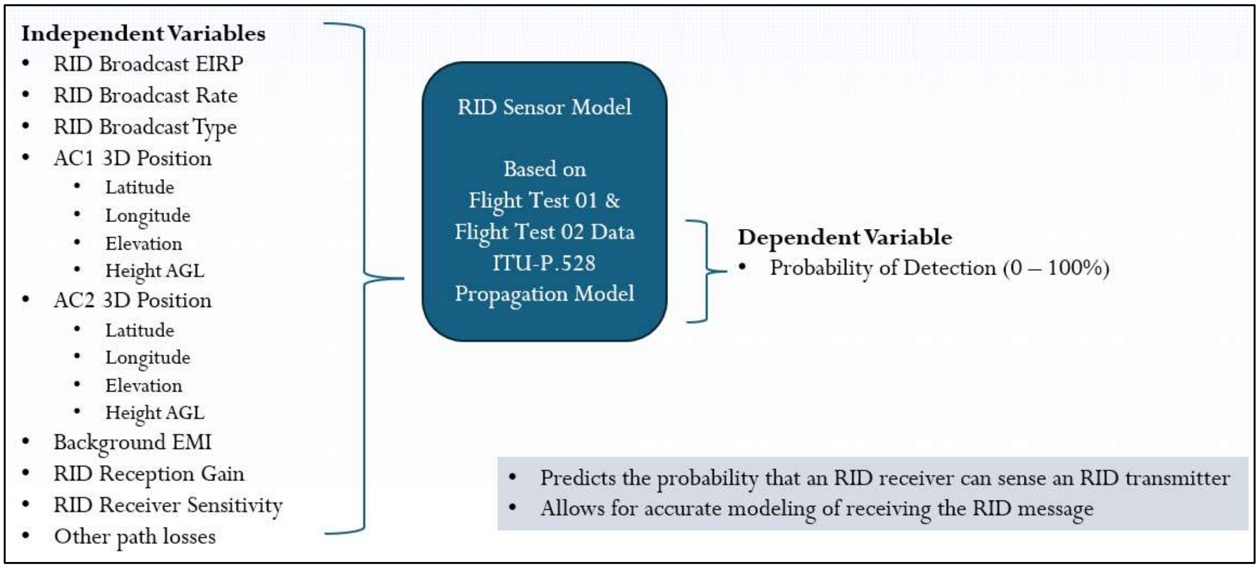


Figure 14. RID Sensor Model.

2. Data Collection

The goal of the first flight test was to characterize RID link performance to help inform design of the RID sensor model. The first flight test featured a variety of RID transmitters and RID receivers. The flight test design was relatively straightforward involving a group of stationary RID receivers mounted atop plastic tables. Figure 15 and Figure 16, respectively, share the RID transmitters and RID receivers used during Flight Test 1. All RID transmitters have an FAA accepted declaration of compliance (DOC).

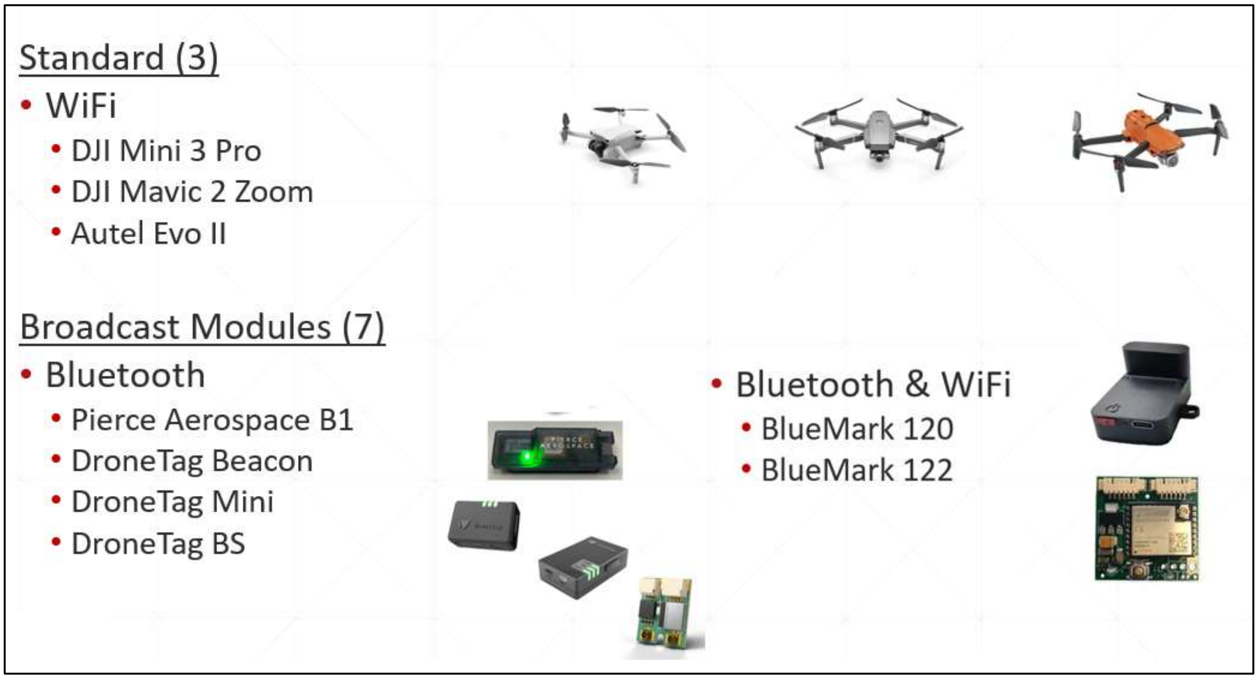


Figure 15. Flight Test 1 RID Transmitters.

Figure 16. Flight Test 1 RID Receivers.

The team separated the RID receivers by a minimum of two feet (five RID wavelengths) to prevent mutual coupling, which is an RF phenomenon where antenna patterns may be adversely impacted. Data collection instrumentation collected several key RF performance parameters. Figure 17 shares the data collection instrumentation used by the team during the first flight test. Figure 18 shares how the team oriented the various workstations and RID receivers for collecting data. The team flew one test aircraft at a time, alternating RID transmitters. The aircraft flew the same out-and-back flight profile four times in the flight, extending to 600 meters from the data collection area. After these four legs, the aircraft started down the same flight profile path but stopped at the mid-way point – 300 meters – and slowly rotated in the air, completing two revolutions, for a fifth and final leg. To illustrate the flight profile through data, Figure 19 provides an example chart where horizontal distance from the collection area (i.e., the tables hosting the RID receivers) is plotted for the aircraft and for RID message receipts. The design of the flight profile was not only to understand how distance impacted RID reception but to also understand the impacts of sUAS roll, pitch, and yaw. Flight Test #1 took place in the same location as Flight Test #2. Please see Figure 1 above regarding VT MAAP's Kentland Farm's UAS test site for more information on the testing location.

#	System	Description
1	B&K Precision 2650A Handheld Spectrum Analyzer	• Capture of 2.4 and 5.0 GHz RF traffic
2	Ground Control Station Flight Software	• Capture of aircraft state data (3D location, roll, pitch, and true heading)
3	PC Workstations with Wireless Packet Analyzer Software	• Capture of RID performance parameters (RID receipt, RID receipt rate, RSSI, RF receipt channel)

Figure 17. Remote ID Sensor Model - Flight Test 1 Data Collection Instrumentation.

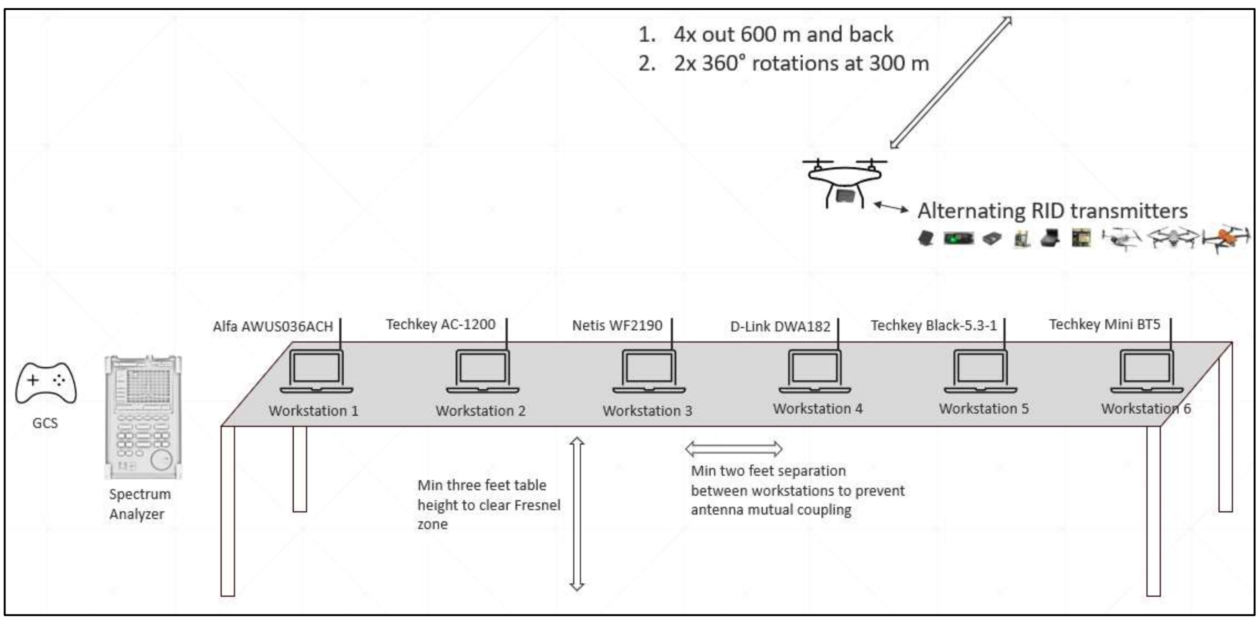


Figure 18. Remote ID Sensor Model - Flight Test 1 Data Collection Configuration.

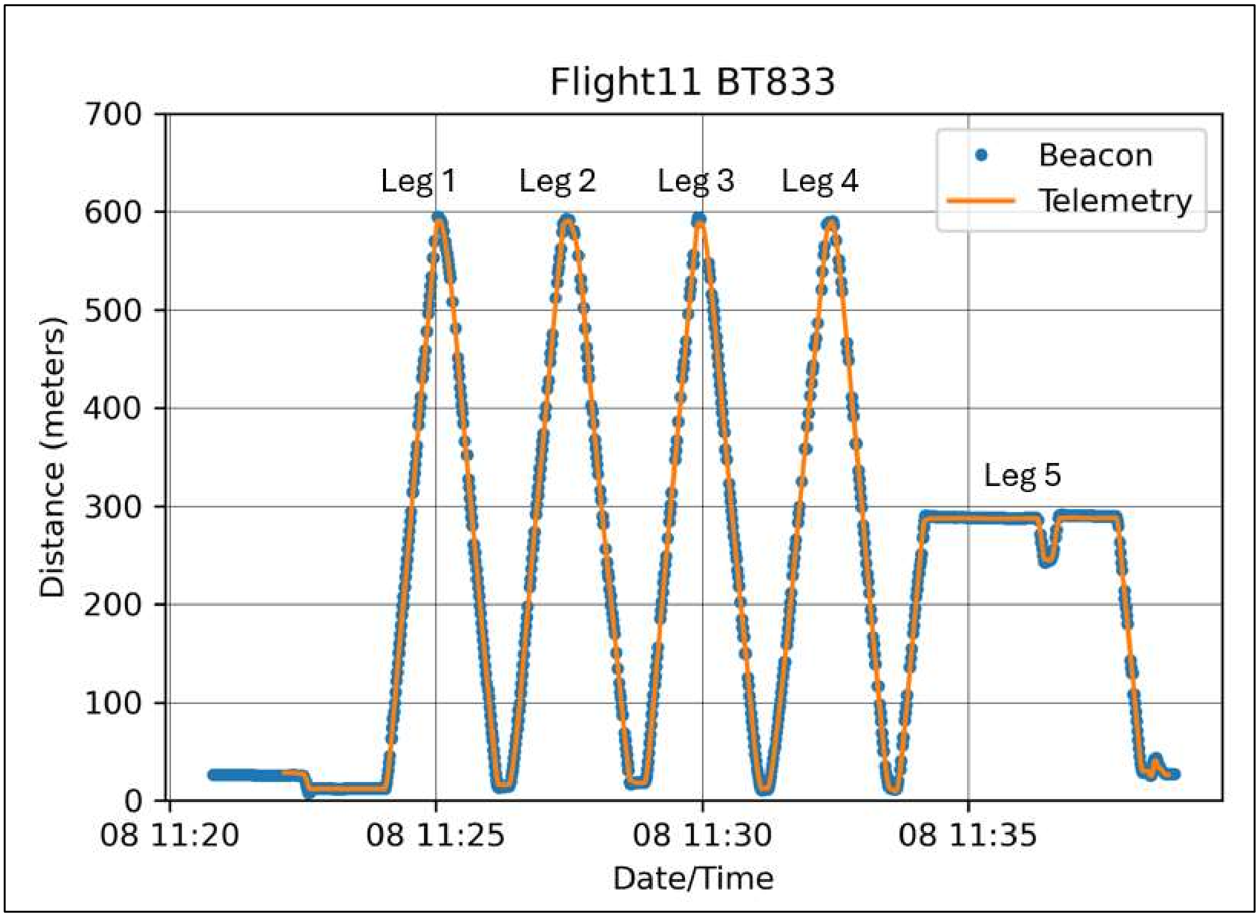


Figure 19. Flight Test 1 Example Chart.

3. *Flight Test 1 Test Matrix*

Table 5 shares the test matrix for Flight Test 1. Flight Test 1, conducted over four days, featured twenty individual flights with various aircraft and RID transmitters.

Table 5. Flight Test 1 Flight Test Matrix.

Test No		Aircraft	Beacon	Beacon	Beacon
Dryrun	Day 1	DJI Inspire 2	Bluemark 120	BT	WiFi
Flight01	Day 1	DJI Inspire 2	Bluemark 120	BT	WiFi
Flight02	Day 2	DJI Inspire 2	Bluemark 120	BT	WiFi
Flight03	Day 2	DJI Inspire 2	Pierce Aerospace B1	BT	
Flight04	Day 2	DJI Inspire 2	DroneTag Mini	BT	
Flight05	Day 2	DJI Inspire 2	DroneTag BS	BT	
Flight06	Day 2	Autel Evo 2	Autel Evo 2		WiFi
Flight07	Day 2	DJI Mini 3 Pro	DJI Mini 3 Pro		WiFi
Flight08	Day 2	DJI Mavic 2 Zoom	DJI Mavic 2 Zoom		WiFi
Flight09	Day 2	DJI Inspire 2	DroneTag Beacon	BT	
Flight10	Day 3	DJI Inspire 2	Bluemark 120	BT	WiFi
Flight11	Day 3	DJI Inspire 2	Bluemark 120	BT	WiFi
Flight12	Day 3	DJI Inspire 2	Bluemark 120	BT	
Flight13	Day 3	DJI Inspire 2	Bluemark 120		WiFi
Flight14	Day 4	DJI Inspire 2	Bluemark 120	BT	WiFi
Flight15	Day 4	DJI Inspire 2	Pierce Aerospace B1	BT	
Flight16	Day 4	MAAP Quadcopter	Bluemark 120	BT	WiFi
Flight17	Day 4	MAAP Quadcopter	Pierce Aerospace B1	BT	
Flight18	Day 4	MAAP Quadcopter	DroneTag Beacon	BT	
Flight19	Day 4	MAAP Quadcopter	DroneTag Mini	BT	
Flight20	Day 4	MAAP Quadcopter	DroneTag BS	BT	

B. DAA Encounter Simulation - Approach

1. Overview

The VT MAAP DAA encounter simulation is written in Python with a modular structure and with a primary goal to simulate the outcome of DAA encounters and compute risk-ratios for small Near Mid-air Collision (NMAC) and Well Clear (WC) definitions, all with as little CPU time as possible (re: fast-time simulation). For this study, the encounter simulation computed risk-ratios for sNMAC and sWC. This enables a Monte-Carlo approach of sweeping the design space of multiple independent variables to conduct trade studies on select variables. The independent variables are those that should naturally vary in a DAA encounter like aircraft speed, altitude, and heading. Statistically representative distributions are used for the independent variables if there is sufficient data to support it, like a speed distribution of sUA. Otherwise, uniform distributions are typically used to reduce the introduction of bias. The trade study variables are controlled variables selected for study, for example, the size of the well-clear & alerting volume and the RID detection range performance. Since it is a Monte-Carlo simulation, an increasing number of encounters are simulated until a convergence in the objective is observed (the risk-ratio).

2. *Design of Experiments*

Uncorrelated encounters

The simulation was configured to simulate uncorrelated encounters between the ownship and a cooperative intruder. Uncorrelated signifies DAA is performed without relying on strategic deconfliction services, like UTM or other air traffic control services. A cooperative intruder in this context for RID means the intruder is cooperating by actively broadcasting its location with RID, normally cooperative means the intruder is using any type of transponder.

Aircraft Models

The simulation operates using aircraft kinematic models in three dimensions and a configurable time step size. Aircraft trajectories are simulated with kinematic constraints of min/max velocities, lateral acceleration, vertical acceleration, and turn rate or bank angle. The aircraft have a series of built-in functions for trajectory control, for example, turns to headings and horizontal and vertical speed commands that all obey the physics and constraints of the aircraft. The simulation does not include forces on the aircraft, it is a pure kinematic model. If an aircraft is not commanded to maneuver, it will remain at a constant velocity until it is commanded to do otherwise. In this simulation, the ownship was configured to remain on present heading and arrest any climb/descent caused by the avoidance.

In this simulation, both the intruder and ownship share a common set of performance constraints:

- **Airplane physics:** the significance is when airplanes maneuver, they do not substantially change speeds like multi-rotor UA's do.
- **15 deg max bank angle** (all turns are performed at this bank angle): Most sUA flight controllers limit maneuvering to a fixed max bank angle, so it is expected this angle would be reached during a collision avoidance maneuver. Also, the max bank angle was favored over a max turn rate due to the large range of possible sUA speeds which would result in low-speed aircraft using very shallow bank angles and high-speed aircraft using steep bank angles, as shown below.
    - 20 kt airspeed at 7 deg/s turn rate = 7.3 deg bank angle & 84.1 m turn radius
    - 60 kt airspeed at 7 deg/s turn rate = 21.0 deg bank angle & 252.4 m turn radius

- **Skewed normal distribution of sUA speeds:** this distribution of speeds is referenced to a previous DAA study for UA's by Timothy M. Bagnall (Figure 20) [2].
- **Max climb/descent rate of 500 feet per minute:** A nominal vertical rate for many sUA's.
- **Vertical acceleration limits of 0.75G to 1.25G:** This allows a fairly aggressive initiation of a climb and descent.

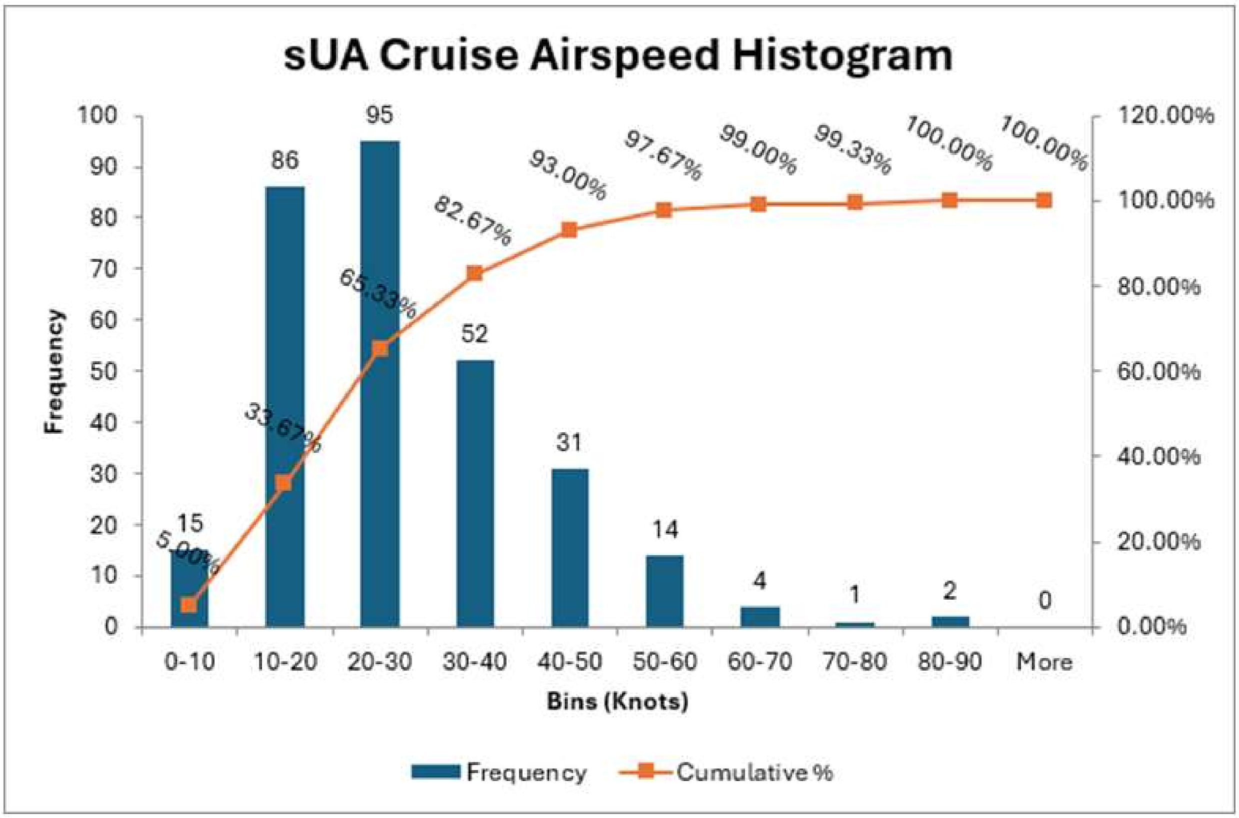


Figure 20. sUA Cruise Airspeed Histogram.

Sensor Model

A simple sensor model was implemented for the sole purpose of performing the trade study in comparing the effect of RID detection range on the needed sWC volume size. The sensor model was configured to allow the ownship to detect the intruder where it was less than the prescribed RID detect range allowed for a particular trade study test point. For example, three different points would be 100 m, 200 m, and 300 m. This allows performing a trade study that is agnostic to particular RID transmitter and receiver devices and antenna combinations. Ultimately, such combinations dictate the detection range of a system in an encounter. Likewise, the WRC RID sensor model produces an estimated detect range for a given combination of transmitter, receiver, and environment. These estimated detect ranges can be applied as minimum range constraints in the simulation's trade study.

Avoidance Algorithm – NASA DAIDALUS

Version 2 of the NASA LaRC DAIDALUS algorithm was used for the avoidance algorithm in the simulation. The recommended configuration for DO-365 was used as a starting point for the DAIDALUS configuration which prescribes multiple alert levels with an early alert before WC, one for WC violation, and another for recovery from WC violation. In the simulation DAIDALUS was configured to use only one alert level, the one for sWC violation, where DAIDALUS will maneuver just enough to prevent a sWC violation. DAIDALUS can use turns, vertical maneuvers, and airspeed changes for avoidance. In this simulation DAIDALUS was configured to only use turns and vertical maneuvers. Speed changes for avoidance was not used to ensure the aircraft stayed on its assigned speed from the sUA speed distribution. Also, the configuration was modified to use the previously established sNMAC definition of 50 ft lateral and 15 ft vertical [3]. Sensor uncertainty modeling was removed since the simulation was not configured to model GPS accuracy of the RID beacons. Throughout the simulation trade study, the only DAIDALUS configuration values adjusted were those for the alert level to maintain sWC. The lateral and vertical distance for that alert level was matched to the changes in the sWC definition throughout the trade study.

Encounter Generation

Encounters are simulated between a single aircraft pair, one ownship and one intruder (i.e., pairwise encounters). The intruder path is initially configured as a straight, constant velocity trajectory. The encounter generation generator dictates the starting positions and velocities of the intruder and ownship to cause a desired horizontal miss distance (HMD) and vertical miss distance (VMD) and the closest point of approach (CPA).

This is the primary component used to create the Monte-Carlo component of the simulation by creating distributions of possible values for:

- A uniform distribution of headings for each aircraft between 0-359° true course, otherwise termed "wagon-wheel"
- A skewed-normal distribution of sUA speed, as previously discussed in the aircraft model section
- A randomized distribution of HMD and VMD at CPA (Figure 21)

- Randomization of intruder maintaining straight & level or turning to random rollout headings (Figure 22)

The HMD and VMD of encounters were generated to 50% larger than the sWC definition under test, as shown in Figure 21. For example, if the sWC radius was 100ft for a given trade study condition, encounters were generated between 0 - 150 ft. This variation is important to generate encounters of varying severity and in order to adequately sample enough sNMAC and sWC encounters for computing the risk-ratio. Also, simulating encounters beyond sWC was found to be important to capture failures in avoidance logic. Sometimes it was observed that DAIDALUS would fail by causing a sNMAC violation when only a sWC violation would have occurred if it had not avoided. A common scenario was DAIDALUS would climb into the intruder's flight path because it ruled out descent as an option due to proximity to the ground.

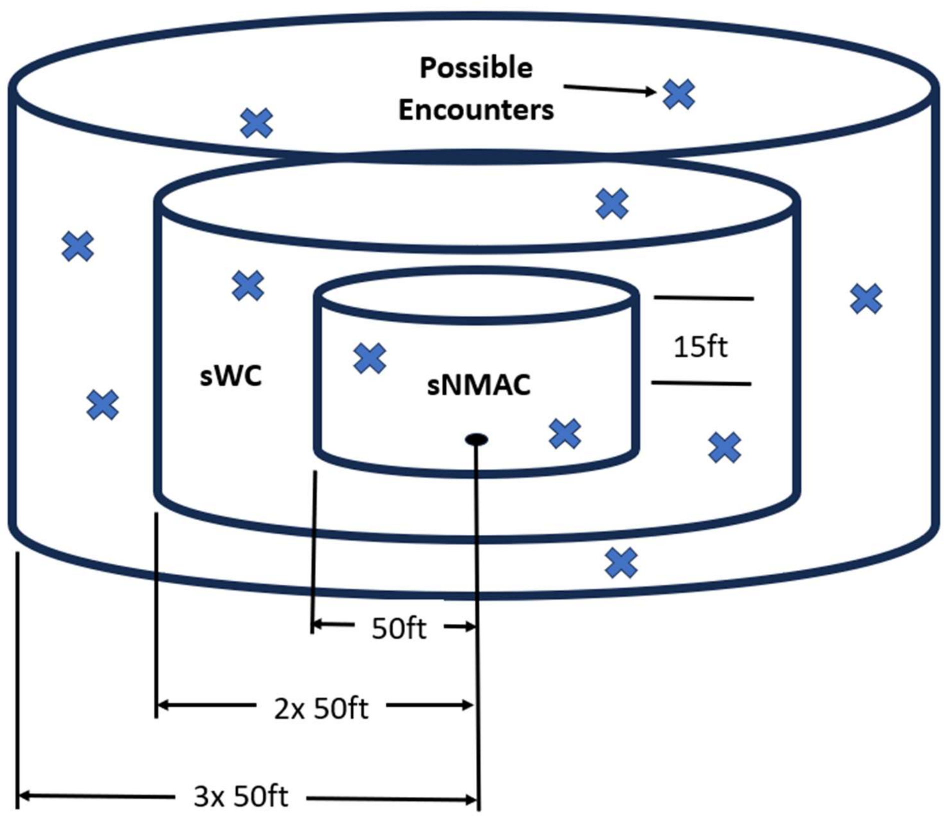


Figure 21. Encounter Generation with Respect to sWC and sNMAC Volumes.

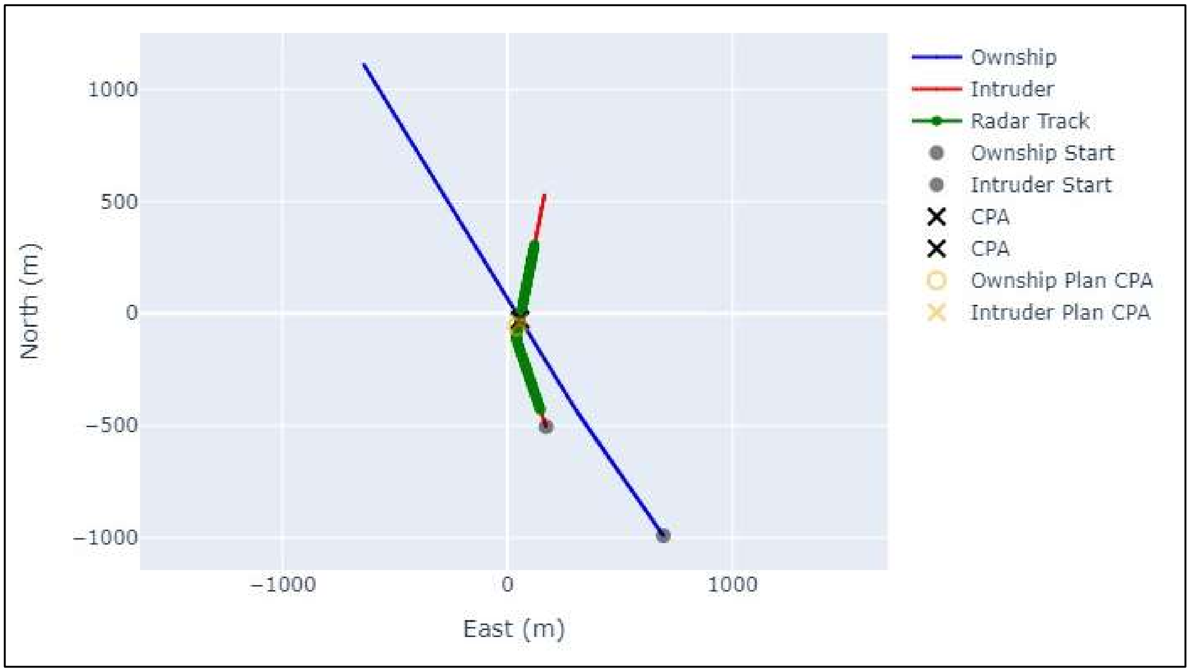


Figure 22. Trajectories from a Single Sim Run with Intruder Turning Right to a Random Rollout Heading.

Risk-ratio Calculation

The risk ratio is defined by the ASTM standard F3442M-23 (Figure 23). The generalized form of the risk ratio for a specific type of encounter (near mid-air, well clear violation, etc.) is:

$$\text{Risk Ratio} = \frac{P_{\text{mitigated}}}{P_{\text{unmitigated}}}$$

Where, $P_{mitigated}$ is the probability of the specific encounter (a violation of either NMAC or WC or other criteria) while using the DAA system for avoidance and $P_{unmitigated}$ is the probability of the specific encounter violation without the DAA system in use. The ASTM standard defines maximum risk ratio values for near mid-air collision (NMAC) and well clear (WC) violations between UA and human occupied aircraft. However, such definitions for sNMAC and sWC for small UAS do not exist, hence finding sWC recommendations is one of the purposes of this project and simulation.

When computing the risk-ratio from the simulation results, all the outcomes for the encounters are counted into mitigated and unmitigated violations of sNMAC and sWC, respectively. The number of encounters with an unmitigated violation of sNMAC or sWC are the denominator term in the risk-ratio equation. This is where the encounter generator planned the aircraft to have a sNMAC or sWC violation independent of any maneuvering caused by DAIDALUS's avoidance logic. The numerator is the number of mitigated violations is where DAIDALUS tried to avoid an sNMAC or sWC but failed to do so, causing a sNMAC or sWC violation. This number also includes encounters where DAIDALUS caused an sNMAC/sWC violation by maneuvering when not maneuvering would have prevented a violation.

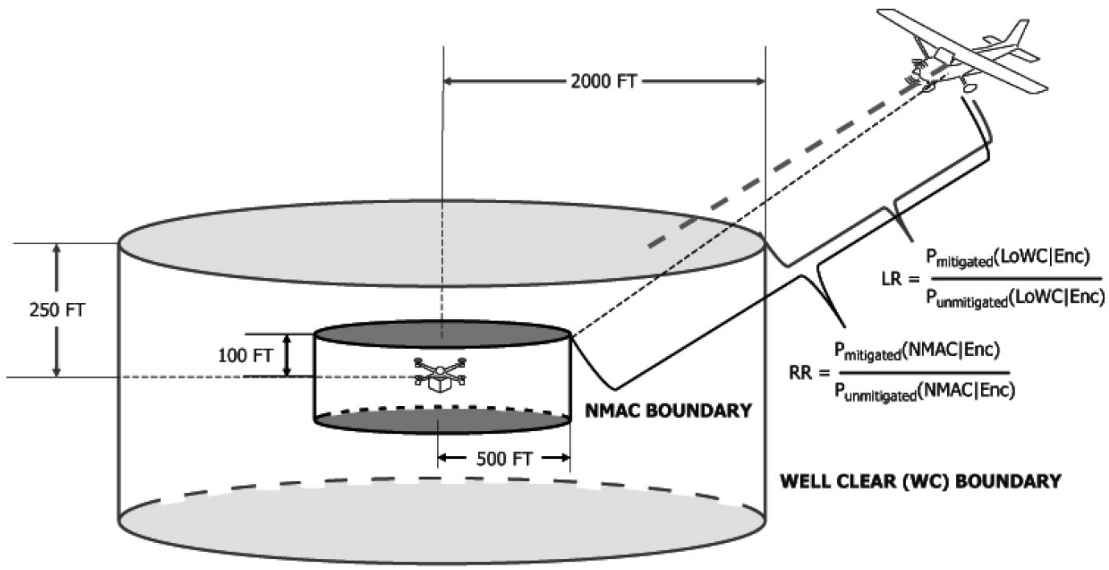


Figure 23. NMAC and Well Clear Definitions from ASTM Standard F3342M-23.

Trade Study

The simulation's trade study involves changing key variables that drive DAA system performance and thus risk-ratios. Since one of the simulation's objectives is to understand the effect of RID performance and recommend a sWC size. As shown in Table 6, the trade study makes sWC dimensions and RID detection range both controlled independent variables. This is done by assuming a simple RID system where the simulation only allows detection at the prescribed detection range for a given trade study configuration. The sWC size is changed in proportion to the sNMAC size, preserving the same aspect ratio of width to height, which allows consolidating the two variables of radius and height into a single scaling factor. Initial simulations with fewer encounters were performed to ensure the studied variables covered the design space, showing risk-ratios from zero to 0.6. Table 6 helps illustrate the approach taken by the team with its DAA encounter simulation. It is shared as a preview with answers to the question marks revealed in the subsequent data analysis section.

Table 6. Trade Study of sWC Dimensions and RID Detection Range. (Answers to question marks revealed in the Data Analysis Section.)

	Radius (ft)	100	150	200
	Vertical Sep. (ft)	30	45	60
	x sNMAC scale	2	3	4
RID Detection Range (ft)	328	?	?	?
	492	?	?	?
	656	?	?	?
	820	?	?	?
	984	?	?	?
	1312	?	?	?
	1640	?	?	?

VI. Data Analysis

This section describes the two primary data analyses the team performed in the effort. The first section regards the data analysis the team performed in its design and implementation of the RID sensor model, an integral component to the DAA encounter simulation. It also includes charts and data from sensor characterization flight test (i.e., Flight Test #1) and follow up charts from the demonstration and validation flight test (i.e., Flight Test #2). The second section regards the data analysis the team performed using the DAA encounter simulation. It includes tables, charts, and summary statistics culled from the analysis.

A. Remote ID Sensor Model - Data Analysis

1. Overview

The data analysis the team performed to design and build the RID sensor model can be simplified as an effort to fit RID message received signal strength indicator (RSSI) values against a) sUAS distance from the receiver, and b) attitude relative to the receiver. From this analysis effort, the team designed an RF link budget. Figure 24 provides an overview of the data analysis process the team followed to design the RID sensor model. In short, each leg of the flight profile provided details of how RSSI values fluctuated by separation distance. The four outbound and inbound legs provided details of how RSSI changed with aircraft pitch and roll. The fifth leg – with the two 360-degree rotations – provided information on how RSSI changed with aircraft yaw. Lastly, the team correlated RSSI to RID update rate. RID update rate may be estimated using output from the RID sensor model where the update rate is approximately one divided by the estimated probability of detection (e.g., a POD prediction of 0.20 is approximately equivalent to a 5 second update rate).

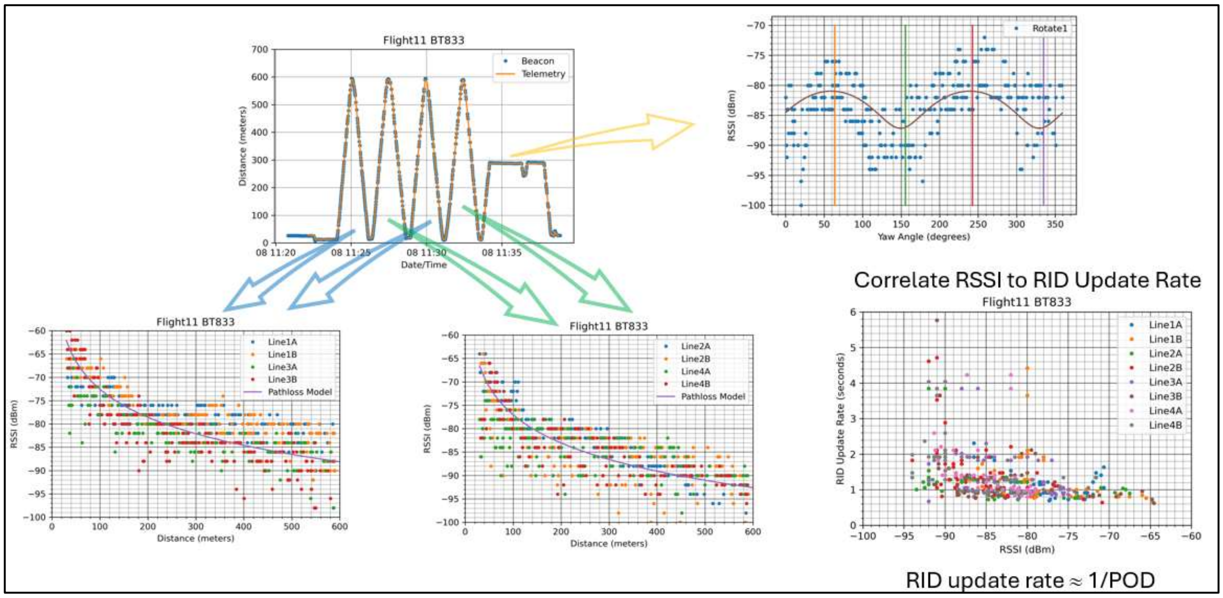


Figure 24. RID Sensor Model Data Analysis Process Overview.

Figure 25 shares a snippet of the actual RID sensor model Python programming code. It captures the class implementation of an omnidirectional antenna. Below this class is the beginning of a class implementation for a directional antenna.

```python
link_probability_r4.py

    @classmethod
    def omni(cls, pol_ratio=1.0, peakgain=1.7):

        def patfunc(az, el):
            pedestal = 1e-2
            return (1-pedestal)*np.cos(np.radians(el))+pedestal

        if pol_ratio < 0:
            pol_ratio = 0
        elif pol_ratio > 1:
            pol_ratio = 1

        az = np.linspace( start: 0,  stop: 360,  num: 2)
        el = np.linspace(-90,  stop: 90,  num: 181)
        az_ang, el_ang = np.meshgrid( *xi: az, el, indexing='ij')
        vdata = 20*np.log10(patfunc(az_ang, el_ang)*pol_ratio+1e-10)+peakgain
        hdata = 20*np.log10(patfunc(az_ang, el_ang) *
                            (1-pol_ratio)+1e-10)+peakgain
        peak_v = np.max(vdata)
        peak_h = np.max(hdata)

        vpat = RegularGridInterpolator( points: (az, el), vdata)
        hpat = RegularGridInterpolator( points: (az, el), hdata)
        return cls( pattern_type: "omni", vpat, hpat, peak_v, peak_h)

    @classmethod
    def directional(cls, pol_ratio=1.0, peakgain=4):
        def patfunc(az, el):
            pedestal = 1e-2
            return (1-pedestal)*np.cos(np.radians(el))*np.power(np.abs(np.cos(np.radians(az)*0.5)), 2)+pe
```

Figure 25. RID Sensor Model - Snippet of Python Code.

2. Analysis Charts

Please refer to Appendix C for a gamut of charts the team produced in its sensor characterization data analysis. The charts include a wealth of RID transmitter and RID receiver data and information. Figure 26 below shares an example of the type of chart the reader will find in Appendix C.

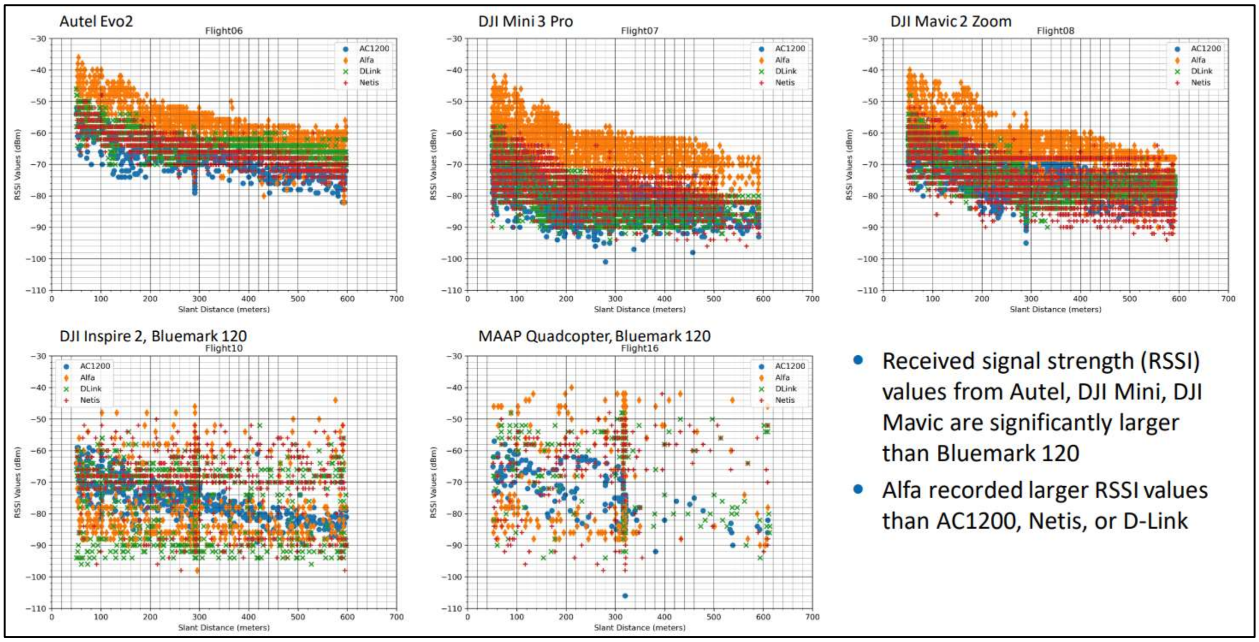


Figure 26. Example of Chart Produced during RID Sensor Model Data Analysis.

3. *Conclusions*

The RID sensor model implemented by the team produces fair estimates of the probability of detection between an RID transmitter and RID receiver. It considers several independent variables such as horizontal separation between transmitter and receiver, as well as EMI introduced by desense (see the bullets below for a description of desense). Its accuracy is limited by the amount of data collected during Flight Test 1 and Flight Test 2. The RID sensor model could be improved with additional lab tests. Lab tests provide a stable and repeatable environment to increase the number of measurement sample points. Below are some general conclusions made by the team regarding RID probability of detection:

- Bluetooth 5 (BT5) generally has a better POD at all separation distances than WiFi.
  - BT5 is less impacted by environmental interference due to using a narrower frequency bandwidth.
  - Additionally, because RID transmitters must also broadcast BT4 to satisfy the standard, the additional BT4 messages - broadcast simultaneously over three BT channels - yields a higher opportunity to receive an RID message.
  - RF desense significantly reduces the range for both BT5 and WiFi. RF desense is a degradation in receiver sensitivity caused by nearby RF noise sources. Collocation of the RID transmitter and the RID receiver on ownship degrades reception of intruder RID messages, causing shorter overall

reception ranges and intermittent reception rates. (Transceivers – such as those like ADS-B implementations - often alternate between broadcasting and receiving to avoid desense).

4. Probability of Detection Charts

Please refer to Appendix D for probability of detection charts estimated by the RID sensor model. Figure 27 is included here to provide an example of the type of chart found in Appendix D.

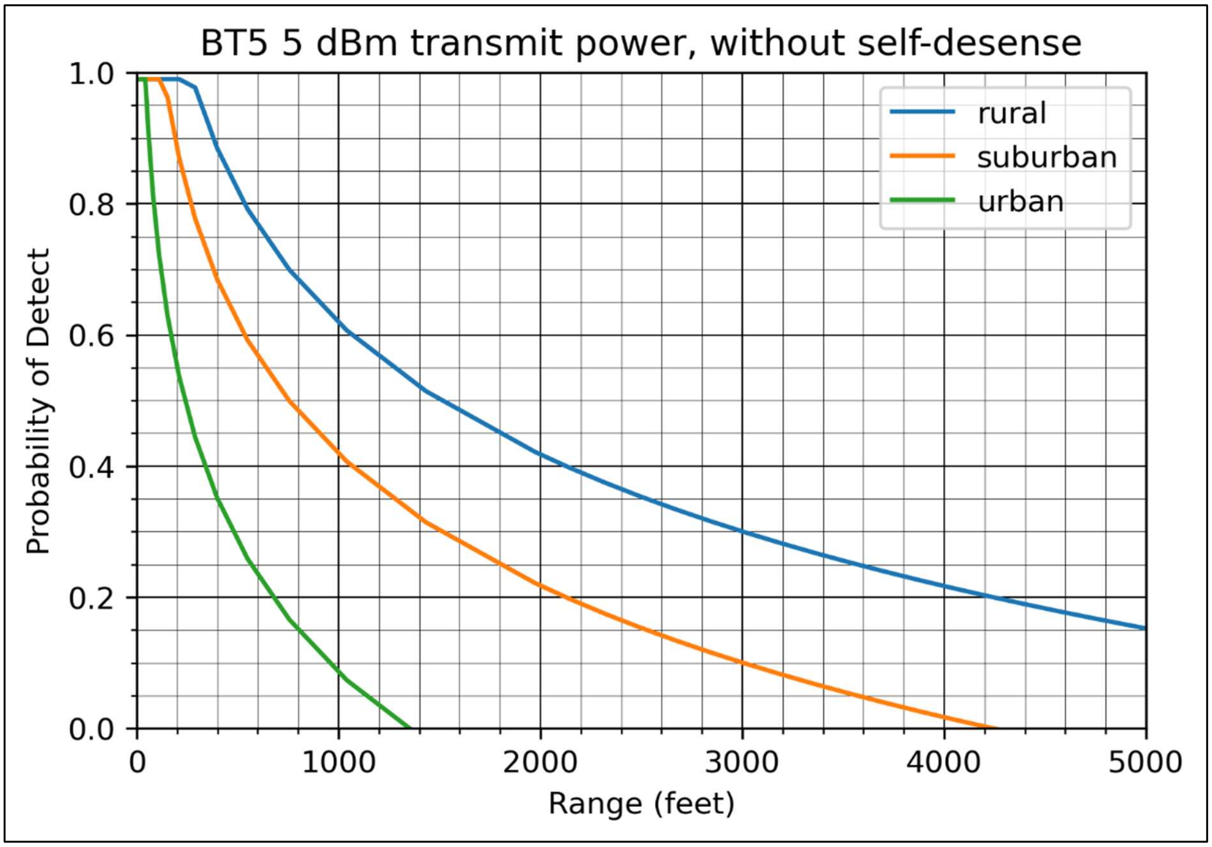


Figure 27. RID Sensor Model POD Chart – Bluetooth 5 (BT5) 5 dBm without Self-Desense.

B. DAA Encounter Simulation - Data Analysis

For each point of the trade study, the numbers of encounters simulated was chosen to ensure convergence of the risk-ratio solution. As seen in Figure 28 and Figure 29, 5,000 encounters were sufficient to achieve convergence for the trade study condition of 100 ft sWC radius and 656 ft RID detection range. In Figure 29, the risk-ratio reliably stabilizes to a 5% change for each additional 100 encounters simulated. Other test conditions with larger sWC sizes required as many as 15,000 encounters for the sNMAC risk-ratio to converge, due to a greater proportion of encounters being sWC encounters rather than sNMAC encounters.

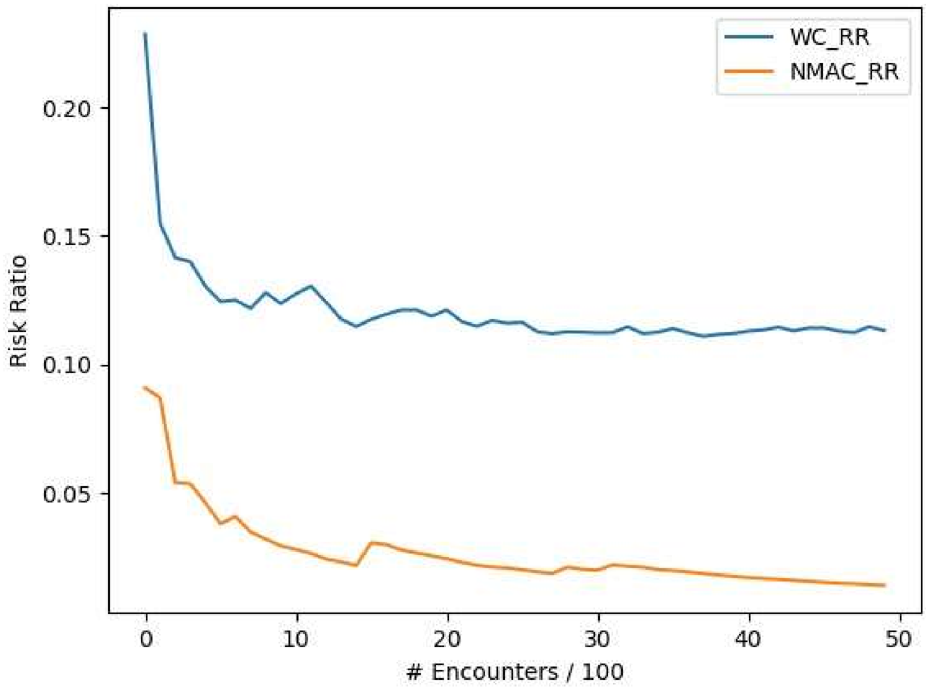


Figure 28. Risk-ratio Convergence for 100 ft sWC Radius and 656 ft Detect Range.

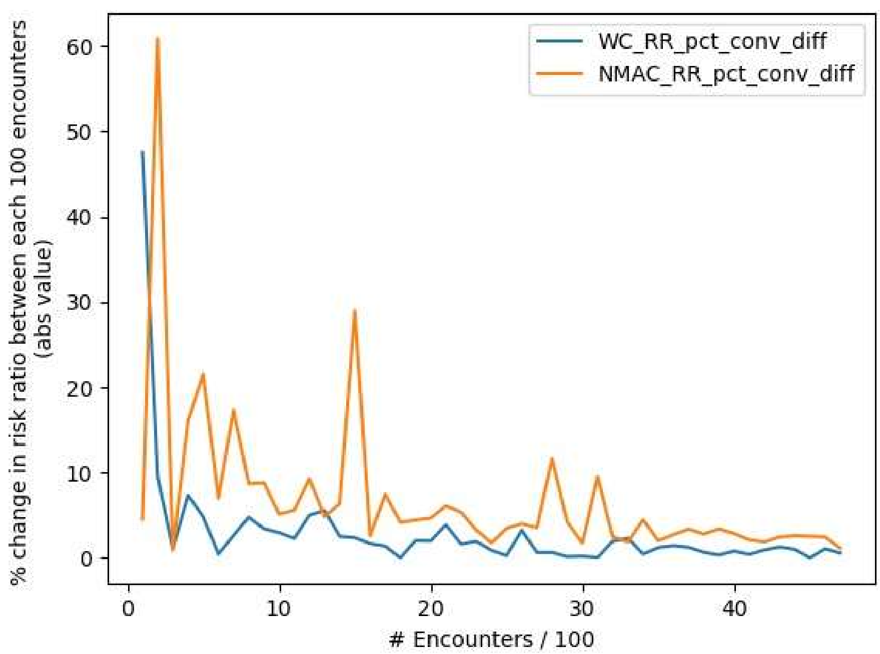


Figure 29. Percent Change in Risk-ratio Convergence for 100 ft WC Radius and 656 ft Detect Range.

1. Evidence-based sWC Recommendations

The following subsection shows the final results of the trade study and pairs the RID sensor model with GPS accuracy recommendations to formulate possible sWC recommendations. The trade study shows it is feasible for sUA-to-sUA DAA to work with RID. However, this is assuming certain levels of risk in selecting specific risk-ratio targets. These risk-ratio targets are largely dependent on the overall desired mid-air collision risk and the corresponding risk to persons or property on the ground. Following the footsteps of related previous research and after collaborating with other experts in the field, the team pursued sNMAC risk ratio objectives of 5 and 10 percent.

Table 7 and Table 8 show the results of the trade study. These values are used in the risk-ratio contour plots below the tables. Not applicable (N/A) cells indicate configurations not simulated in the trade study.

Table 7. Trade Study Result for sWC Risk-ratio.

sWC Risk-Ratio

		RID Detect Range						
	feet	**328**	**492**	**656**	**820**	**984**	**1312**	**1640**
sWC Radius	**100**	0.466	0.226	0.115	0.061	0.048	0.022	0.020
	150	0.596	N/A	0.239	N/A	0.113	N/A	N/A
	200	0.723	N/A	0.326	N/A	0.186	0.102	N/A

Table 8. Trade Study Result for sNMAC Risk-ratio.

sNMAC Risk-Ratio

		RID Detect Range						
	feet	**328**	**492**	**656**	**820**	**984**	**1312**	**1640**
sWC Radius	**100**	0.354	0.130	0.044	0.018	0.005	0.008	0.004
	150	0.548	N/A	0.161	N/A	0.043	N/A	N/A
	200	0.553	N/A	0.251	N/A	0.092	0.020	N/A

The trade study results were paired with GPS accuracy constraints and RID detection range constraints to propose a few possible sWC definitions. Two GPS accuracy cases were considered: one for a low-cost, lower accuracy GPS chip, and a second for an easily attainable GPS accuracy for normal-cost receivers, both of which are commonly used in electronic devices. Since the DAA system uses GPS for both the intruder and ownship position, the GPS accuracies must be doubled to account for the compounding of position uncertainty.

1. Vertical: 50 ft; Horizontal: 167 ft

   Based on the accuracy of a commonly available and cheap GPS chip where lateral accuracy should be around 2.5 m and vertical accuracy at 2.7x lateral accuracy = 6.7 m (~22 feet). Plus ~2x the vertical accuracy for staying outside the margin of error. Horizontal value following shape of sNMAC definition of Vertical: 15 ft; Horizontal: 50 ft. [4]

2. Vertical: 34 ft; Horizontal: 113 ft

   Based on easily attainable GPS chip vertical accuracy of 5 meters (~16 feet). Plus ~2x the vertical accuracy for staying outside the margin of error. Horizontal value following shape of sNMAC definition of Vertical: 15 ft; Horizontal: 50 ft. [5]

Selection Process

1. The two proposed GPS accuracies are used to form a constraint for the smallest acceptable sWC volume and are drawn as the dashed lines in Figure 30 and Figure 31.
2. Candidate sWC points are identified by the intersection of the GPS accuracy constraints with the 0.05 and 0.10 risk-ratio contours.
3. The constraints for the lowest allowable RID detection ranges are drawn as vertical green, orange, and blue lines (Figure 30 and Figure 31) according to the previously discussed RID probability of detection model. The desense RID model was used as a worst-case scenario. The range selected from the RID model corresponds to a 0.20 probability of detection. A 0.20 probability of detection indicates that the ownship's RID receiver will receive a position update at least every 5 seconds since probability of detection is equal to the reception period. The DAIDALUS avoidance logic with a 5 sec hysteresis requires reliable position updates of traffic every 5 seconds to continue avoidance. Slower update rates will result in DAIDALUS intermittently issuing resolution advisories and thus the ownship will not reliably continue avoidance.
4. Candidate points that offer valid sWC recommendations must be less than the RID detection range constraints and greater than the GPS accuracy constraints.

For Bluetooth 5 (BT5) - following the selection process provides a couple candidates for Bluetooth 5 (BT5) and WiFi, however, only in certain EMI environments. Choice #3 in Figure 30 is the proposed sWC definition for 0.10 sNMAC risk, but only for suburban and rural environments. Likewise, choice #2 is the proposed sWC definition for 0.05 sNMAC in suburban and rural environments. Since little is known about the EMI in urban environments, we cannot definitively say Bluetooth 5 offers an adequate detection range. More EMI RF research is needed before coming to a full conclusion.

For WiFi - the selection process provides only two valid candidates, both only appropriate for rural environments. For 0.05 sNMAC, choice #2 is sufficient. For 0.10 sNMAC, choice #1 is sufficient.

Other candidates are possible as long as they obey the GPS and RID constraints. For example, for suburban BT5 and a 0.05 NMAC, a sWC radius of ~135ft is feasible. Additionally, higher or lower acceptable sNMAC risk-ratios offer other candidates.

We should highlight that these recommendations were made assuming self-desense is limiting RF reception range and without fully understanding the EMI of urban environments. Mitigation of desense, something the authors believe is technically feasible, should greatly enhance the probability of detection for all ranges, significantly improving the efficacy of RID-based DAA in all EMI operating environments.

# choice	Desense Density	sWC radius (ft)	Reqd. RID Range (ft)	sNMAC RR
1	suburban	113	600	0.1
2	suburban	113	740	0.05
3	**suburban**	**167**	**870**	**0.1**
4	rural	167	1050	0.05

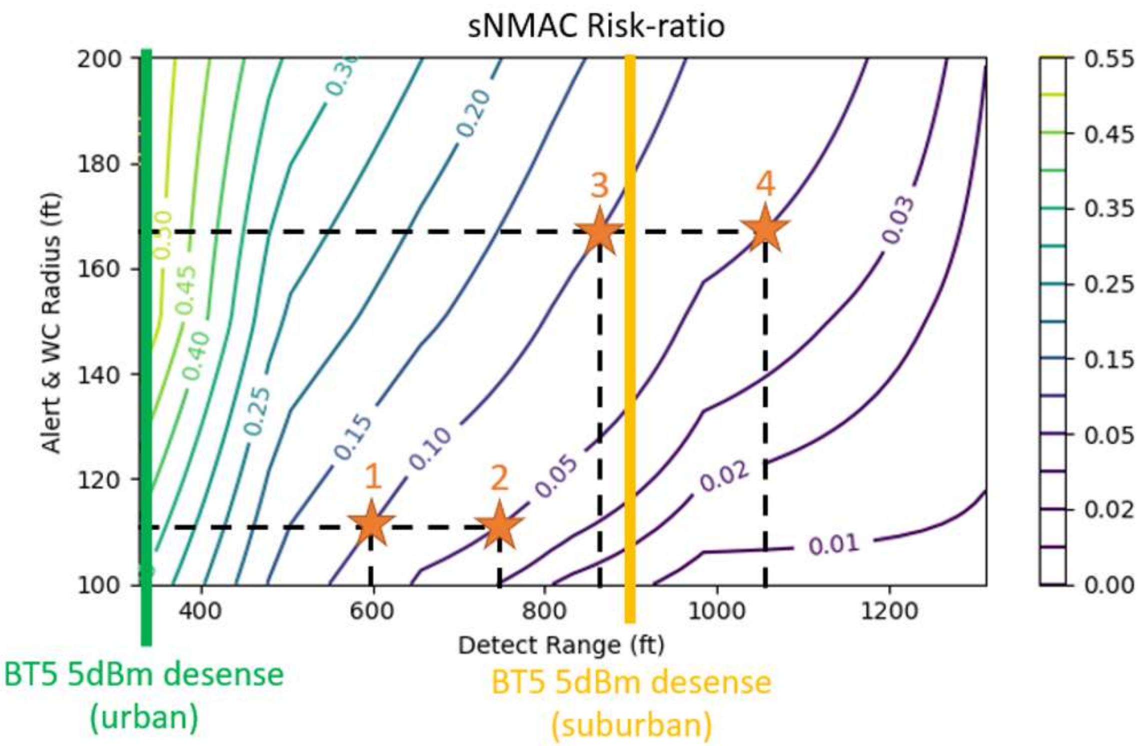


Figure 30. Proposed sWC Recommendation for BT5 with Desense. Recommend Candidate #3.

# choice	Desense Density	sWC radius (ft)	Reqd. RID Range (ft)	sNMAC RR
1	rural	113	600	0.1
2	**rural**	**113**	**740**	**0.05**
~~3~~		~~167~~	~~870~~	~~0.1~~
~~4~~		~~167~~	~~1050~~	~~0.05~~

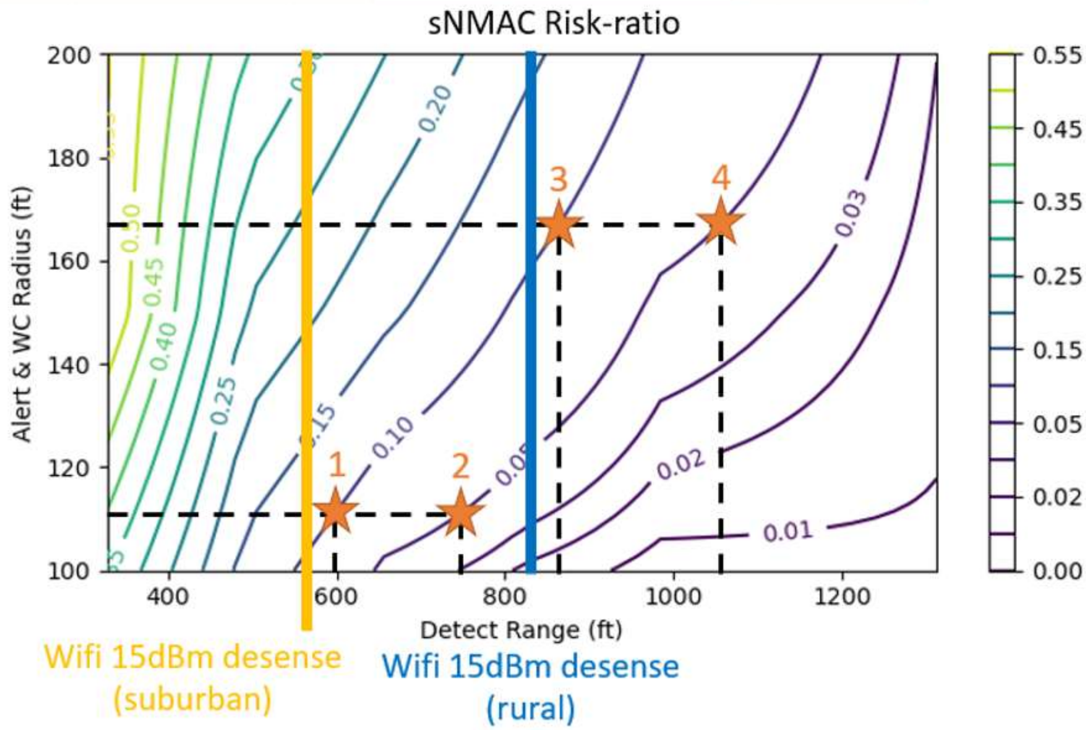


Figure 31. Proposed sWC Recommendation for WiFi with Desense. Recommend Candidate #2.

VII.Challenges

This section describes the technical challenges the team confronted and overcame throughout the project.

A. ACAS sXu Implementation

The most formidable challenge the team faced in the project was its implementation of the ACAS sXu DAA system. The team was able to implement its own version by following the publicly available ACAS sXu V3 reference architecture.

Related to this challenge, early in the project, owing to the risk of not having ACAS sXu to support the effort, the team also decided to implement a DO-365 DAA capability. To do so, the team leveraged the NASA Langley Research Center Detect and Avoid Alerting Logic for Unmanned Systems (DAIDALUS) system (https://nasa.github.io/daidalus/), a reference DO-365 DAA capability. The team found DAIDALUS to be extremely intuitive to use and highly configurable, well suited for supporting the exploratory research nature of the project.
In the end, overcoming this challenge proved to be a significant, unintended boon to the project, as the RID DAA prototype capability would come to include not one but two DAA logics for demonstration and validation.

B. ACAS sXu Sensitivity to Intermittent Input

One of the basic requirements of the ACAS sXu V3 capability is the continuous receipt of ownship telemetry and intruder position reports at an arrival rate of 1 Hz. Though ACAS sXu will continue to function for a small fraction of time in the absence of ownship telemetry and intruder position reports (in testing about 2 – 3 seconds), the fickle nature of the RID broadcast where the interarrival rate of position reports may easily extend to five or more seconds poses an immediate challenge for effective RID DAA with ACAS sXu as the DAA logic. To overcome this challenge, the team decided to implement a persistence feature in its DAA prototype software architecture. The system would send ACAS sXu the last known intruder position report for up to five seconds at 1 Hz. This persistence feature was simple and did not use any dead reckoning to guess at the intruder's position. This solution helped stabilize ACAS sXu's performance during the live flight testing and demonstration.

C. ACAS sXu Configuration Difficulty

Relative to DAIDALUS, configuration of the ACAS sXu system was difficult and not fully accomplished in the project. The DAIDALUS configuration file is much more intuitive and better documented. The configuration of ACAS sXu (for example having it use 500 fpm ascent rates rather than 1000 fpm) was too difficult for the team to solve within the timeframe. This lack of agility with ACAS sXu capability led the team to focus on solely using DO-365 for its encounter simulation.

D. High-Speed Air-to-Ground Datalink

This section describes the extent the team went to implementing a reliable air-to-ground datalink for communicating avoidance maneuvers, RID messages, pilot confirmations, and ArduPilot Copter status. In the end the team used a HereLink C2 system which, after some highly technical troubleshooting, worked exceedingly well. However, one unwelcome side effect of the HereLink C2 system was the noteworthy electromagnetic interference (EMI) of WiFi RID messages. The team noticed a considerable drop in range and reception rate of WiFi RID messages when using the HereLink C2 system. Online searches reveal that disruption of ancillary WiFi services (e.g., internet browsing and video streaming) are not uncommon around the HereLink C2 system.

E. Variability in COTS RID Transmitter Performance

The team ensured that all RID transmitters utilized during testing had an FAA accepted declaration of compliance (DOC). Even though all had DOCs, the team measured a wide variability in performance between the different transmitters. This included several instances of deviations from the accepted ASTM means of compliance (MOC).

Examples of the variability include:

- Missing data fields, specifically heading
- Broadcasting the incorrect altitudes (using orthometric altitude instead of geometric altitude)
- Unexplained reduced performance, specifically in reception range. This seems to be dependent on the exact transmitter design and likely has to do with how the company chose to design the antenna and casing.
- Erroneous latitude and longitudes included in broadcasts

F. Plug and Play WiFi and Bluetooth Adapters

Another challenge the team faced was the implementation of its air-based Remote ID receiver solution. To receive Remote ID messages in the air, the team selected several Bluetooth and WiFi USB adapters advertised by their manufacturers as “monitor mode” capable. A monitor mode, which can also be thought of as a listening mode, is required for receiving RID messages. The team had incorrectly assumed that use of the various selected adapters would be almost as easy as “plug and play;” however, the team found making the adapters function properly required finding the correct software driver for the target operating system and performing a number of fairly complex technical configuration steps (e.g., UNIX commands for turning on monitor mode and UNIX commands for setting the monitor mode channel).

VIII. Lessons Learned

- RID-based DAA feasibility. The primary lesson learned by the team, through demonstration and validation flight testing and high-fidelity encounter simulation, was that RID-based DAA is not only technically feasible but shows promise for improving airspace safety related to the integration of sUAS into the NAS. Though the team had been previously involved with DAA of sUAS by General Aviation (GA) aircraft using RID broadcasts, there was some healthy skepticism within the team on whether RID-based DAA for sUAS vs. sUAS was feasible. The highly successful demonstration and validation flight test proved that not only was RID-based DAA feasible but also effective. The ultimate viability of RID-based DAA, however, is heavily dependent on RID performance, which the team unfortunately saw fluctuate between RID transmitters. Since all RID transmitters have accepted FAA DOCs, this points to the need to either ensure these transmitters fully comply with the ASTM standards and/or enforce more performance-based standards. Unless all RID transmitters can be guaranteed to operate per the ASTM standards, RID-based DAA will be intractable.
- Maneuver coordination may be challenging. DAA outcomes typically improve when aircraft can coordinate maneuvers (e.g., in a head-on encounter both aircraft agree to turn right). Coordinating maneuvers between two peer aircraft (i.e., aircraft similarly equipped with DAA sensors and logic) requires a datalink to share maneuver intent. A direct vehicle-to-vehicle (V2V) link is most desirable as it eliminates superfluous communication networking. However, there is no such widely available link currently available. To coordinate maneuvers between sUCAS DAA prototype applications, the team shared intent via a ground network. In the future, one potential improvement to the RID standard that could help alleviate this challenge is to include an RID field that carries DAA intent.
- Terrain and other obstacles. Though both ACAS sXu and DO-365 can include terrain and other obstacles (e.g., water towers) in their solution space, the team, in its demonstration flight testing, did not have time to pursue any related in-depth tests on managing the complexity of terrain. The relatively low above ground level (AGL) altitude of sUAS operations inherently adds risk of collision with terrain and other obstacles and limits the available airspace for executing maneuvers.
- Electromagnetic Interference.
    - RF Desense

- RF desense is a degradation in antenna sensitivity caused by nearby RF noise sources. Collocation of the RID transmitter and the RID receiver on ownship degrades reception of intruder RID messages, causing shorter overall reception ranges and intermittent reception rates. (Transceivers - e.g., ADS-B - often alternate between broadcasting and receiving to mitigate desense). A fully mature RID-based DAA system would have to mitigate the adverse effects of desense through coordinating ownship's RID broadcasts with ownship's RID receptions.

- HereLink C2
  - The HereLink C2 system used by the team during flight testing resulted in electromagnetic interference (EMI) that significantly reduced RID reception performance for WiFi RID broadcasts. Due to this, the team transitioned to Bluetooth broadcasts during the live flight testing. The EMI caused by HereLink EMI seems to be a known issue as users have commented on the disruption to local WiFi performance during HereLink operation.

IX.Conclusions

Despite some limitations, RID-based DAA for sUAS vs. sUAS is feasible and, as demonstrated and validated via flight testing and modeling and simulation, shows promise for improving aviation safety. The two primary limitations impacting RID-based DAA include:

1. **Subpar RID transmitter performance.** Though the RID standard includes specifications on effective isotropic radiated power (EIRP) and broadcast rate, actual performance seen during flight testing for some RID transmitters was worse than expected. Transmitter casing and integrated antenna design can adversely affect achieved EIRP. A better way to measure and verify EIRP, in the final product state, could help achieve a minimum operational performance.
    - Other examples of RID transmitter issues the team witnessed during testing include RID messages that omitted the heading/track value, RID messages that included orthometric instead of geometric altitude, and RID messages with erroneous latitudes and longitudes. These issues point to RID transmitters that do not fully meet the accepted ASTM means of compliance (MOC).
2. **RF desense.** RF desense is a degradation in receiver sensitivity caused by nearby RF noise sources. Collocation of the RID transmitter and the RID receiver on ownship degrades reception of intruder RID messages, causing shorter overall reception ranges and intermittent reception rates. (Transceivers - e.g., ADS-B - often alternate between broadcasting and receiving to mitigate desense).

These two limitations must be resolved for RID-based DAA to be fully effective. Fortunately, both can be resolved. The first through better verification and validation of RID transmitter compliance to the standard. Verification and validation should be on the proposed final product including any encasements. Encasements and other enclosures have been known to adversely affect performance. Third party testing of RID transmitters may also help to ensure validation of compliance to the ASTM standards. The second limitation can be overcome through better RID receiver design and software upgrades to coordinate RID broadcasts and RID sensing.

Other limitations to the RID DAA concept include susceptibility to spoofing (which the team assesses as a very low risk), complexity of operations near terrain, and lack of a RID message field for pairwise DAA maneuver coordination.

A near mid-air collision risk ratio contour map produced from results of the high-fidelity, fast-time DAA encounter simulation shows the relationship between RID detection range, sWC volume, and mid-air collision risk. The contour map allows the FAA to size the sWC volume according to the overall risk it is willing to assume for the target operational environment. To help illustrate how the risk ratio contour map may be used by the FAA, the research team proposed two sWC definitions based on estimated GPS accuracies for relatively economical GPS chips available on the commercial market. The reference sWCs posited by the team include: 1) 167 ft lateral and 50 ft vertical, and 2) 113 ft lateral and 34 ft vertical. The first appears compatible with achieving a 10% sNMAC risk ratio for Bluetooth 5 operations in rural and suburban environments. The second appears compatible for achieving a 5% sNMAC risk for WiFi operations in rural environments. Since sUAS operators may use either BT or WiFi to conform with the RID standard, the smaller sWC definition (113 ft lateral and 34 ft vertical) seems more sensible.

X.Recommendations

Though the research team believes that RID DAA has the potential to improve UAS integration airspace safety and help expand BVLOS operations in the NAS, there is still much work to be completed before fully realizing RID DAA. Here, the famous George Box 1976 aphorism applies: "*All models are wrong, some are useful*." DAA studies are extremely complex, not straightforward, and often take years of effort to compile sufficient evidence. Challenges associated with DAA studies include encounter simulation design and live flight-testing constraints. Part of the challenge of encounter simulation design is the modeling of the operational airspace, specifically the modeling of realistic, uncorrelated encounters between sUAS aircraft, for current day operations and for future time horizons. Live flight testing is time and cost intensive. Although the research team exceeded the deliverables stipulated by the contract statement of work, there were many more DAA concepts and scenarios the team wished to run.

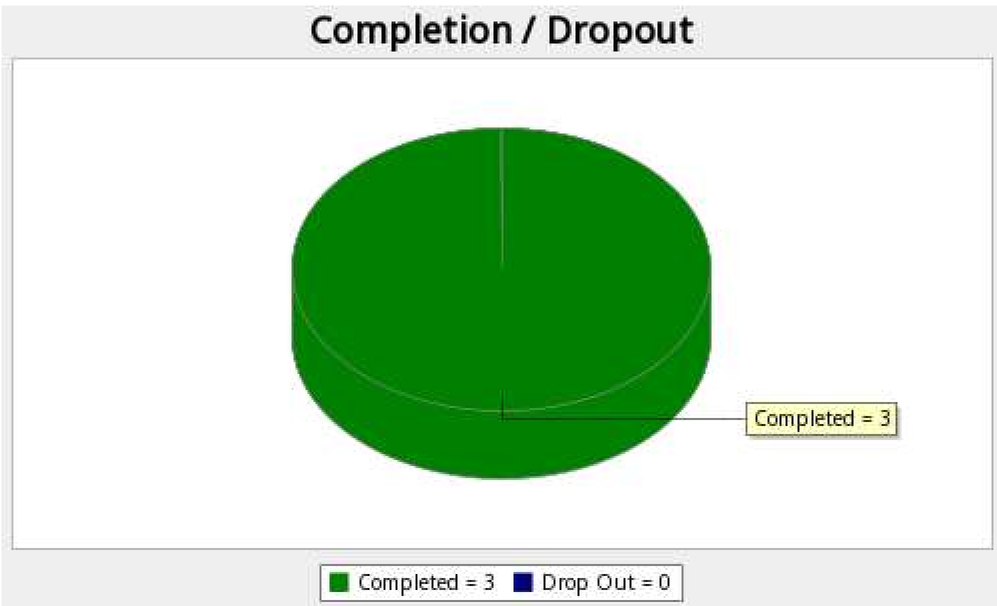
To continue to explore the potential of RID-based DAA, the team recommends the FAA pursue the following research and development and process improvement efforts:

- Additional RID DAA simulation studies
- Additional demonstration and validation flight testing
- Additional RF experiments to improve RID sensor models:
    - Desense
    - EMI of urban and suburban areas
- Improved processes for verification and validation of RID transmitter conformance (i.e., a stricter declaration of compliance process)

Appendices

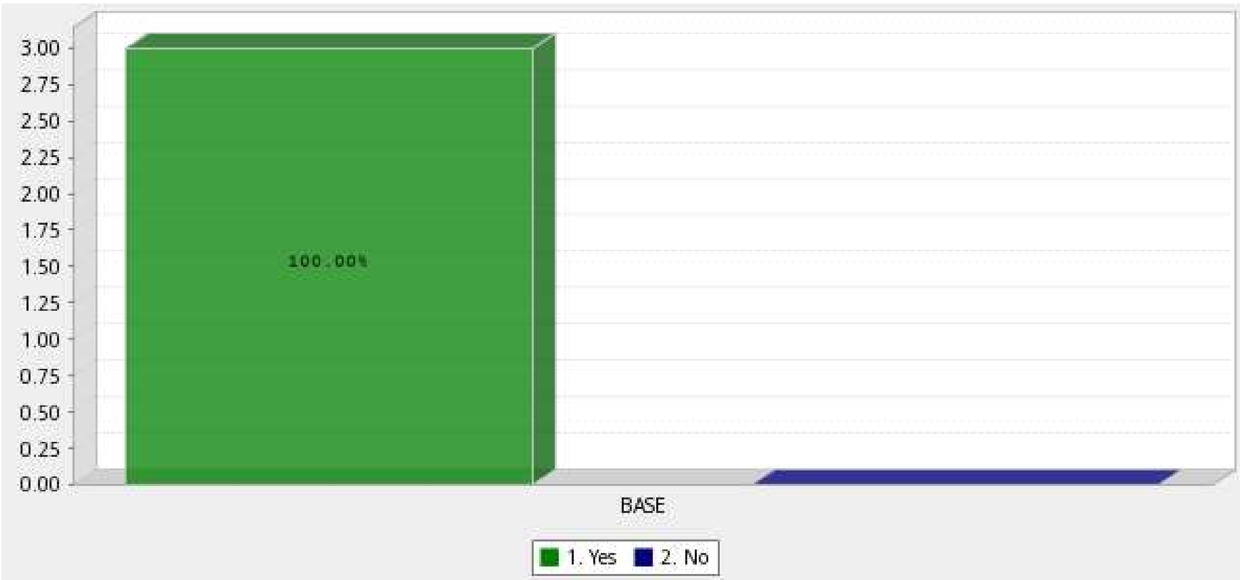
A. sUCAS Prototype Pilot Human Factors Engineering Survey

MOSAIC ATM sUCAS RID DAA HFE Survey Overview



Viewed	Started	Completed	Completion Rate	Drop Outs (After Starting)	Average Time to Complete Survey
22	**3**	**3**	**100%**	**0**	**8 minutes**

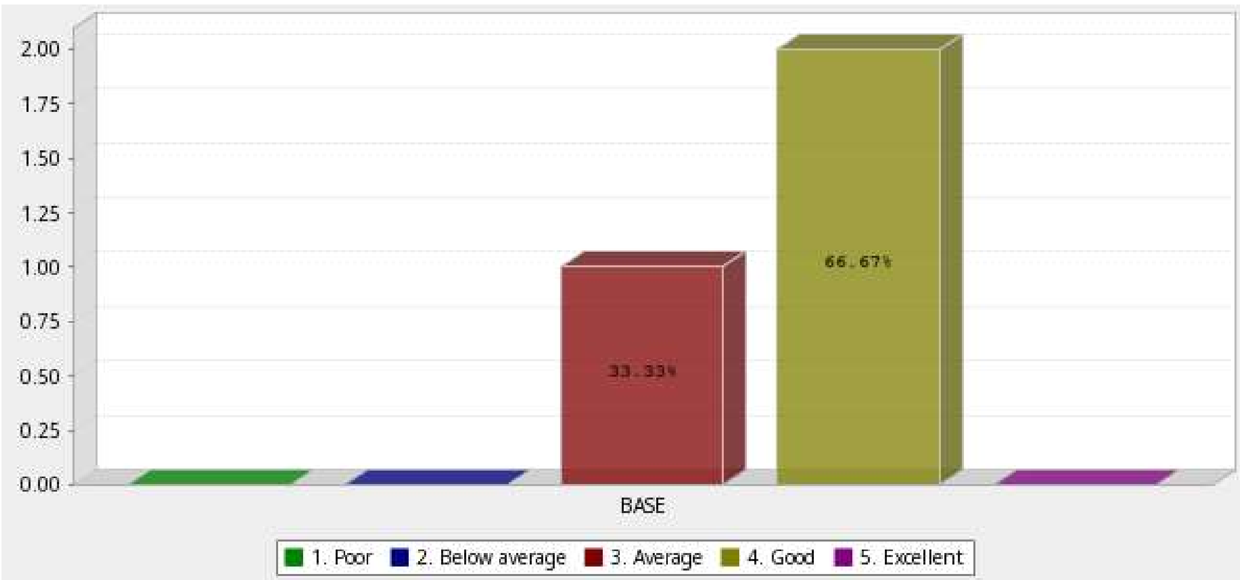
Q17. Did the sUCAS display provide you with the information expected?



	Answer	Count	Percent
1.	Yes	3	100.00%
2.	No	0	0.00%
	Total	3	100%

Mean : **1.000**	Confidence Interval @ 95% : **[1.000 - 1.000]**	Standard Deviation : **0.000**	Standard Error : **0.000**

Q17. What was the overall usability of the sUCAS display and interface?



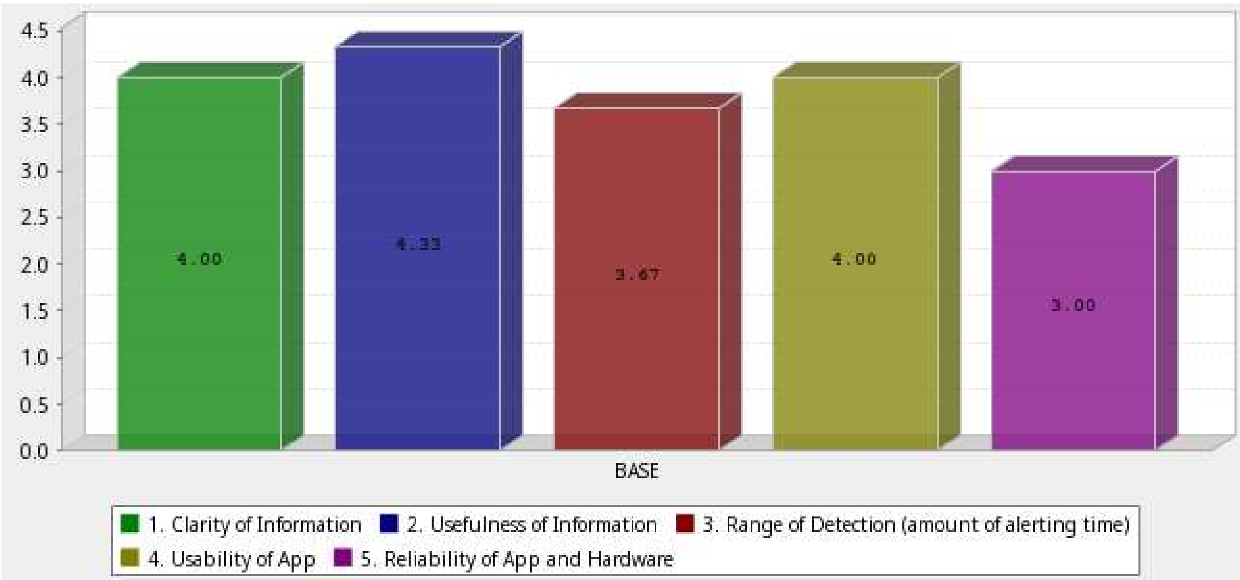
	Answer	Count	Percent
1.	Poor	0	0.00%
2.	Below average	0	0.00%
3.	Average	1	33.33%
4.	Good	2	66.67%
5.	Excellent	0	0.00%
	Total	3	100%

Mean : **3.667**	Confidence Interval @ 95% : **[3.013 - 4.320]**	Standard Deviation : **0.577**	Standard Error : **0.333**

Q3. Please provide comments on the overall usability of the sUCAS display.

140391938	The interface provided easy to identify items for the UA pilot. It was simple to understand what maneuvers the pilot needed to make when prompted by the display.
140152234	The overall display of the UI was good, though a few small features could be improved. First, if altitudes or other values are reported in decimals, often the UI will display a value on the altimeter between 0 and 9, and it becomes difficult to read. Not a major problem. Further, in the UI, as the ownship performs a turn, other RID beacons in the area often seemed to be delayed in adjusting their heading appropriately (i think the problem is shifting reference frame). I think this just might produce ambiguity in where the aircraft is going. If it's actually a problem, maybe could be resolved by having their absolute heading populated on the intruder marker at all times, so even if reference frame changes there's a constant reference.
140080427	The sUCAS app looked exactly as expected and it worked in a real world test environment as it did in simulation which were shown to us before live test events took place.

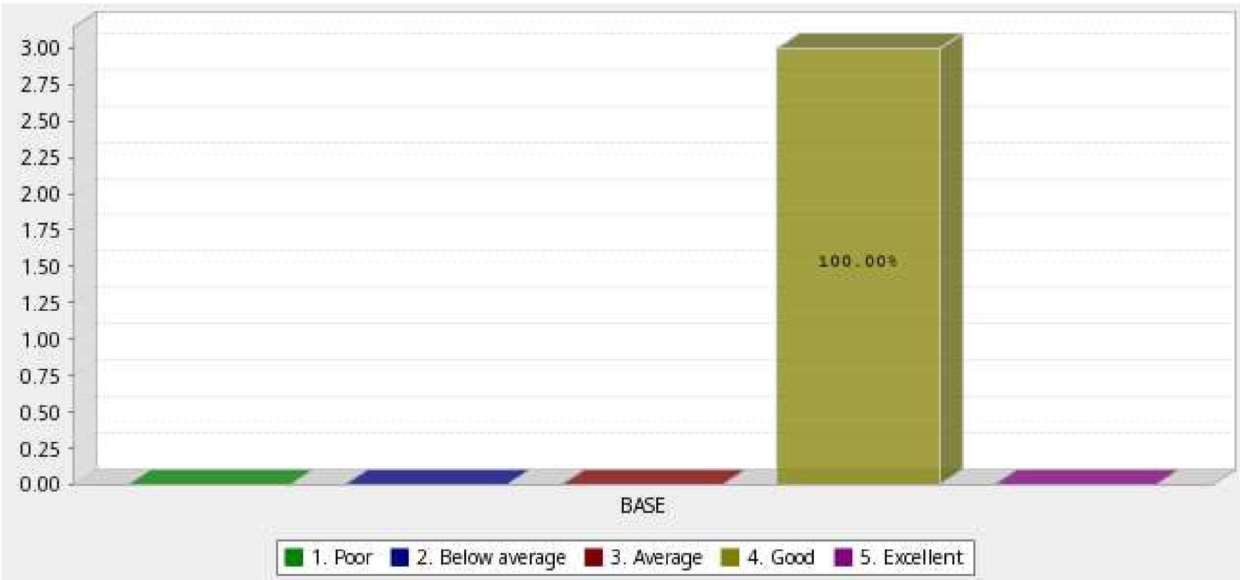
Q14. Please rate the following aspects of the sUCAS display and alerting:



Q14. Overall Matrix Scorecard : Please rate the following aspects of the sUCAS display and alerting:

	Question	Count	Score	
1.	Clarity of Information	3	4.000	
2.	Usefulness of Information	3	4.330	
3.	Range of Detection (amount of alerting time)	3	3.670	
4.	Usability of App	3	4.000	
5.	Reliability of App and Hardware	3	3.000	
		Average	**3.800**	

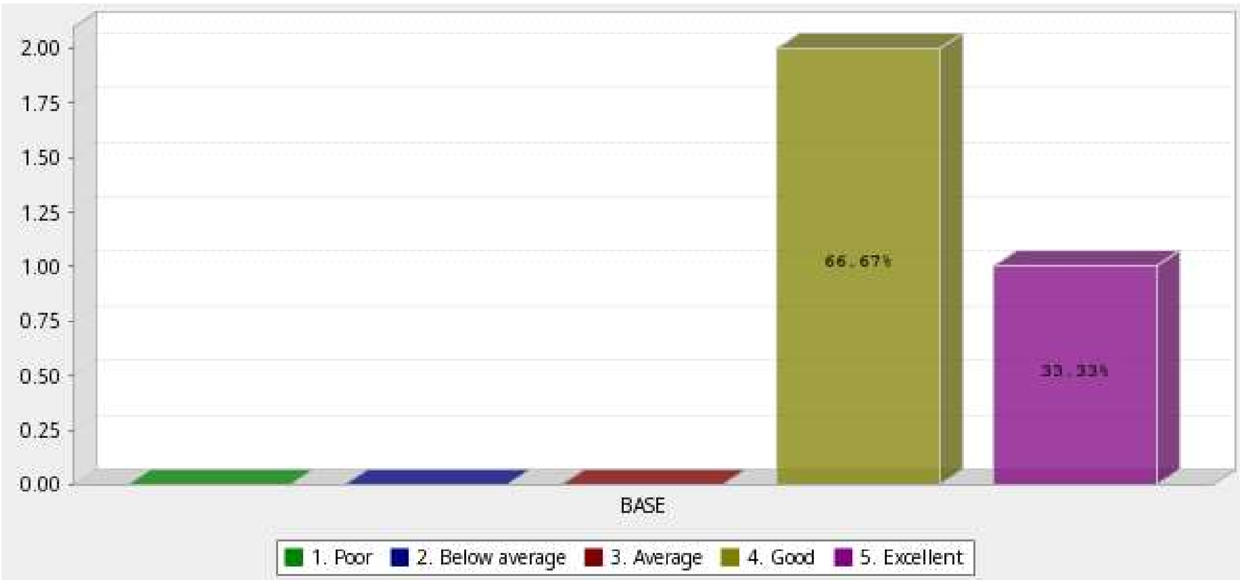
Q14. Clarity of Information



	Answer	Count	Percent
1.	Poor	0	0.00%
2.	Below average	0	0.00%
3.	Average	0	0.00%
4.	Good	3	100.00%
5.	Excellent	0	0.00%
	Total	3	100%

Mean : **4.000**	Confidence Interval @ 95% : **[4.000 - 4.000]**	Standard Deviation : **0.000**	Standard Error : **0.000**

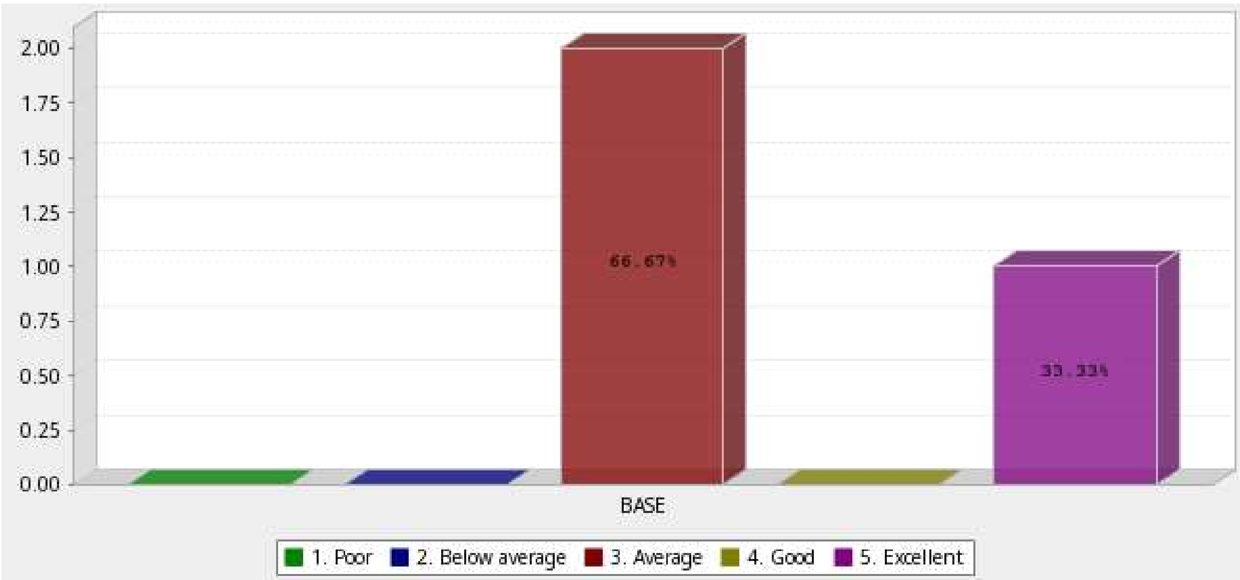
Q14. Usefulness of Information



	Answer	Count	Percent
1.	Poor	0	0.00%
2.	Below average	0	0.00%
3.	Average	0	0.00%
4.	Good	2	66.67%
5.	Excellent	1	33.33%
	Total	3	100%

Mean : **4.333**	Confidence Interval @ 95% : **[3.680 - 4.987]**	Standard Deviation : **0.577**	Standard Error : **0.333**

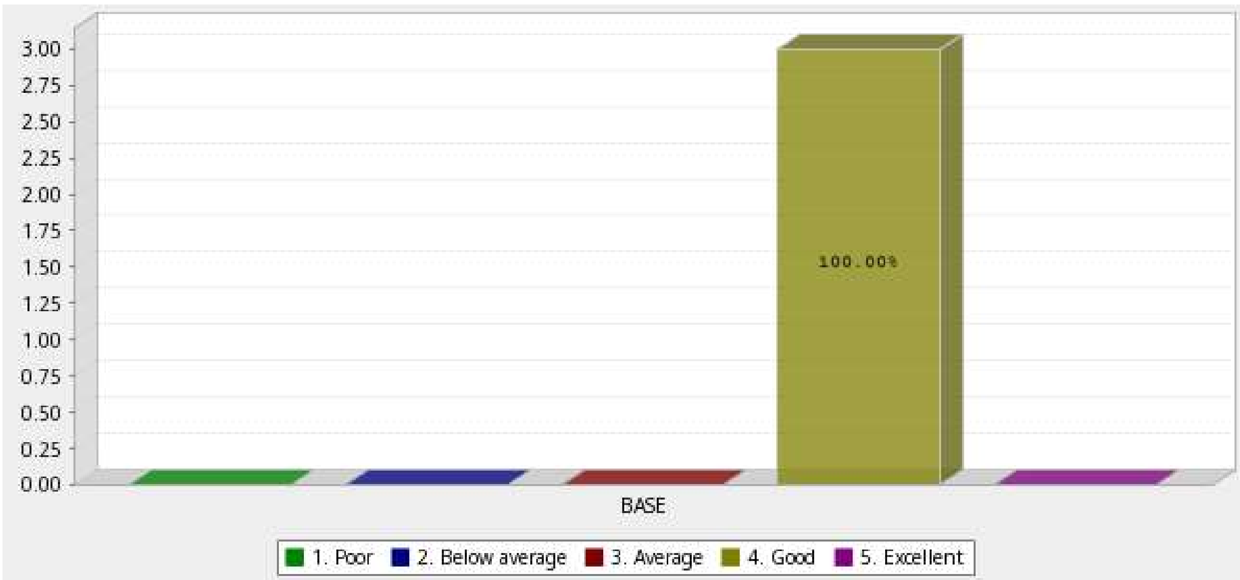
Q14. Range of Detection (amount of alerting time)



	Answer	Count	Percent
1.	Poor	0	0.00%
2.	Below average	0	0.00%
3.	Average	2	66.67%
4.	Good	0	0.00%
5.	Excellent	1	33.33%
	Total	3	100%

Mean : **3.667**	Confidence Interval @ 95% : **[2.360 - 4.973]**	Standard Deviation : **1.155**	Standard Error : **0.667**

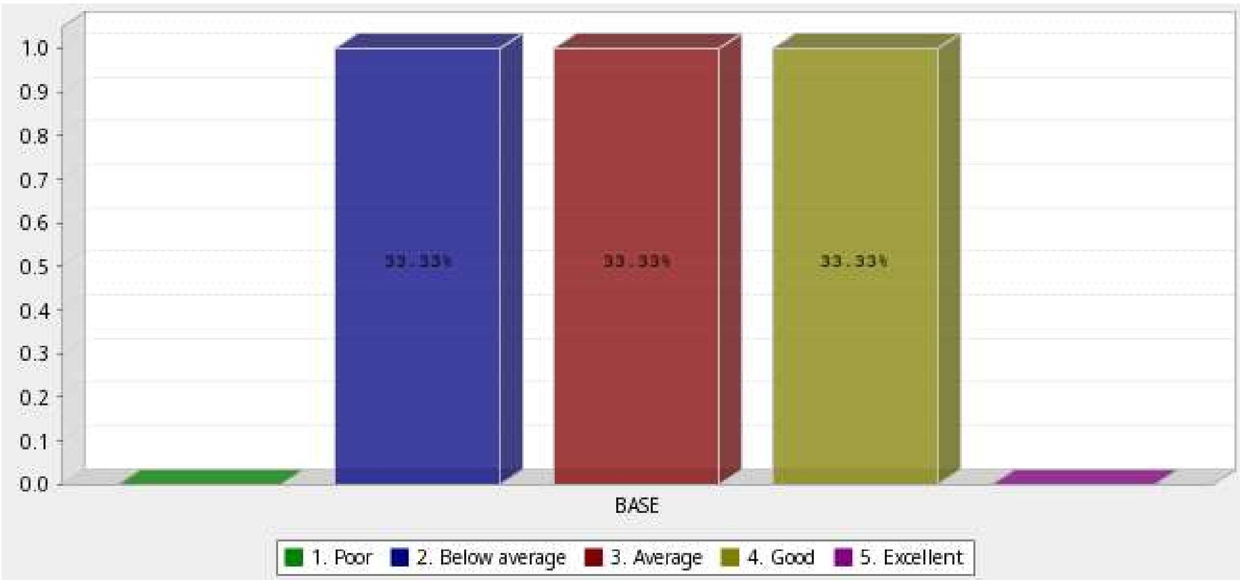
Q14. Usability of App



	Answer	Count	Percent
1.	Poor	0	0.00%
2.	Below average	0	0.00%
3.	Average	0	0.00%
4.	Good	3	100.00%
5.	Excellent	0	0.00%
	Total	3	100%

Mean : **4.000**	Confidence Interval @ 95% : **[4.000 - 4.000]**	Standard Deviation : **0.000**	Standard Error : **0.000**

Q14. Reliability of App and Hardware



	Answer	Count	Percent
1.	Poor	0	0.00%
2.	Below average	1	33.33%
3.	Average	1	33.33%
4.	Good	1	33.33%
5.	Excellent	0	0.00%
	Total	3	100%

Mean : **3.000**	Confidence Interval @ 95% : **[1.868 - 4.132]**	Standard Deviation : **1.000**	Standard Error : **0.577**

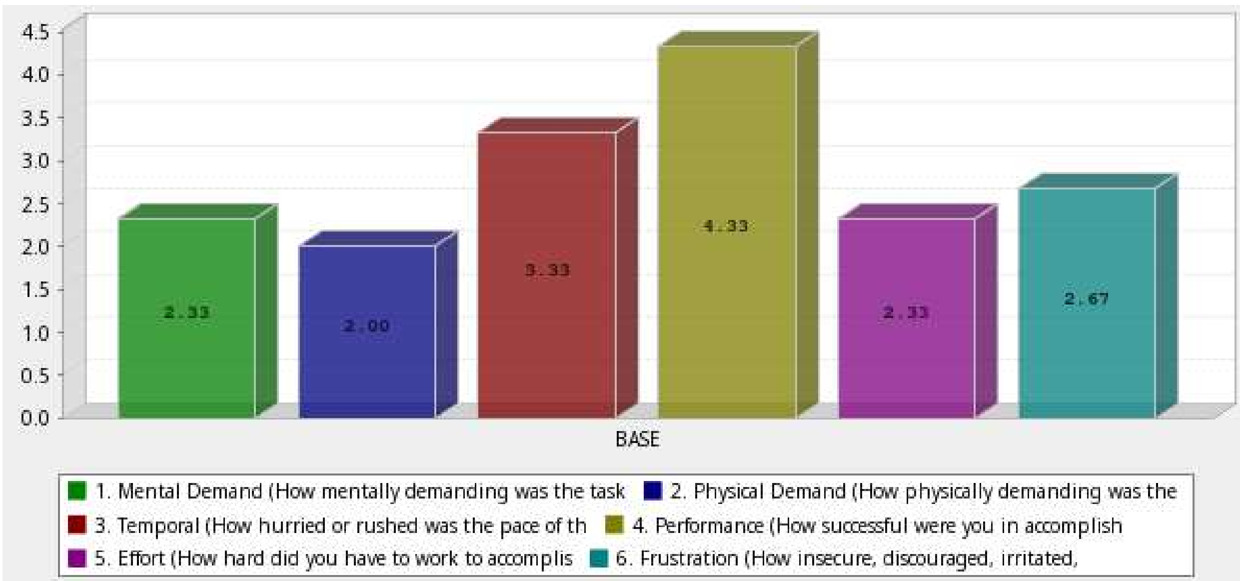
Q15. Please provide comments on the ratings above:

140391938	While the interface was easy to interpret quickly, the reliability and range of detection depended greatly on the sensor being used. Sensors with reliable performance made the interaction very easy to use, while the less reliable sensors created a situation in which the pilot would have to second guess the guidance and direction.
140152234	In base terms, the usability of information is very good as it provides an alert and advised heading and shows the advised path for the aircraft. In terms of clarity, previous comments about altitude and heading are relevant. Further, with multiple avoidance algorithms incorporated (acas, do-365), there may be value in standardizing how the UI prompts a warning / alert / etc. This is dependent on how these algorithms report (acas no warning, do-365 some warning time before alerting) but it seems like it could be confusing to an end-user to see alerts generated differently on UI based on algorithm selected. Maybe a tutorial? Overall usability and reliability good. Sometimes difficult to find / understand specific settings. Perhaps help text associated with each field in the future, such as a little question mark or "i" symbol that gives help on mouse hover? Some delay in switching between ACAS and DO-365, though that might not be the fault of the app overall.
140080427	The system as a whole is still in a very prototype state, but it performed as well as to be expected.

Q16. Do you have any feedback, based on the experience during testing, on what would be required to make the use of the sUCAS system operational?

140391938	The testing was a good way to show the difference between different sensors. There are definitely some sensors that showed they should not be used in this capacity.
140152234	See above comments, as I combined ratings / suggestions. I think for operational usage, tutorial / training / help-text would be very nice for an operator. In its current state, its close to operational status, but there are some "quirks", I'd say, that would need to be elaborated upon for an operator to feel comfortable.
140080427	The system would need to go through more trouble shooting and bug fixes to be fully operational. The system was made for this specific test, and not to be given to pilot in a real world scenario.

Q9. Rate each of the following based on using the sUCAS app to avoid other drones. For this question please consider when using the sUCAS app to perform MANUAL avoidance.

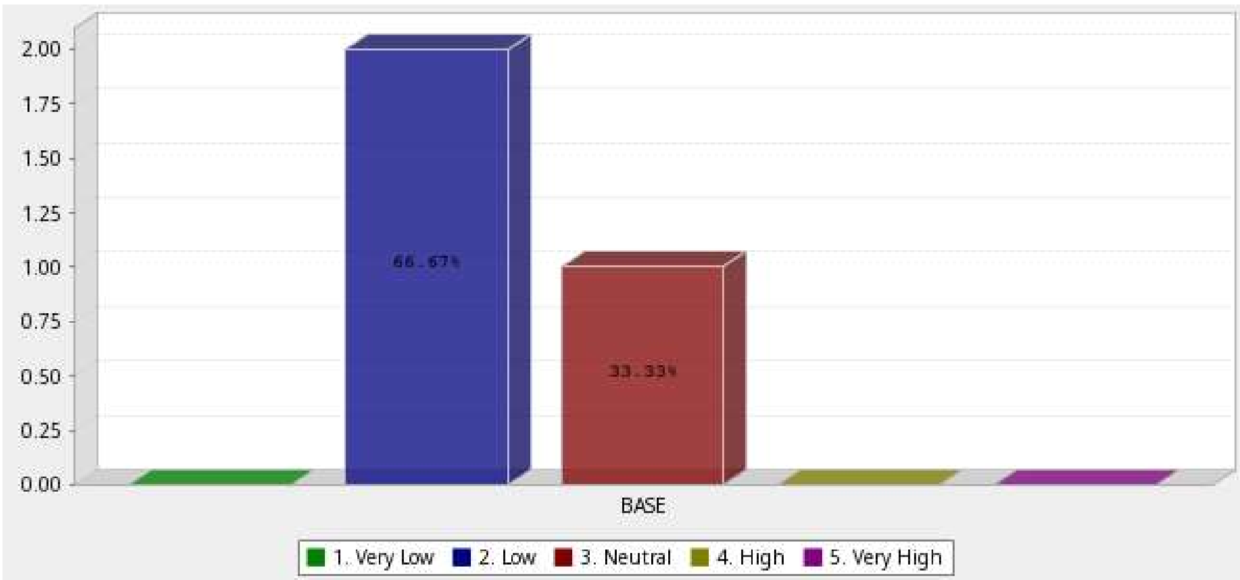


Q9. Overall Matrix Scorecard : Rate each of the following based on using the sUCAS app to avoid other drones. For this question please consider when using the sUCAS app to perform MANUAL avoidance.

	Question	Count	Score	
1.	Mental Demand (How mentally demanding was the task?)	3	2.330	
2.	Physical Demand (How physically demanding was the task?)	3	2.000	
3.	Temporal (How hurried or rushed was the pace of the task?)	3	3.330	
4.	Performance (How successful were you in accomplishing what you were asked to do?)	3	4.330	
5.	Effort (How hard did you have to work to accomplish your level of performance?)	3	2.330	
6.	Frustration (How insecure, discouraged, irritated,	3	2.670	

	stressed, and annoyed were you?)			
		Average	**2.832**	

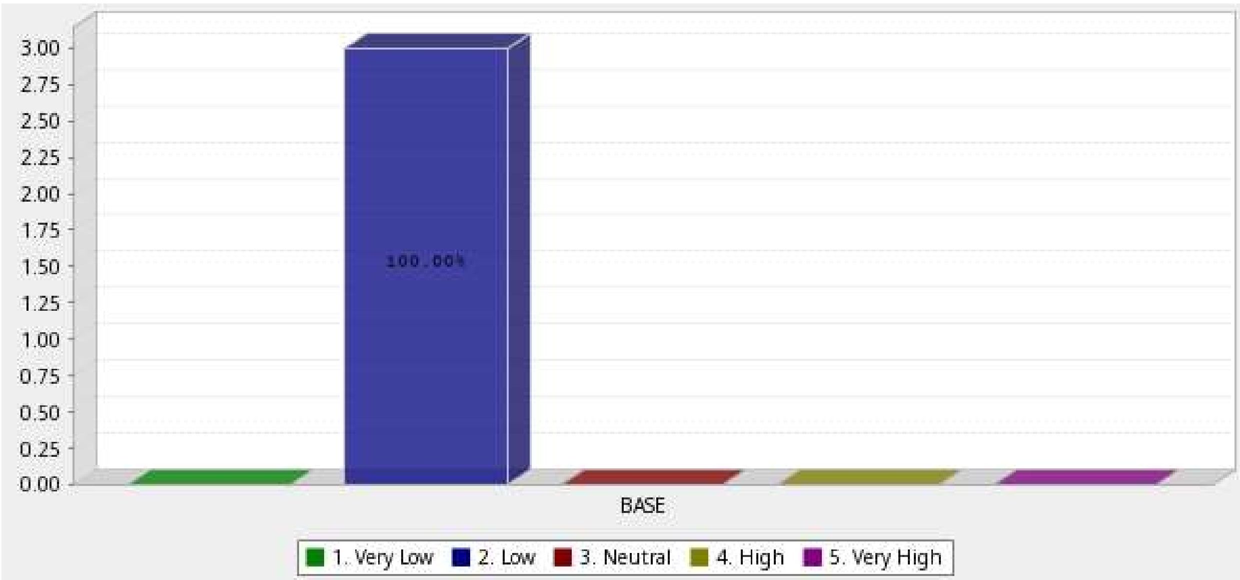
Q9. Mental Demand (How mentally demanding was the task?)



	Answer	Count	Percent
1.	Very Low	0	0.00%
2.	Low	2	66.67%
3.	Neutral	1	33.33%
4.	High	0	0.00%
5.	Very High	0	0.00%
	Total	3	100%

Mean : **2.333**	Confidence Interval @ 95% : **[1.680 - 2.987]**	Standard Deviation : **0.577**	Standard Error : **0.333**

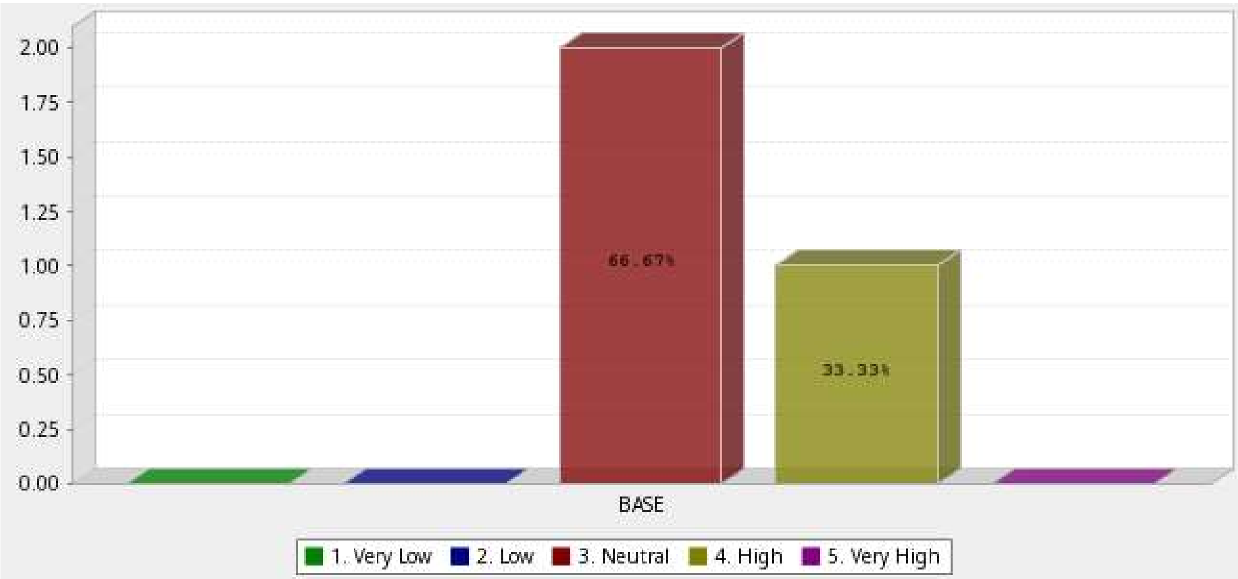
Q9. Physical Demand (How physically demanding was the task?)



	Answer	Count	Percent
1.	Very Low	0	0.00%
2.	Low	3	100.00%
3.	Neutral	0	0.00%
4.	High	0	0.00%
5.	Very High	0	0.00%
	Total	3	100%

Mean : **2.000**	Confidence Interval @ 95% : **[2.000 - 2.000]**	Standard Deviation : **0.000**	Standard Error : **0.000**

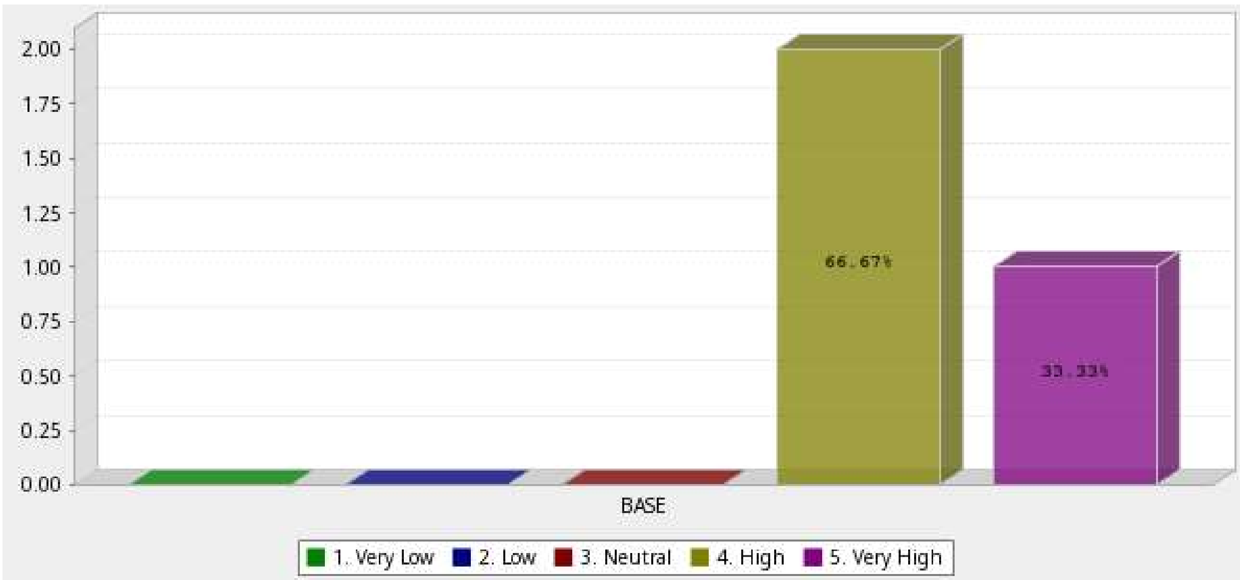
Q9. Temporal (How hurried or rushed was the pace of the task?)



	Answer	Count	Percent
1.	Very Low	0	0.00%
2.	Low	0	0.00%
3.	Neutral	2	66.67%
4.	High	1	33.33%
5.	Very High	0	0.00%
	Total	3	100%

Mean : **3.333**	Confidence Interval @ 95% : **[2.680 - 3.987]**	Standard Deviation : **0.577**	Standard Error : **0.333**

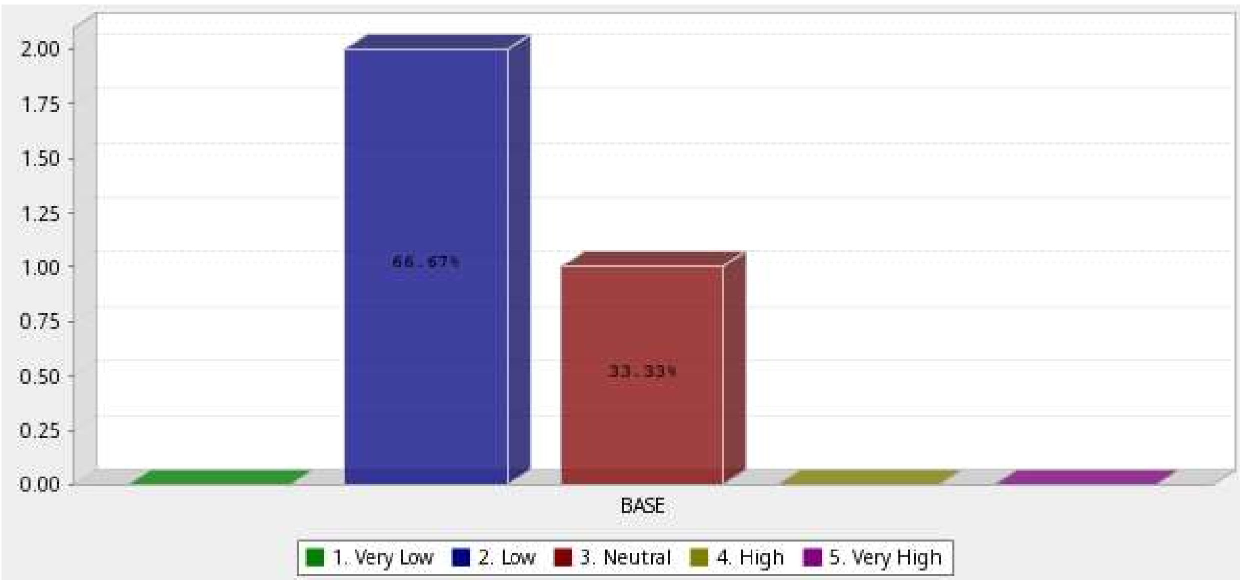
Q9. Performance (How successful were you in accomplishing what you were asked to do?)



	Answer	Count	Percent
1.	Very Low	0	0.00%
2.	Low	0	0.00%
3.	Neutral	0	0.00%
4.	High	2	66.67%
5.	Very High	1	33.33%
	Total	3	100%

Mean : **4.333**	Confidence Interval @ 95% : **[3.680 - 4.987]**	Standard Deviation : **0.577**	Standard Error : **0.333**

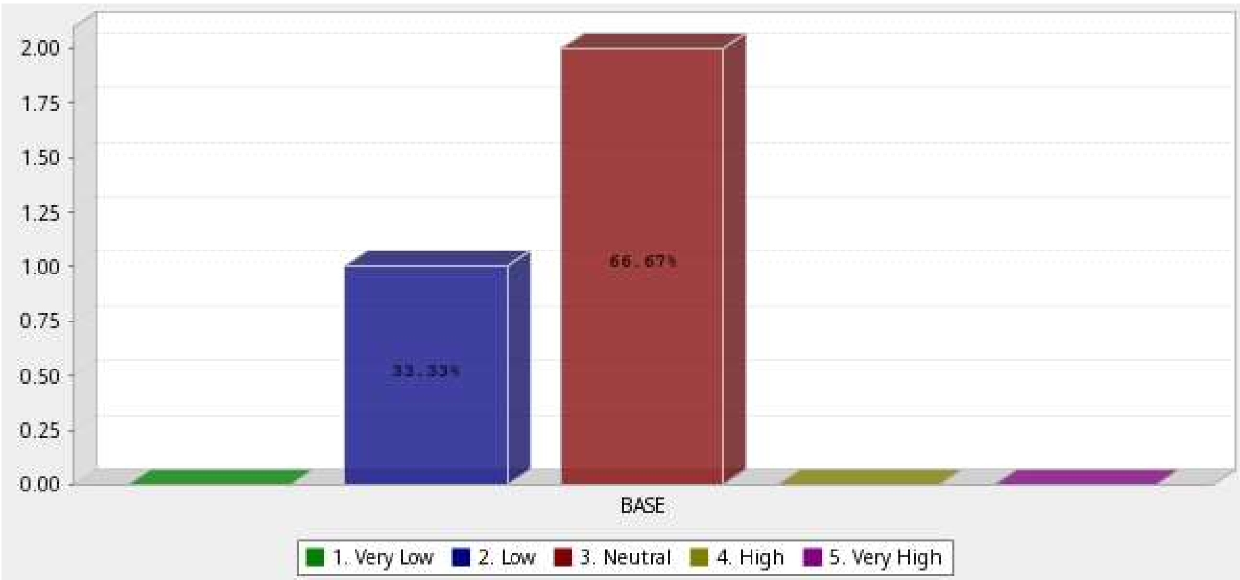
Q9. Effort (How hard did you have to work to accomplish your level of performance?)



	Answer	Count	Percent
1.	Very Low	0	0.00%
2.	Low	2	66.67%
3.	Neutral	1	33.33%
4.	High	0	0.00%
5.	Very High	0	0.00%
	Total	3	100%

Mean : **2.333**	Confidence Interval @ 95% : **[1.680 - 2.987]**	Standard Deviation : **0.577**	Standard Error : **0.333**

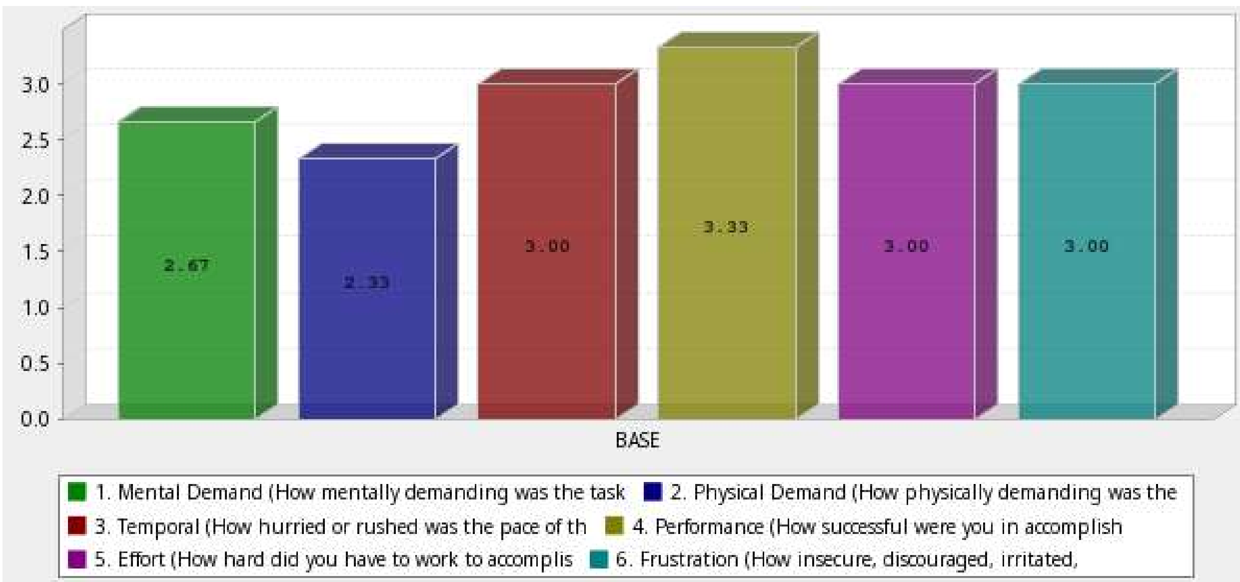
Q9. Frustration (How insecure, discouraged, irritated, stressed, and annoyed were you?)



	Answer	Count	Percent
1.	Very Low	0	0.00%
2.	Low	1	33.33%
3.	Neutral	2	66.67%
4.	High	0	0.00%
5.	Very High	0	0.00%
	Total	3	100%

Mean : **2.667**	Confidence Interval @ 95% : **[2.013 - 3.320]**	Standard Deviation : **0.577**	Standard Error : **0.333**

Q9-C9. Rate each of the following based on using the sUCAS app to avoid other drones. For this question please consider when using the sUCAS app to perform an AUTOMATED avoidance.

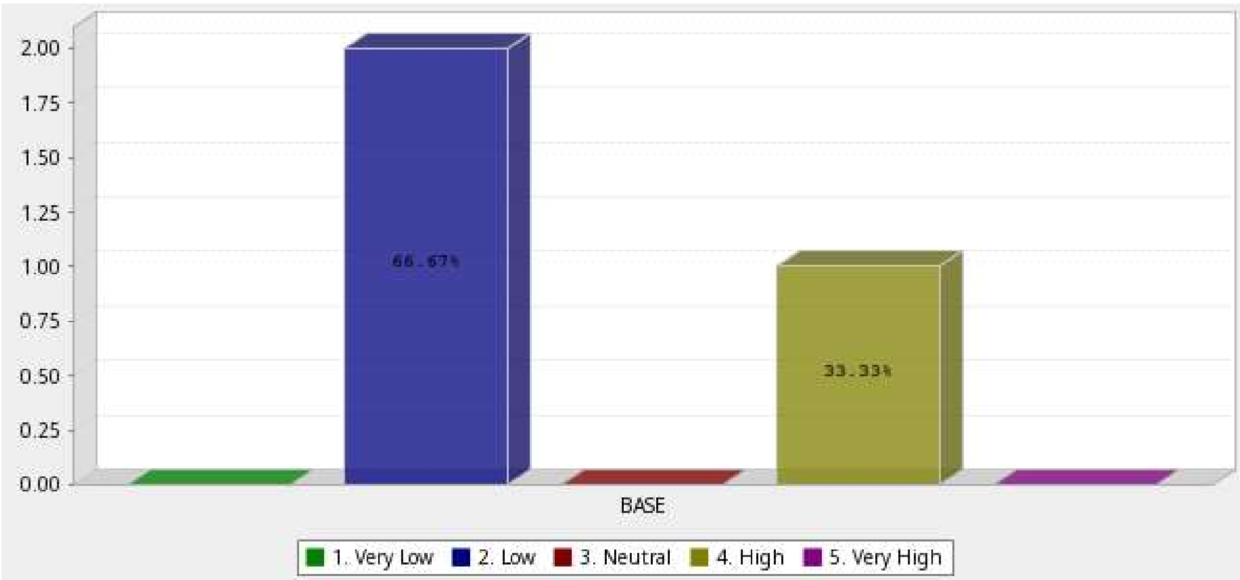


Q9-C9. Overall Matrix Scorecard : Rate each of the following based on using the sUCAS app to avoid other drones. For this question please consider when using the sUCAS app to perform an AUTOMATED avoidance.

	Question	Count	Score	
1.	Mental Demand (How mentally demanding was the task?)	3	2.670	
2.	Physical Demand (How physically demanding was the task?)	3	2.330	
3.	Temporal (How hurried or rushed was the pace of the task?)	3	3.000	
4.	Performance (How successful were you in accomplishing what you were asked to do?)	3	3.330	
5.	Effort (How hard did you have to work to accomplish your level of performance?)	3	3.000	
6.	Frustration (How insecure, discouraged, irritated,	3	3.000	

	stressed, and annoyed were you?)			
		Average	**2.888**	

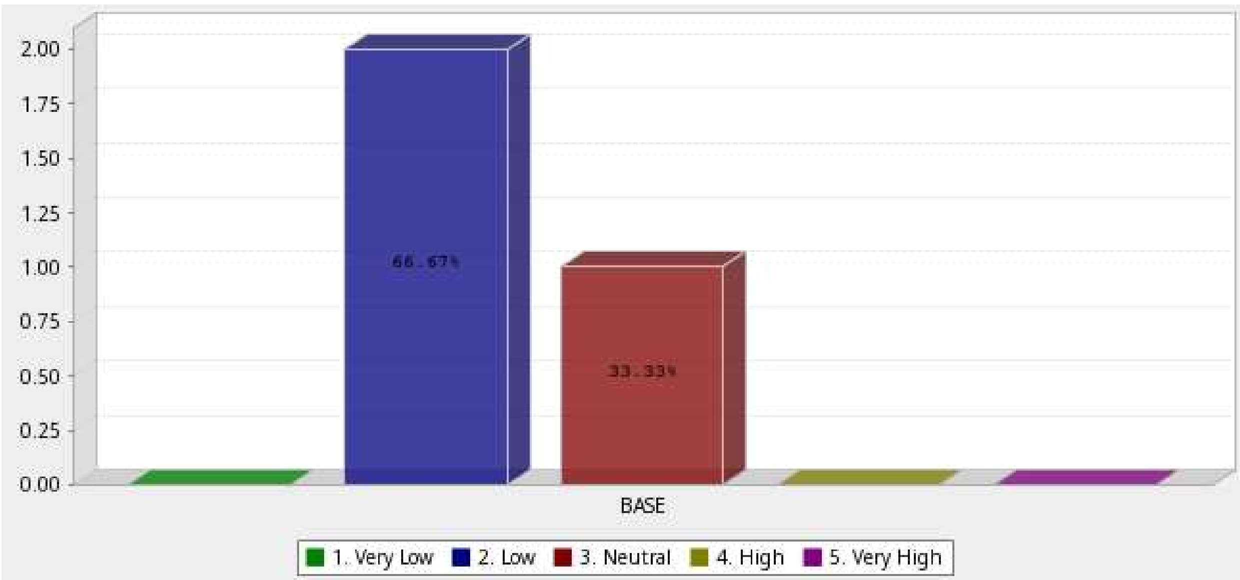
Q9-C9. Mental Demand (How mentally demanding was the task?)



	Answer	Count	Percent
1.	Very Low	0	0.00%
2.	Low	2	66.67%
3.	Neutral	0	0.00%
4.	High	1	33.33%
5.	Very High	0	0.00%
	Total	3	100%

Mean : **2.667**	Confidence Interval @ 95% : **[1.360 - 3.973]**	Standard Deviation : **1.155**	Standard Error : **0.667**

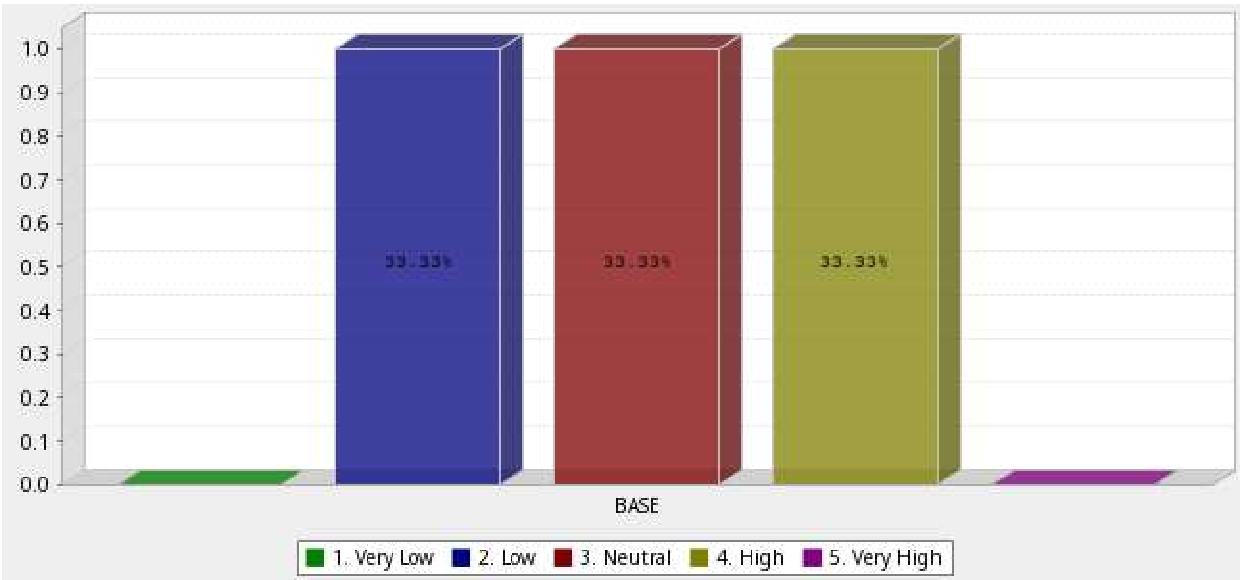
Q9-C9. Physical Demand (How physically demanding was the task?)



	Answer	Count	Percent
1.	Very Low	0	0.00%
2.	Low	2	66.67%
3.	Neutral	1	33.33%
4.	High	0	0.00%
5.	Very High	0	0.00%
	Total	3	100%

Mean : **2.333**	Confidence Interval @ 95% : **[1.680 - 2.987]**	Standard Deviation : **0.577**	Standard Error : **0.333**

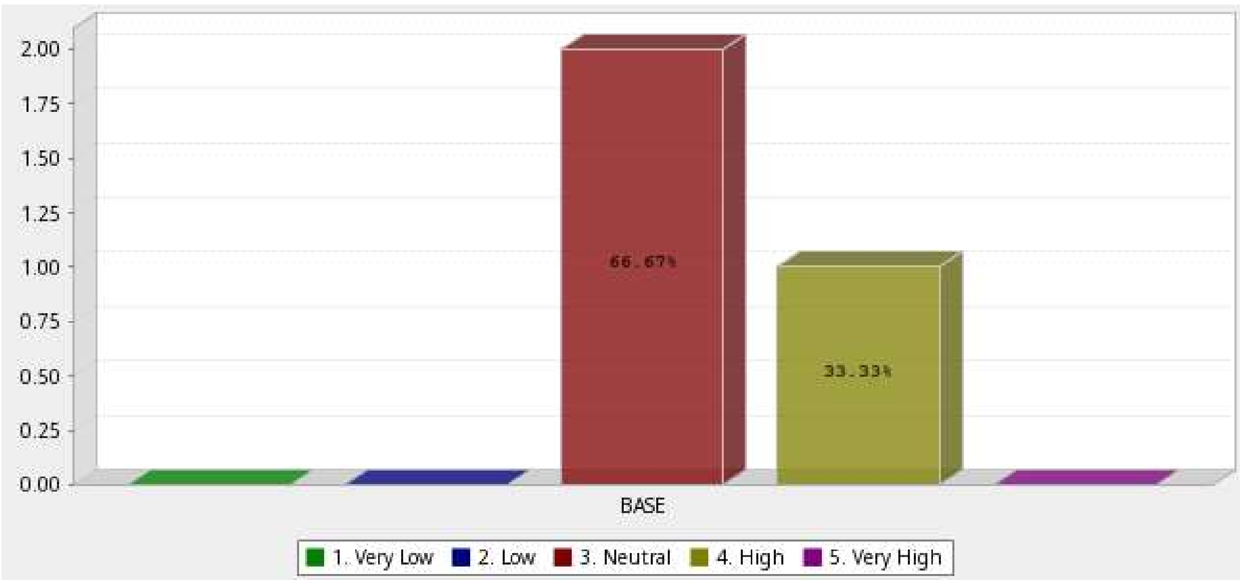
Q9-C9. Temporal (How hurried or rushed was the pace of the task?)



	Answer	Count	Percent
1.	Very Low	0	0.00%
2.	Low	1	33.33%
3.	Neutral	1	33.33%
4.	High	1	33.33%
5.	Very High	0	0.00%
	Total	3	100%

Mean : **3.000**	Confidence Interval @ 95% : **[1.868 - 4.132]**	Standard Deviation : **1.000**	Standard Error : **0.577**

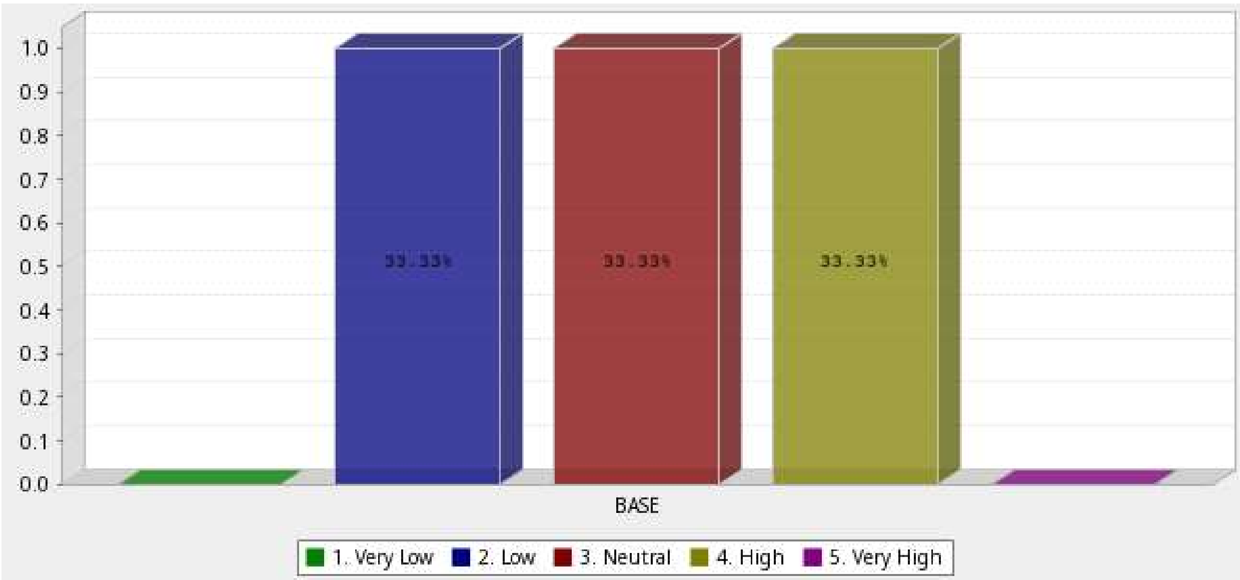
Q9-C9. Performance (How successful were you in accomplishing what you were asked to do?)



	Answer	Count	Percent
1.	Very Low	0	0.00%
2.	Low	0	0.00%
3.	Neutral	2	66.67%
4.	High	1	33.33%
5.	Very High	0	0.00%
	Total	3	100%

Mean : **3.333**	Confidence Interval @ 95% : **[2.680 - 3.987]**	Standard Deviation : **0.577**	Standard Error : **0.333**

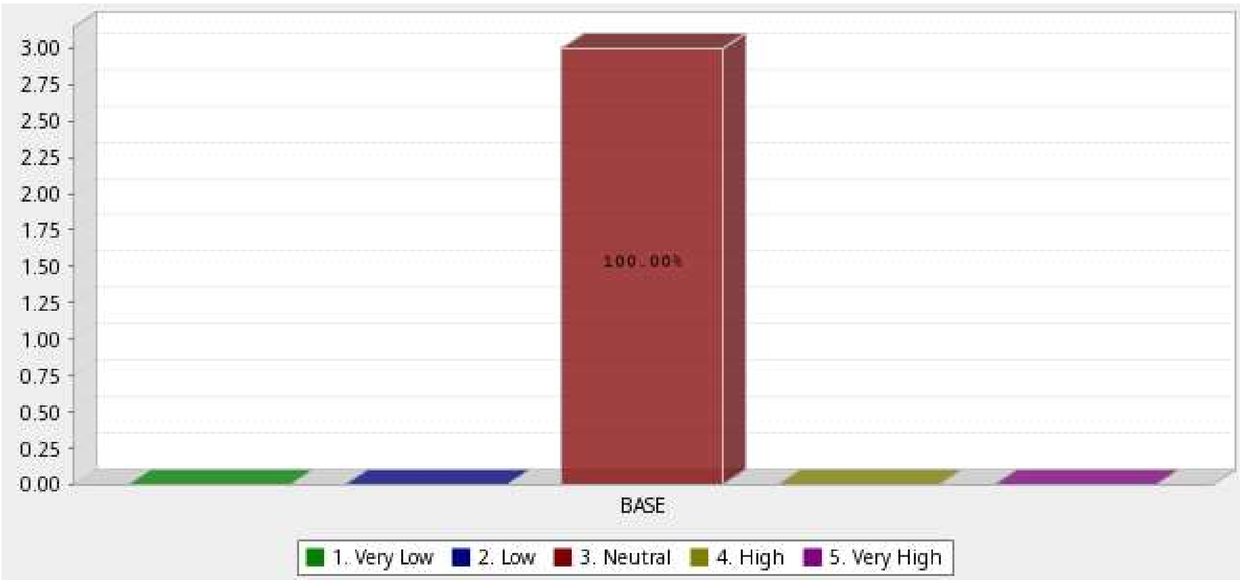
Q9-C9. Effort (How hard did you have to work to accomplish your level of performance?)



	Answer	Count	Percent
1.	Very Low	0	0.00%
2.	Low	1	33.33%
3.	Neutral	1	33.33%
4.	High	1	33.33%
5.	Very High	0	0.00%
	Total	3	100%

Mean : **3.000**	Confidence Interval @ 95% : **[1.868 - 4.132]**	Standard Deviation : **1.000**	Standard Error : **0.577**

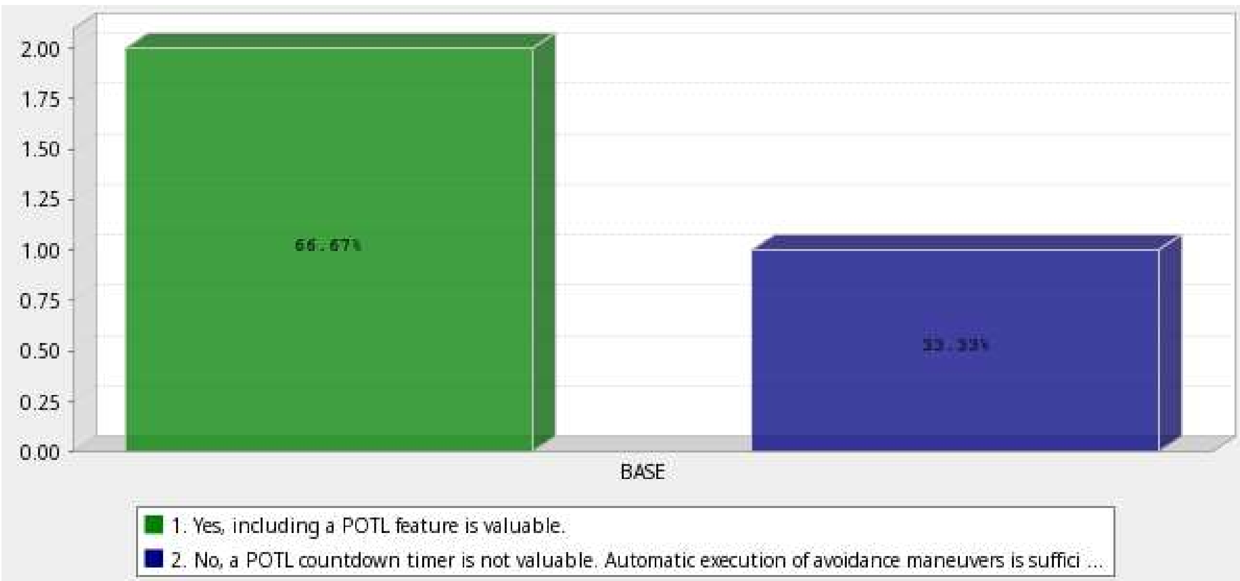
Q9-C9. Frustration (How insecure, discouraged, irritated, stressed, and annoyed were you?)



	Answer	Count	Percent
1.	Very Low	0	0.00%
2.	Low	0	0.00%
3.	Neutral	3	100.00%
4.	High	0	0.00%
5.	Very High	0	0.00%
	Total	3	100%

Mean : **3.000**	Confidence Interval @ 95% : **[3.000 - 3.000]**	Standard Deviation : **0.000**	Standard Error : **0.000**

Q10. Do you see value in the five second pilot-on-the-loop supervision (POTL) countdown timer which gives the pilot five seconds to review and approve or cancel a proposed avoidance maneuver?



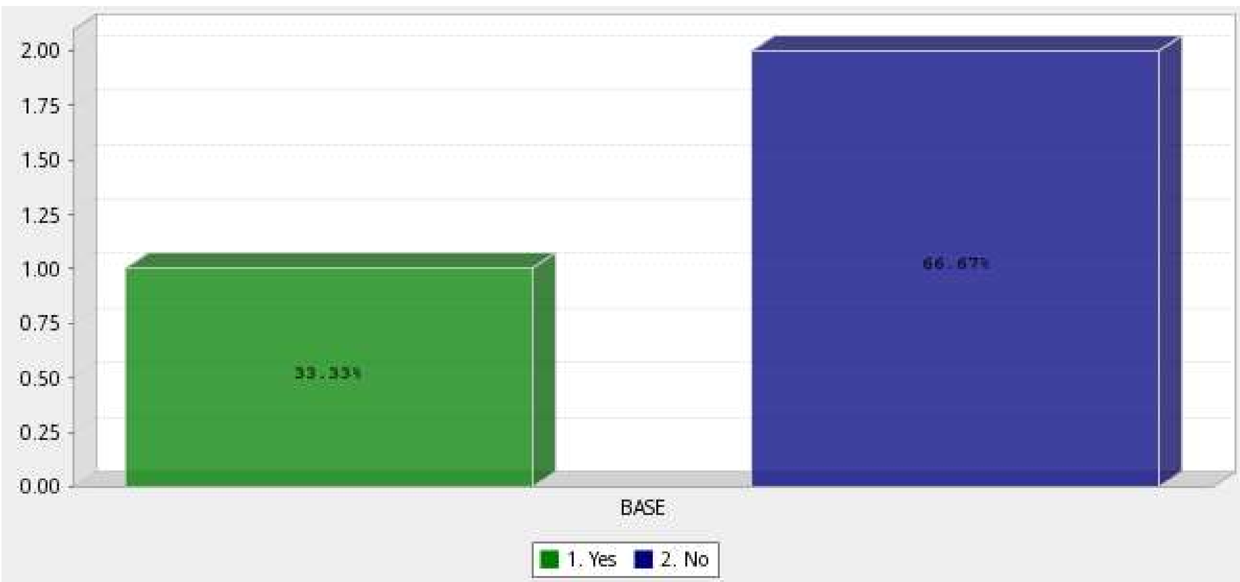
	Answer	Count	Percent
1.	Yes, including a POTL feature is valuable.	2	66.67%
2.	No, a POTL countdown timer is not valuable. Automatic execution of avoidance maneuvers is sufficient.	1	33.33%
	Total	3	100%

Mean : **1.333**	Confidence Interval @ 95% : **[0.680 - 1.987]**	Standard Deviation : **0.577**	Standard Error : **0.333**

Q11. Please explain why you do or don't see value in the five second pilot-on-the-loop supervision (POTL) countdown timer.

140391938	While it may add an additional step to the automated process, I think it is still important for the pilot to ensure they have a choice to dismiss an automated maneuver if they need to for whatever reason.
140152234	In an ideal setting, detection range and reporting would be vastly greater than needed, so the system could report with a longer timer. I think 5s is perhaps the bare minimum for an operator to receive the alert, assess the situation (altitude difference, heading, relative speed, etc), and accept or decline the guidance. I think something to consider is adding configurability for the user to select whether they want timer-elapse to auto-accept, auto-decline, or "hang", perhaps. Configurability for how long a pilot needs. A trained pilot will need less time, same with a non-saturated pilot. Overall, I think there's still value, if only just for user flexibility in how they want to respond to the RAs.
140080427	The POTL timer was not useful in our testing. It may have some value in a real world scenario when you have a false detect or something going on that is preventing you from doing a mission.

Q12. Considering the five second pilot-on-the-loop supervision (POTL) countdown timer, did you feel that five seconds was enough time for you as a pilot to make an informed decision on whether or not to continue with the proposed avoidance maneuver?



	Answer	Count	Percent
1.	Yes	1	33.33%
2.	No	2	66.67%
	Total	3	100%

Mean : **1.667**	Confidence Interval @ 95% : **[1.013 - 2.320]**	Standard Deviation : **0.577**	Standard Error : **0.333**

Q13. What amount of time for the pilot-on-the-loop supervision (POTL) countdown timer would be more helpful?

140152234	This is arbitrary, but 10s. Assuming I need to: 1) Receive the alert 2) Look at the screen 3) Determine WHO is intruding / conflicting (assuming possibility of multiples in the area) 4) Correlate intruder with its relevant data (altitude, groundspeed, heading, vertical rate, etc) 5) Determine whether the advisory is relevant and should be adhered to I think that requires a little more than 5s
140080427	This is a hard question to answer, because sometimes you might not even have 5 seconds to avoid. If you have a limited detection range then there is no sense in having a POTL countdown timer. However, if you have minutes before an imminent collision, then you would have enough time to really assess the situation and maybe then you could have a dynamic POTL timer. I think this is a very situational based question that could be answered in many different ways.

Q13-C9. Do you have any additional Comments/Suggestions for sUCAS?

140391938	No
140152234	A little more user configurability and help-text (obviously its been more important to get it working before iterating and cleaning it up) would go a long way, I think. Overall in a good state, in my opinion.
140080427	N/A

B. Flight Test 2 Test Matrix

Table 9. Flight Test 2 Flight Test Matrix.

Test Setup									Timestamps (Local, UTC-4)		Avoidance				
Run #	Run Type	Route Type	UA 1	RID 1	UA 2	RID 2	Rx Type	RID Type	Maneuver Start (Local)	Maneuver End (Local)	DAA Logic	Suggestive Guid. DO-365?	Auto RA?	POTL Timer?	Avoid Successful?
0	Dual Aircraft	Hovering Intruder, Ownship C-B	Marty	RID X	Inspire	RID Y	Both	WiFi	2024-06-25 11:58:55	2024-06-25 12:04:47	DO-365	No	No	No	-
1	Dual Aircraft	Hovering Intruder, Ownship C-B	Marty	RID X	Inspire	RID Y	Both	WiFi	2024-06-25 15:35:14	2024-06-25 15:38:31	DO-365	Yes	No	No	Yes
2	Dual Aircraft	Hovering Intruder, Ownship C-B	Marty	RID X	Inspire	RID Y	Both	WiFi	2024-06-25 15:40:52	2024-06-25 15:43:36	DO-365	Yes	No	No	Yes
3	Dual Aircraft	Head-On	Marty	RID X	Inspire	RID Y	Air	WiFi	2024-06-26 09:52:25	2024-06-26 09:54:02	DO-365	Yes	No	No	No
4	Dual Aircraft	Head-On	Marty	RID X	Inspire	RID Y	Air	WiFi	2024-06-26 09:58:14	2024-06-26 10:01:00	DO-365	Yes	No	No	Yes
5	Dual Aircraft	Head-On	Marty	RID X	Inspire	RID Y	Air	Bluetooth	2024-06-26 11:09:32	2024-06-26 11:10:37	DO-365	Yes	No	No	No
6	Dual Aircraft	Head-On	Marty	RID X	Inspire	RID Y	Air	Bluetooth	2024-06-26 11:13:51	2024-06-26 11:15:10	DO-365	Yes	No	No	Yes
7	Dual Aircraft	Head-On	Marty	RID X	Inspire	RID Y	Air	Bluetooth	2024-06-26 11:18:02	2024-06-26 11:19:22	DO-365	Yes	No	No	Yes
8	Dual Aircraft	Head-On	Marty	RID X	Inspire	RID B	Air	Bluetooth	2024-06-26 12:03:09	2024-06-26 12:04:45	DO-365	Yes	No	No	No
9	Single Aircraft	Intruder only to test ground receipt	NA	NA	Inspire	RID Y	Ground	Bluetooth	NA	NA	-	-	-	-	-
10	Single Aircraft	Intruder only to test ground receipt	NA	NA	Inspire	RID A	Ground	Bluetooth	NA	NA	-	-	-	-	-
11	Single Aircraft	Intruder only to test ground receipt	NA	NA	Inspire	RID A	Ground	Bluetooth	NA	NA	-	-	-	-	-
12	Single Aircraft	Intruder only to test ground receipt	NA	NA	Inspire	RID B	Ground	Bluetooth	NA	NA	-	-	-	-	-
13	Dual Aircraft	Head-On	Marty	RID X	Inspire	RID Y	Ground	Bluetooth	2024-06-27 11:49:01	2024-06-27 11:50:21	DO-365	Yes	No	No	No
14	Dual Aircraft	Head-On	Marty	RID X	Inspire	RID Y	Ground	Bluetooth	2024-06-27 11:57:24	2024-06-27 11:59:22	DO-365	Yes	No	No	Yes
15	Dual Aircraft	Head-On	Marty	RID X	Inspire	RID Y	Ground	Bluetooth	2024-06-27 13:52:28	2024-06-27 13:54:01	DO-365	Yes	No	No	Yes
16	Dual Aircraft	Head-On	Marty	RID X	Inspire	RID Y	Ground	Bluetooth	2024-06-27 13:56:48	2024-06-27 13:58:00	DO-365	No	Yes	No	Yes
17	Dual Aircraft	Head-On	Marty	RID X	Inspire	RID Y	Ground	Bluetooth	2024-06-27 14:00:14	2024-06-27 14:01:20	DO-365	No	Yes	No	No
18	Dual Aircraft	Head-On	Marty	RID X	Inspire	RID Y	Ground	Bluetooth	2024-06-27 14:29:57	2024-06-27 14:31:02	DO-365	No	Yes	No	No
19	Dual Aircraft	Head-On	Marty	RID X	Inspire	RID Y	Ground	Bluetooth	2024-06-27 14:39:57	2024-06-27 14:41:22	DO-365	No	Yes	No	Yes
20	Dual Aircraft	Head-On	Marty	RID X	Inspire	RID Z	Ground	Bluetooth	2024-06-27 15:36:36	2024-06-27 15:38:05	DO-365	No	Yes	No	Yes
21	Dual Aircraft	Head-On opposite	Marty	RID X	Inspire	RID Z	Ground	Bluetooth	2024-06-27 15:39:24	2024-06-27 15:40:53	DO-365	No	Yes	No	Yes
22	Dual Aircraft	Head-On	Marty	RID X	Inspire	RID Z	Ground	Bluetooth	2024-06-27 15:42:20	2024-06-27 15:43:25	DO-365	No	Yes	No	Yes
23	Dual Aircraft	Head-On	Marty	RID X	Inspire	RID Y	Ground	Bluetooth	2024-06-28 10:09:28	2024-06-28 10:10:13	DO-365	No	Yes	No	No

24	Dual Aircraft	Head-On	Marty	RID X	Inspire	RID Y	Ground	Bluetooth	2024-06-28 10:12:29	2024-06-28 10:13:19	DO-365	No	Yes	No	No
25	Dual Aircraft	Head-On	Marty	RID X	Inspire	RID Y	Ground	Bluetooth	2024-06-28 10:15:52	2024-06-28 10:17:01	DO-365	No	Yes	No	No
26	Dual Aircraft	Head-On	Marty	RID X	Inspire	RID Y	Ground	Bluetooth	2024-06-28 10:42:26	2024-06-28 10:43:09	DO-365	No	Yes	No	No
27	Dual Aircraft	Head-On	Marty	RID X	Inspire	RID Y	Ground	Bluetooth	2024-06-28 10:45:18	2024-06-28 10:46:45	DO-365	No	Yes	No	Yes
28	Dual Aircraft	Head-On opposite	Marty	RID X	Inspire	RID Y	Ground	Bluetooth	2024-06-28 10:48:43	2024-06-28 10:49:49	DO-365	No	Yes	Yes	Yes
29	Dual Aircraft	Head-On	Marty	RID X	Inspire	RID Y	Ground	Bluetooth	2024-06-28 10:51:20	2024-06-28 10:52:37	DO-365	No	Yes	Yes	Yes
30	Dual Aircraft	Head-On	Marty	RID X	Inspire	RID Y	Ground	Bluetooth	2024-06-28 11:23:44	2024-06-28 11:25:09	ACAS	No	Yes	No	No
31	Dual Aircraft	Head-On	Marty	RID X	Inspire	RID Y	Ground	Bluetooth	2024-06-28 13:13:05	2024-06-28 13:14:25	ACAS	No	Yes	No	Yes
32	Dual Aircraft	Head-On	Marty	RID X	Inspire	RID Y	Ground	Bluetooth	2024-06-28 14:30:55	2024-06-28 14:32:41	ACAS	No	Yes	No	Yes
33	Dual Aircraft	Head-On	Marty	None	Inspire	RID Y	Ground	Bluetooth	2024-06-28 14:51:09	2024-06-28 14:52:27	ACAS	No	Yes	No	Yes
34	Dual Aircraft	Head-On opposite	Marty	None	Inspire	RID Y	Ground	Bluetooth	2024-06-28 14:55:42	2024-06-28 14:57:00	ACAS	No	Yes	No	Yes
35	Dual Aircraft	Head-On	Marty	None	Inspire	RID Y	Air	Bluetooth	2024-06-28 15:17:51	2024-06-28 15:19:23	DO-365	No	Yes	No	Yes
36	Dual Aircraft	Head-On opposite	Marty	None	Inspire	RID Y	Air	Bluetooth	2024-06-28 15:20:15	2024-06-28 15:21:25	DO-365	No	Yes	No	Yes
37	Dual Aircraft	Head-On	Marty	None	Inspire	RID Y	Air	Bluetooth	2024-06-28 15:22:22	2024-06-28 15:23:30	DO-365	No	Yes	No	Yes
38	Dual Aircraft	Head-On opposite	Marty	None	Inspire	RID Y	Air	Bluetooth	2024-06-28 15:24:30	2024-06-28 15:25:56	DO-365	No	Yes	No	Yes
39	Dual Aircraft	Head-On	Marty	None	Inspire	RID Y	Air	Bluetooth	2024-06-28 15:27:18	2024-06-28 15:28:52	DO-365	No	Yes	Yes	Yes
40	Dual Aircraft	Head-On	Marty	None	Inspire	RID Y	Air	Bluetooth	2024-06-28 15:40:37	2024-06-28 15:41:58	ACAS	No	Yes	No	Yes
41	Dual Aircraft	Head-On opposite	Marty	None	Inspire	RID Y	Air	Bluetooth	2024-06-28 15:44:51	2024-06-28 15:46:30	ACAS	No	Yes	No	Yes
42	Dual Aircraft	Head-On	Marty	None	Inspire	RID Y	Air	Bluetooth	2024-06-28 15:49:24	2024-06-28 15:50:57	ACAS	No	Yes	No	Yes
43	Dual Aircraft	Head-On opposite	Marty	None	Inspire	RID Y	Air	Bluetooth	2024-06-28 15:52:47	2024-06-28 15:54:03	ACAS	No	Yes	Yes	No
44	Dual Aircraft	Head-On	Marty	RID X	Inspire	RID Y	Air	Bluetooth	2024-07-02 11:40:57	2024-07-02 11:42:39	ACAS	No	Yes	No	Yes
45	Dual Aircraft	Head-On opposite	Marty	RID X	Inspire	RID Y	Air	Bluetooth	2024-07-02 11:44:29	2024-07-02 11:46:24	ACAS	No	Yes	No	Yes
46	Dual Aircraft	Head-On	Marty	RID X	Inspire	RID Y	Air	Bluetooth	2024-07-02 11:48:13	2024-07-02 11:49:44	ACAS	No	Yes	No	Yes
47	Dual Aircraft	Head-On	Marty	RID X	Inspire	RID Y	Air	Bluetooth	2024-07-02 14:50:20	2024-07-02 14:50:43	ACAS	No	Yes	No	No
48	Dual Aircraft	Head-On	Marty	RID X	Inspire	RID Y	Air	Bluetooth	2024-07-02 14:53:42	2024-07-02 14:55:07	ACAS	No	Yes	No	Yes
49	Dual Aircraft	Head-On opposite	Marty	RID X	Inspire	RID Y	Air	Bluetooth	2024-07-02 14:56:42	2024-07-02 14:58:17	ACAS	No	Yes	No	Yes
50	Dual Aircraft	Head-On	Marty	RID X	Inspire	RID Y	Air	Bluetooth	2024-07-02 14:59:35	2024-07-02 15:01:17	ACAS	No	Yes	Yes	Yes
51	Dual Aircraft	Head-On	Marty	RID X	Doc	RID Y	Air	Bluetooth	2024-07-02 15:49:05	2024-07-02 15:50:27	ACAS	No	Yes	No	No
52	Dual Aircraft	Head-On opposite	Marty	RID X	Doc	RID Y	Air	Bluetooth	2024-07-02 15:52:41	2024-07-02 15:54:26	ACAS	No	Yes	No	Yes
53	Dual Aircraft	Head-On	Marty	RID X	Doc	RID Y	Air	Bluetooth	2024-07-02 15:56:07	2024-07-02 15:57:58	ACAS	No	Yes	No	Yes
54	Dual Aircraft	Head-On opposite	Marty	RID X	Doc	RID Y	Air	Bluetooth	2024-07-02 15:59:23	2024-07-02 16:01:01	ACAS	No	Yes	No	Yes

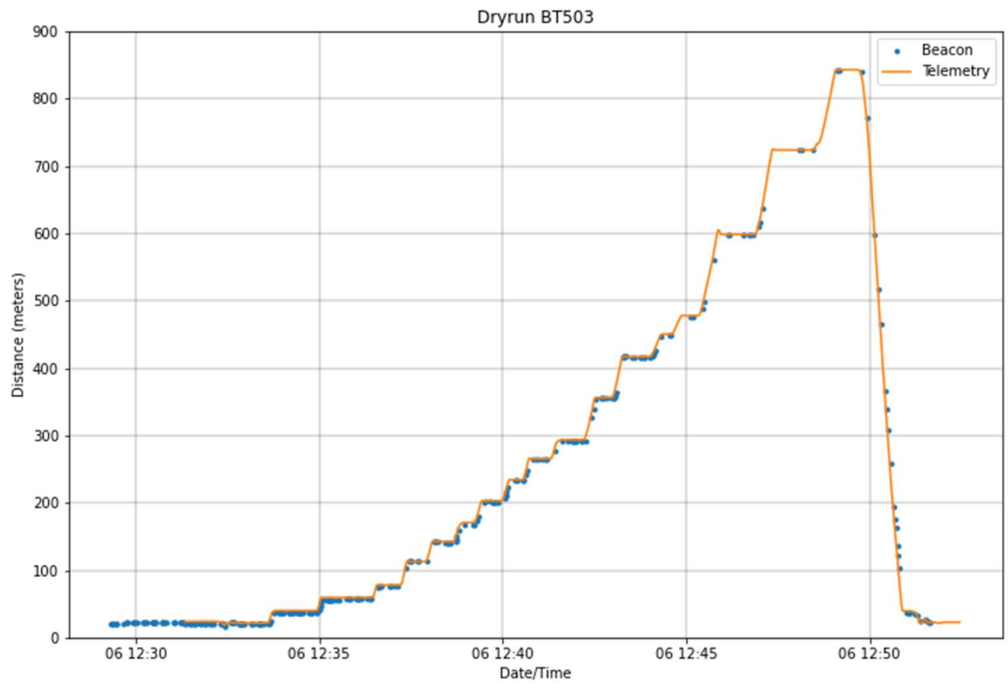
C. RID Sensor Model – Data Analysis Artifacts

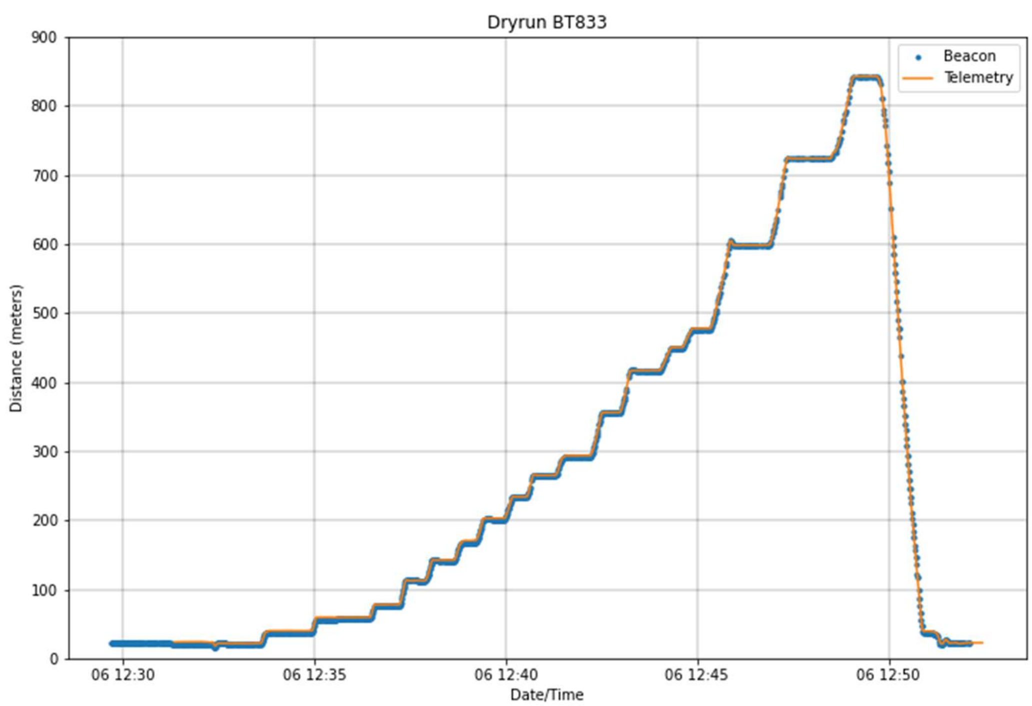
Below we include tables and charts produced from the data collected during Flight Test #1 and used in the formulation of the RID sensor model. We include them here to provide insight into the ways the team reviewed and made sense of the data. General conclusions drawn from the analysis include:

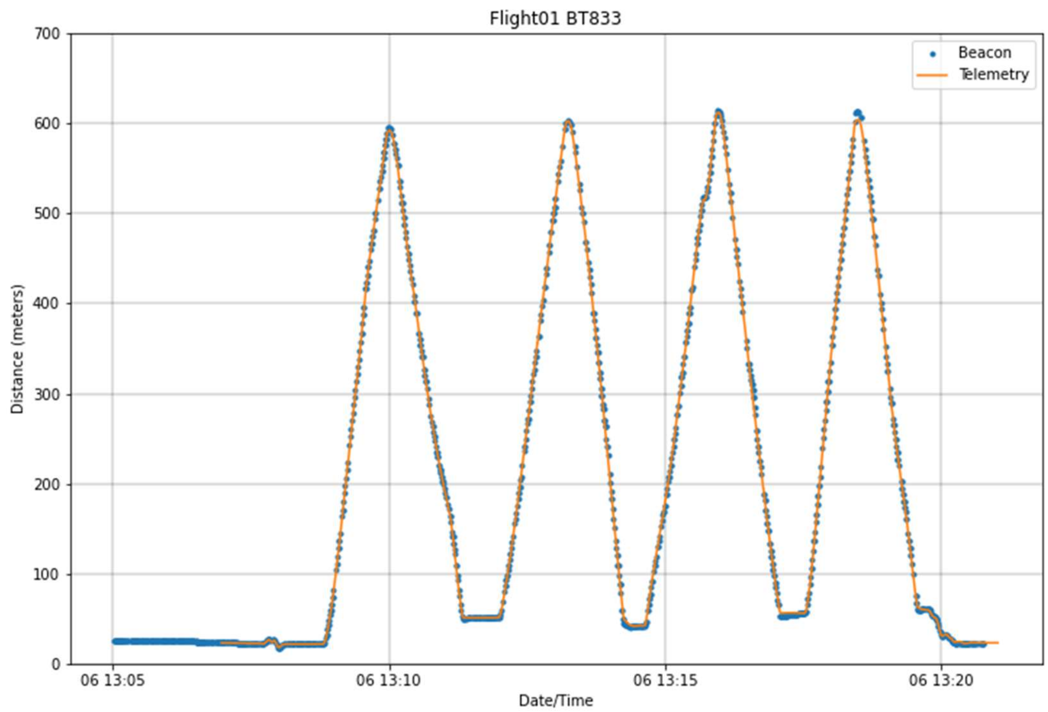
- Bluetooth (rank ordered by measured performance; 1 is best)
  - RID Receivers
    1. BT833
    2. BT503
  - RID Transmitters
    1. Pierce & DroneTag BS
    2. Bluemark 120
    3. DroneTag Mini & DroneTag Beacon
- WiFi (rank ordered by measured performance; 1 is best)
  - RID Receivers
    1. Alfa, Netis
    2. Techkey A1200
    3. D-Link
  - RID Transmitters
    1. DJI Mavic 2 & Autel Evo 2
    2. DJI Mini 3 Pro
    3. Bluemark 120

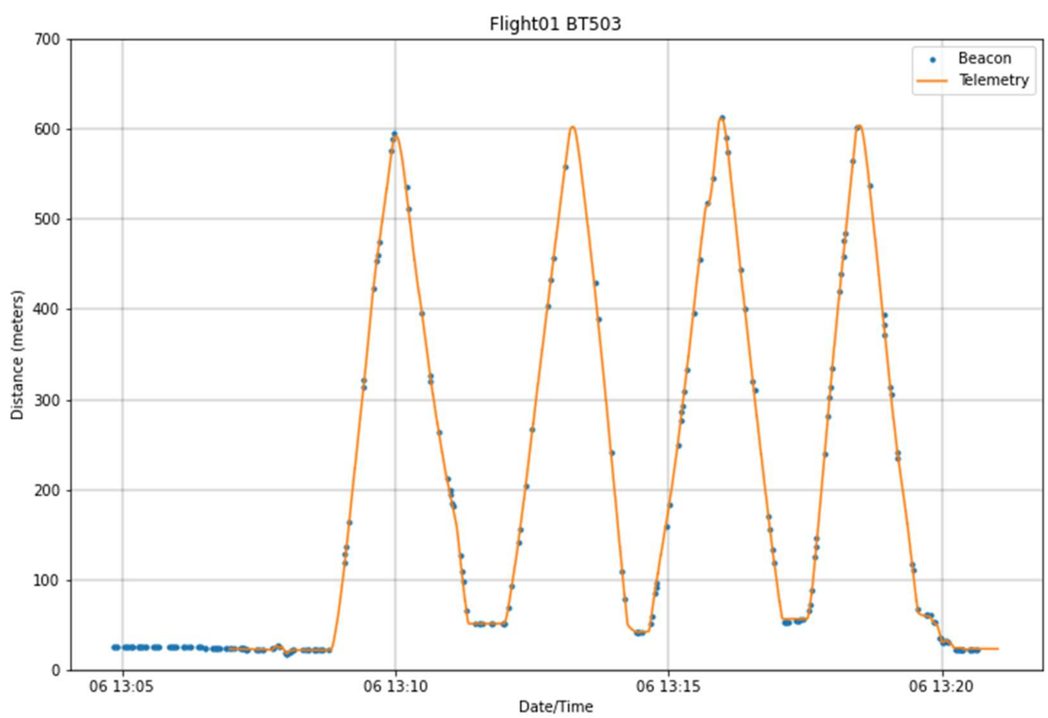
Table 10. Flight Test 1 Flight Test Matrix.

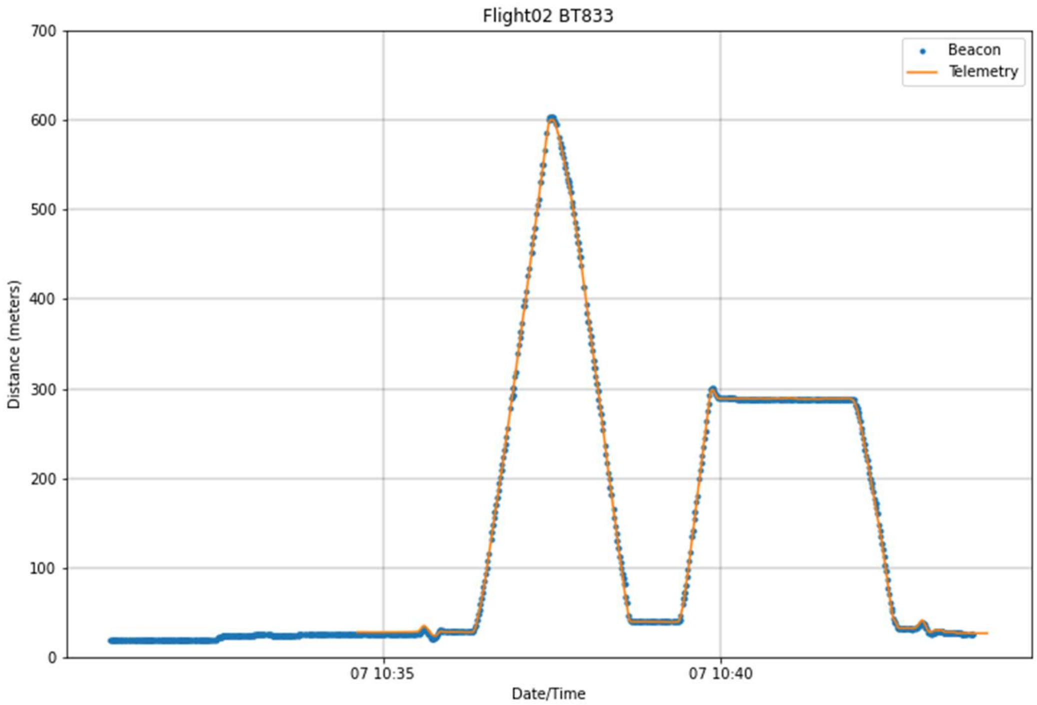
Test No		Aircraft	Beacon	Beacon	Beacon
Dryrun	Day 1	DJI Inspire 2	Bluemark 120	BT	WiFi
Flight01	Day 1	DJI Inspire 2	Bluemark 120	BT	WiFi
Flight02	Day 2	DJI Inspire 2	Bluemark 120	BT	WiFi
Flight03	Day 2	DJI Inspire 2	Pierce Aerospace B1	BT	
Flight04	Day 2	DJI Inspire 2	DroneTag Mini	BT	
Flight05	Day 2	DJI Inspire 2	DroneTag BS	BT	
Flight06	Day 2	Autel Evo 2	Autel Evo 2		WiFi
Flight07	Day 2	DJI Mini 3 Pro	DJI Mini 3 Pro		WiFi
Flight08	Day 2	DJI Mavic 2 Zoom	DJI Mavic 2 Zoom		WiFi
Flight09	Day 2	DJI Inspire 2	DroneTag Beacon	BT	
Flight10	Day 3	DJI Inspire 2	Bluemark 120	BT	WiFi
Flight11	Day 3	DJI Inspire 2	Bluemark 120	BT	WiFi
Flight12	Day 3	DJI Inspire 2	Bluemark 120	BT	
Flight13	Day 3	DJI Inspire 2	Bluemark 120		WiFi
Flight14	Day 4	DJI Inspire 2	Bluemark 120	BT	WiFi
Flight15	Day 4	DJI Inspire 2	Pierce Aerospace B1	BT	
Flight16	Day 4	MAAP Quadcopter	Bluemark 120	BT	WiFi
Flight17	Day 4	MAAP Quadcopter	Pierce Aerospace B1	BT	
Flight18	Day 4	MAAP Quadcopter	DroneTag Beacon	BT	
Flight19	Day 4	MAAP Quadcopter	DroneTag Mini	BT	
Flight20	Day 4	MAAP Quadcopter	DroneTag BS	BT	

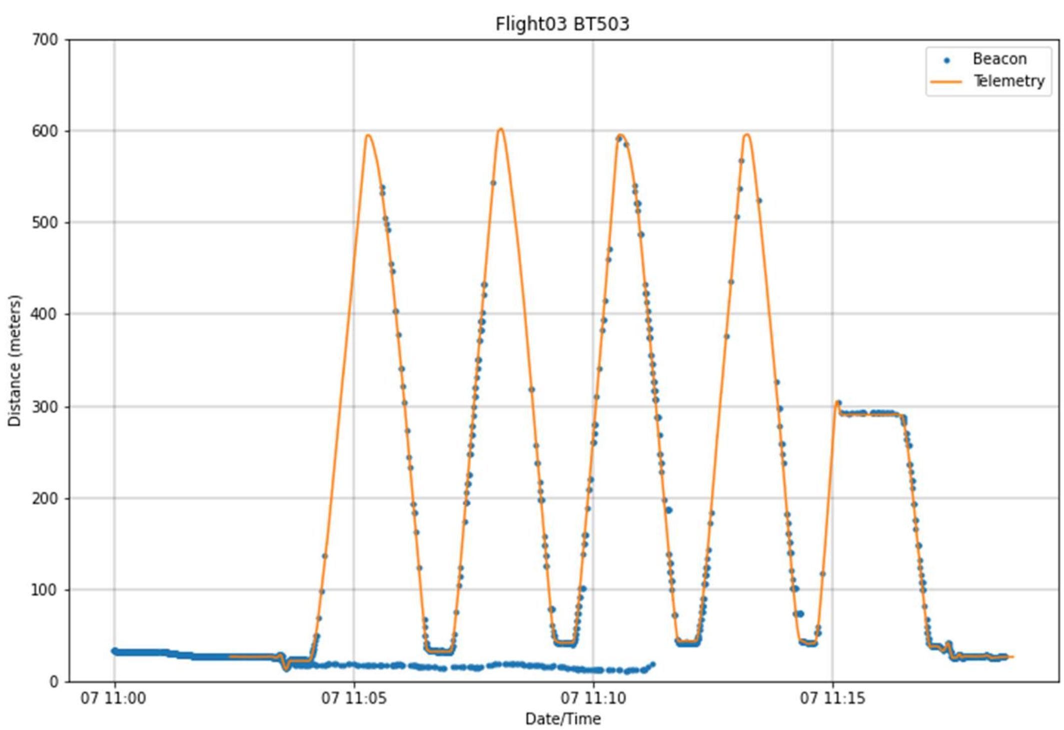

Dryrun BT503
Beacon
Telemetry
Distance (meters)
Date/Time
0
100
200
300
400
500
600
700
800
900
06 12:30
06 12:35
06 12:40
06 12:45
06 12:50

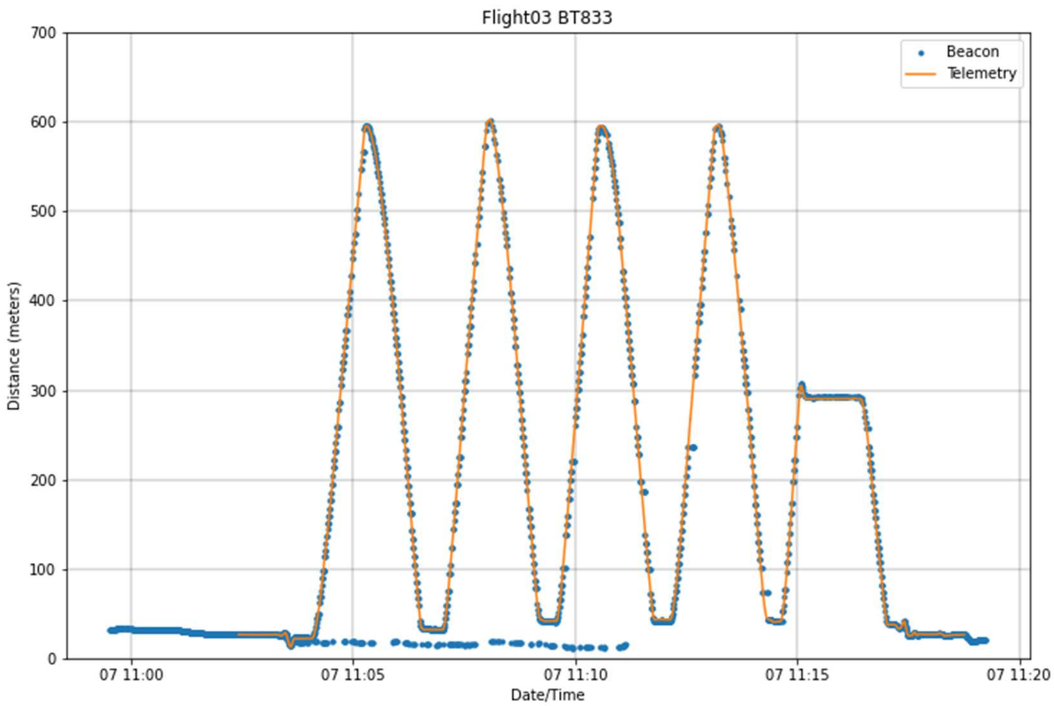

Dryrun BT833
Beacon
Telemetry
Distance (meters)
Date/Time
0
100
200
300
400
500
600
700
800
900
06 12:30
06 12:35
06 12:40
06 12:45
06 12:50


Flight01 BT833
Beacon
Telemetry
Distance (meters)
Date/Time
700
600
500
400
300
200
100
0
06 13:05
06 13:10
06 13:15
06 13:20

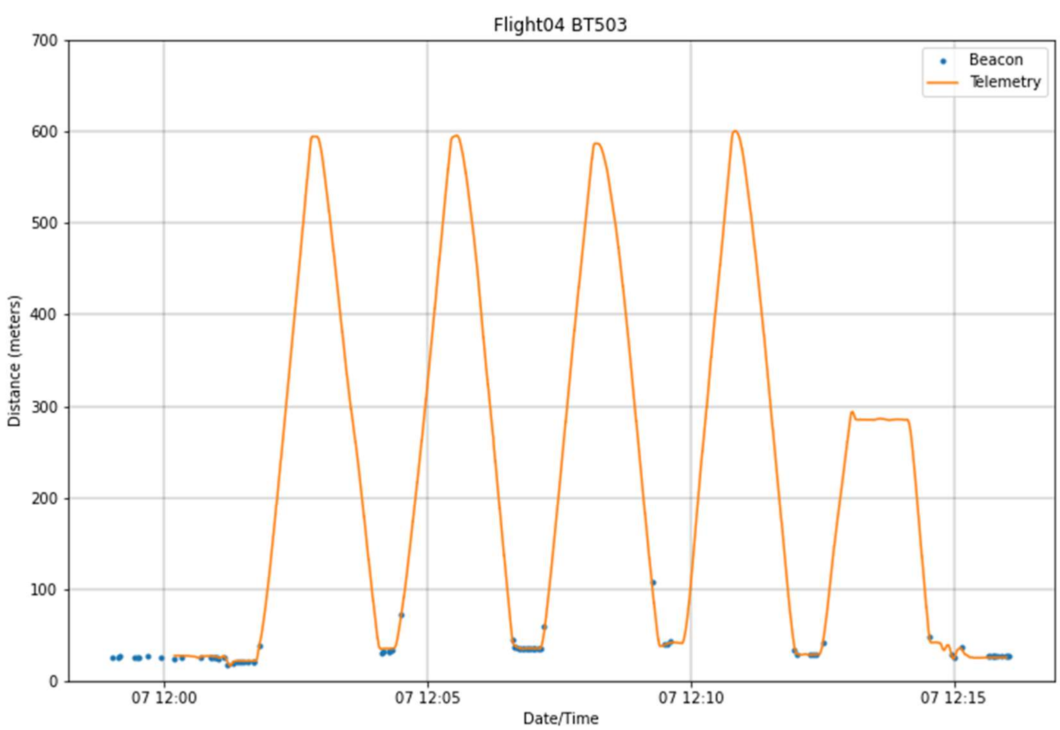

Flight01 BT503
Beacon
Telemetry
Distance (meters)
Date/Time
700
600
500
400
300
200
100
0
06 13:05
06 13:10
06 13:15
06 13:20


Flight02 BT833
Beacon
Telemetry
Distance (meters)
Date/Time
0
100
200
300
400
500
600
700
07 10:35
07 10:40

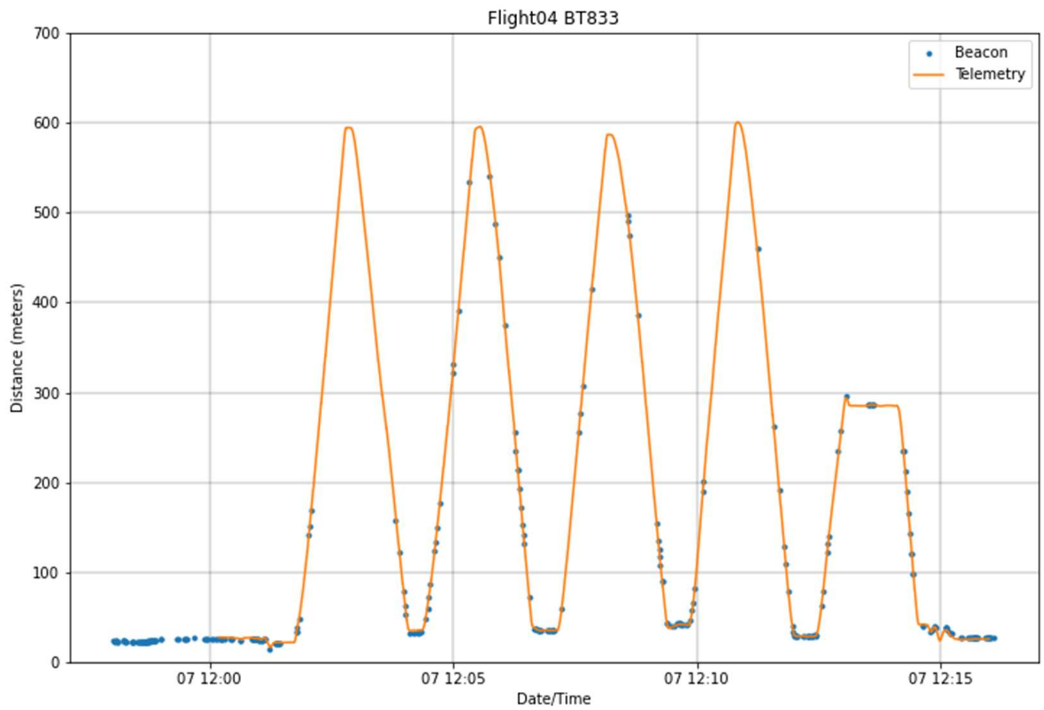

Flight03 BT503
Beacon
Telemetry
Distance (meters)
Date/Time
0
100
200
300
400
500
600
700
07 11:00
07 11:05
07 11:10
07 11:15



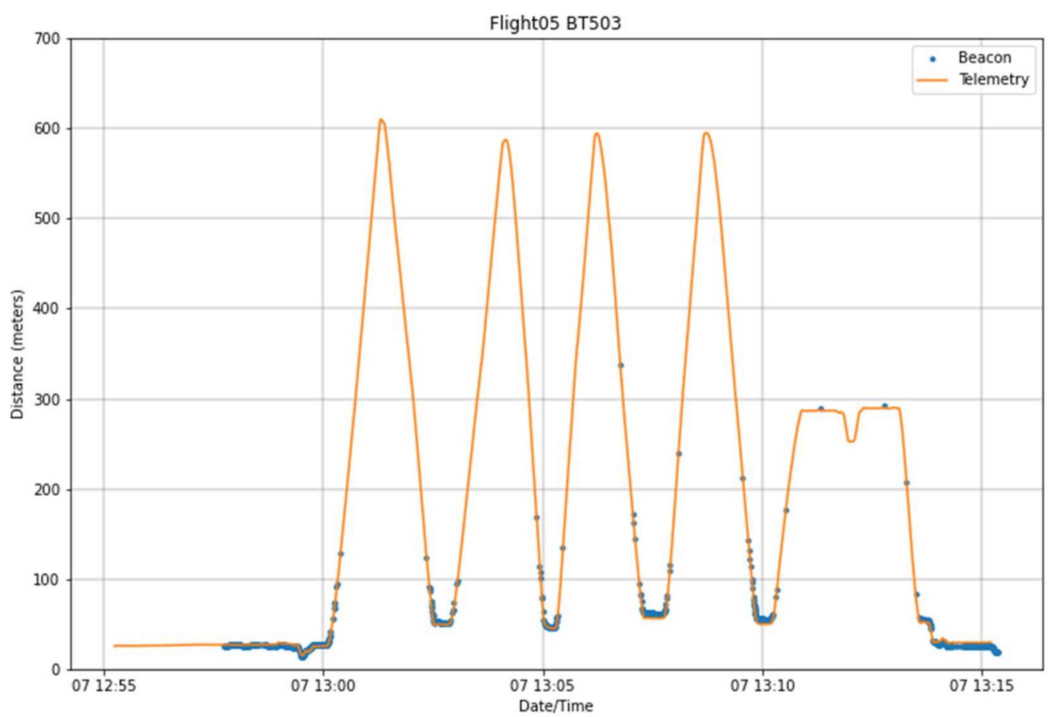
Flight03 BT833
Beacon
Telemetry
Distance (meters)
Date/Time
07 11:00
07 11:05
07 11:10
07 11:15
07 11:20



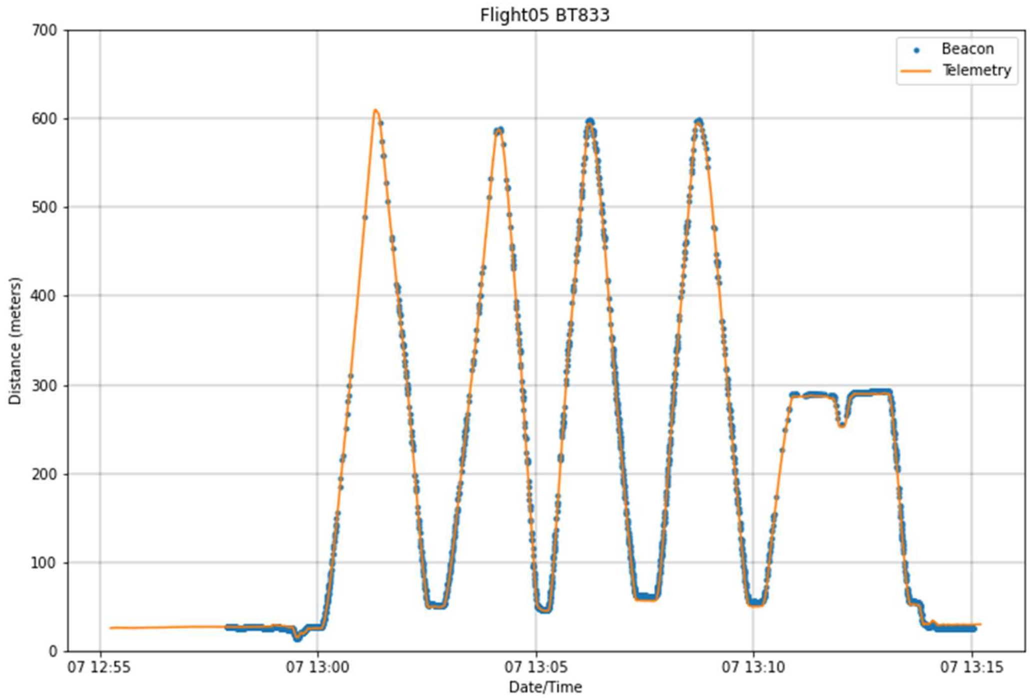
Flight04 BT503
Beacon
Telemetry
Distance (meters)
Date/Time
07 12:00
07 12:05
07 12:10
07 12:15

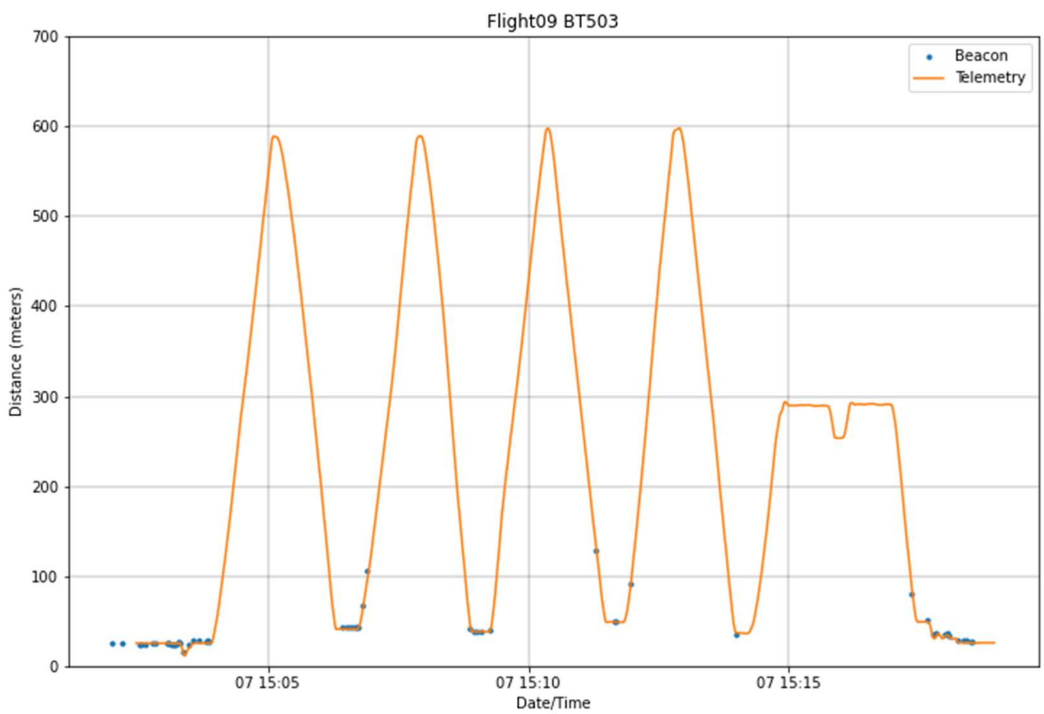


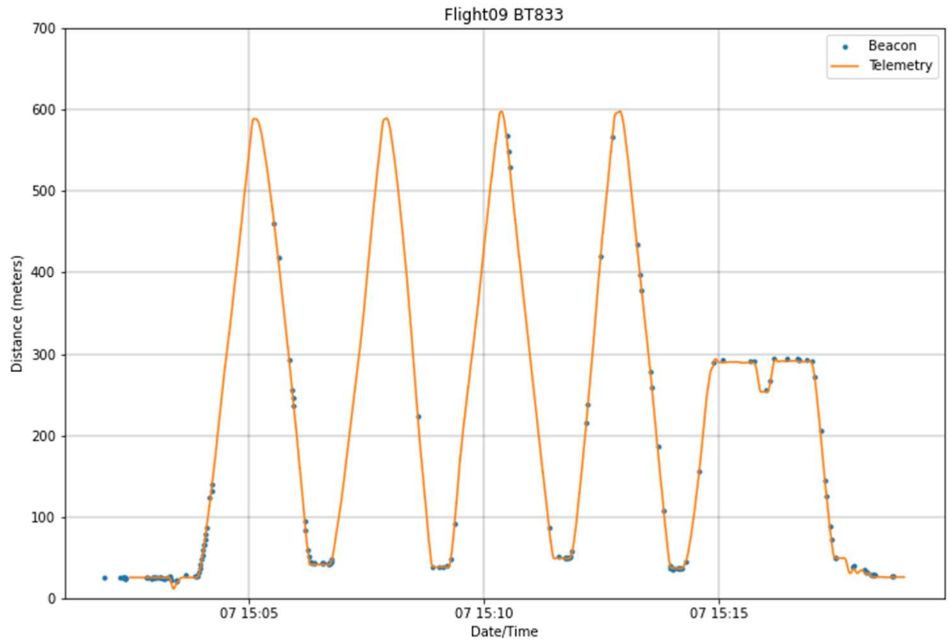
Flight04 BT833
Beacon
Telemetry
Distance (meters)
Date/Time
0
100
200
300
400
500
600
700
07 12:00
07 12:05
07 12:10
07 12:15



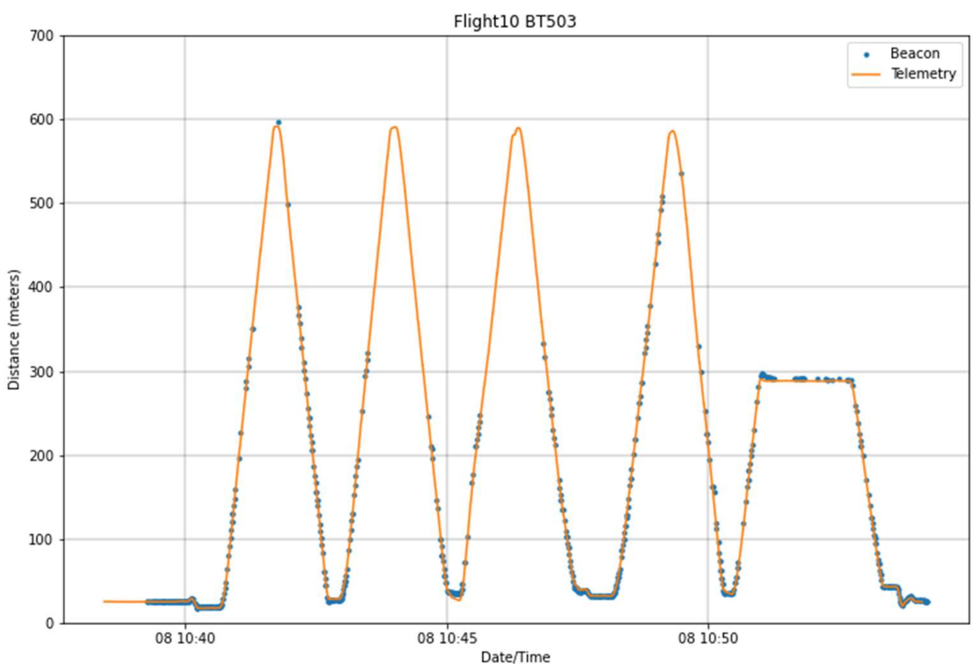
Flight05 BT503
Beacon
Telemetry
Distance (meters)
Date/Time
0
100
200
300
400
500
600
700
07 12:55
07 13:00
07 13:05
07 13:10
07 13:15


Flight05 BT833
Beacon
Telemetry
Distance (meters)
Date/Time
0
100
200
300
400
500
600
700
07 12:55
07 13:00
07 13:05
07 13:10
07 13:15

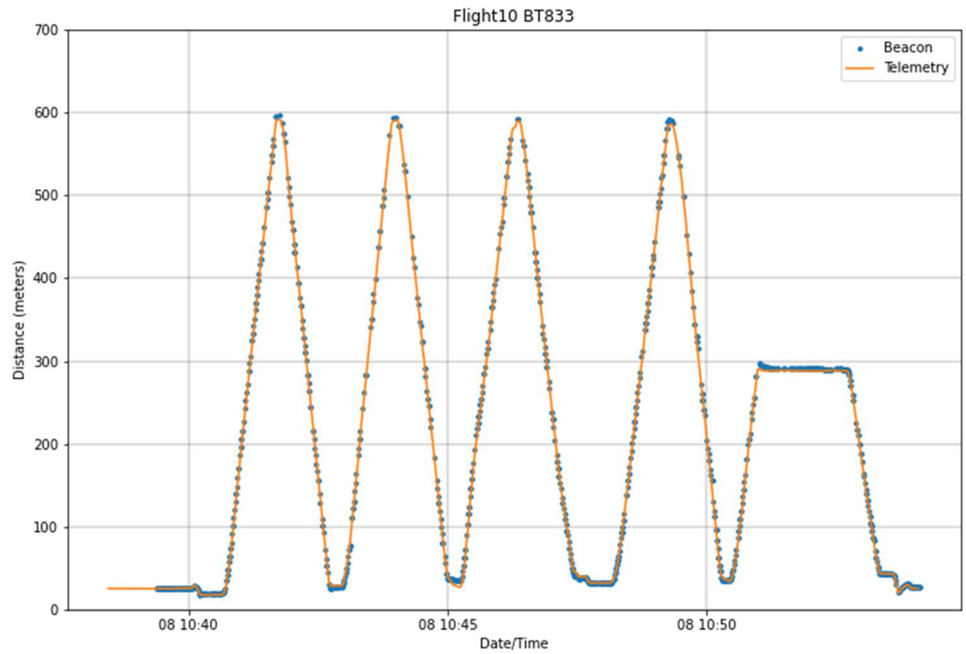

Flight09 BT503
Beacon
Telemetry
Distance (meters)
Date/Time
0
100
200
300
400
500
600
700
07 15:05
07 15:10
07 15:15

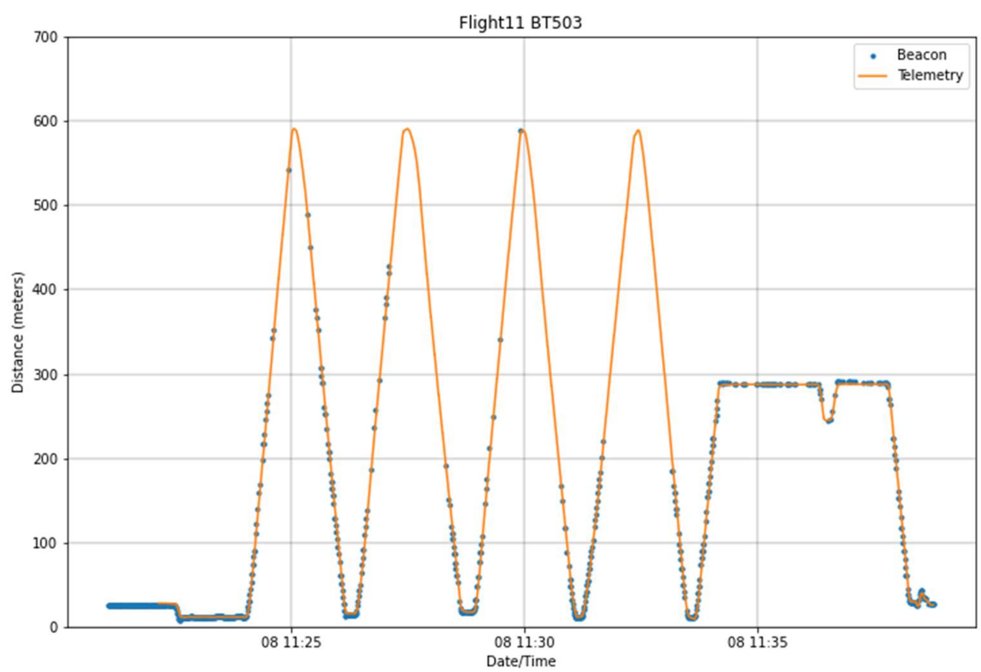


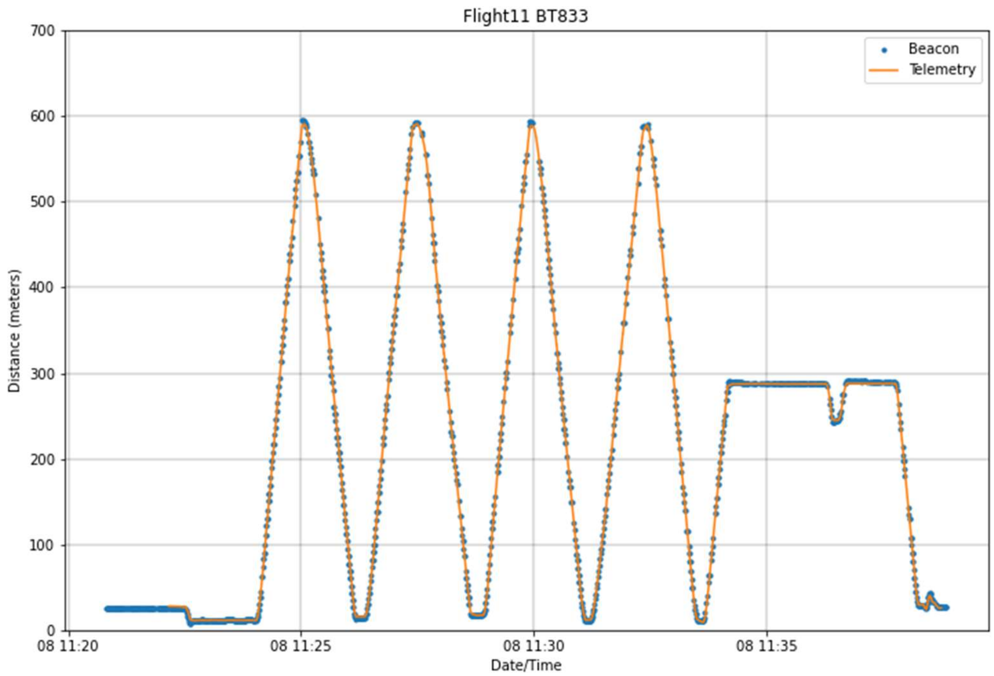
Flight09 BT833
Beacon
Telemetry
Distance (meters)
Date/Time
0
100
200
300
400
500
600
700
07 15:05
07 15:10
07 15:15

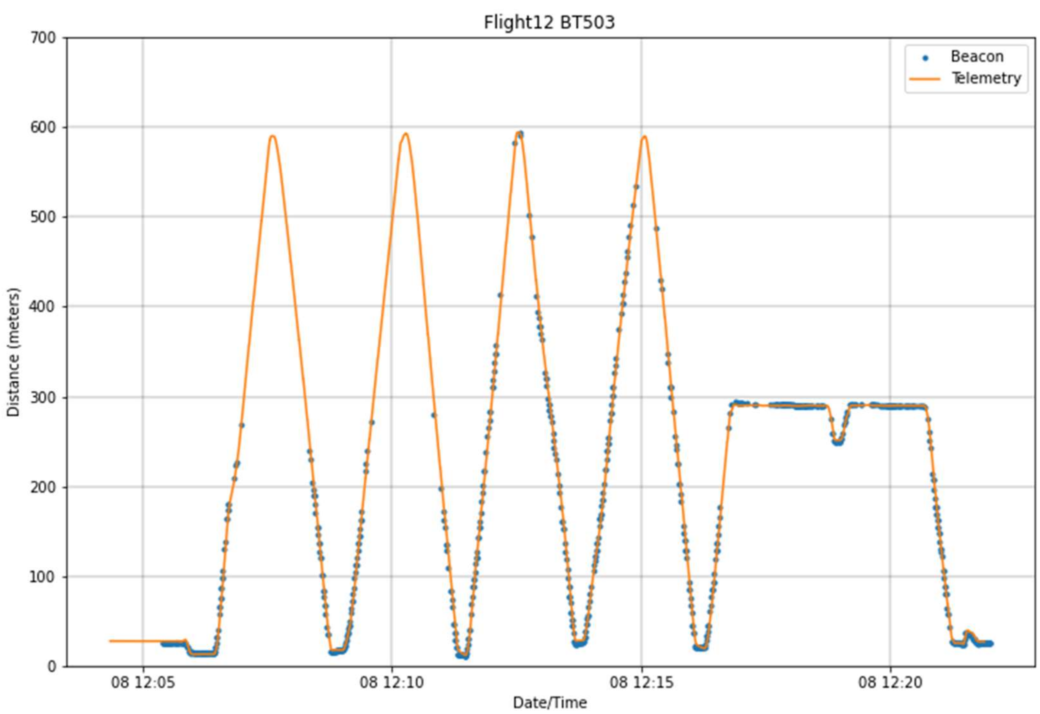


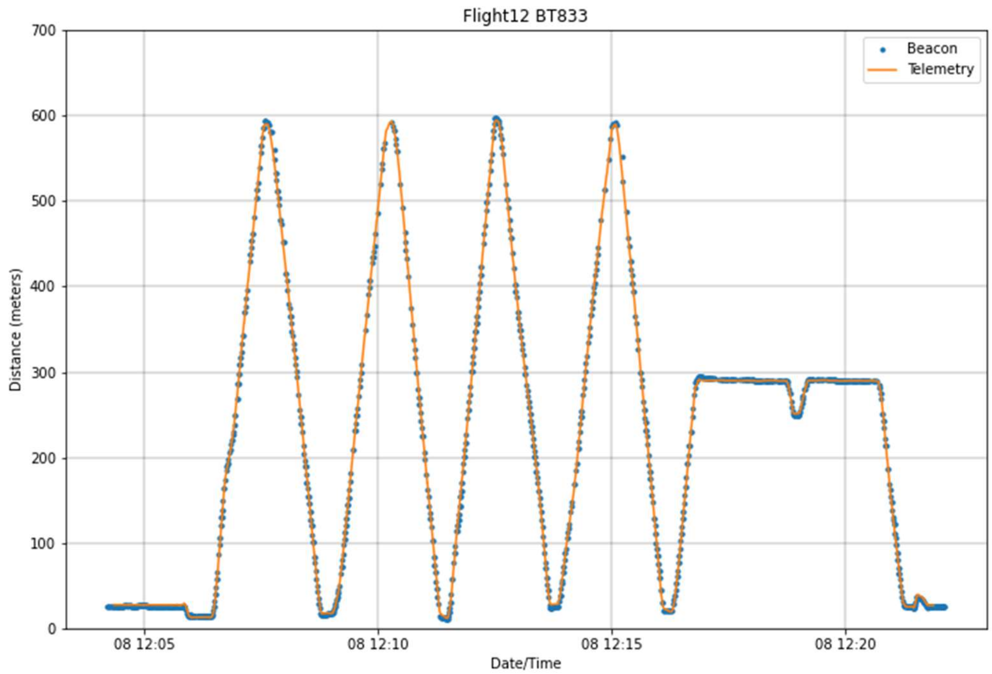
Flight10 BT503
Beacon
Telemetry
Distance (meters)
Date/Time
0
100
200
300
400
500
600
700
08 10:40
08 10:45
08 10:50

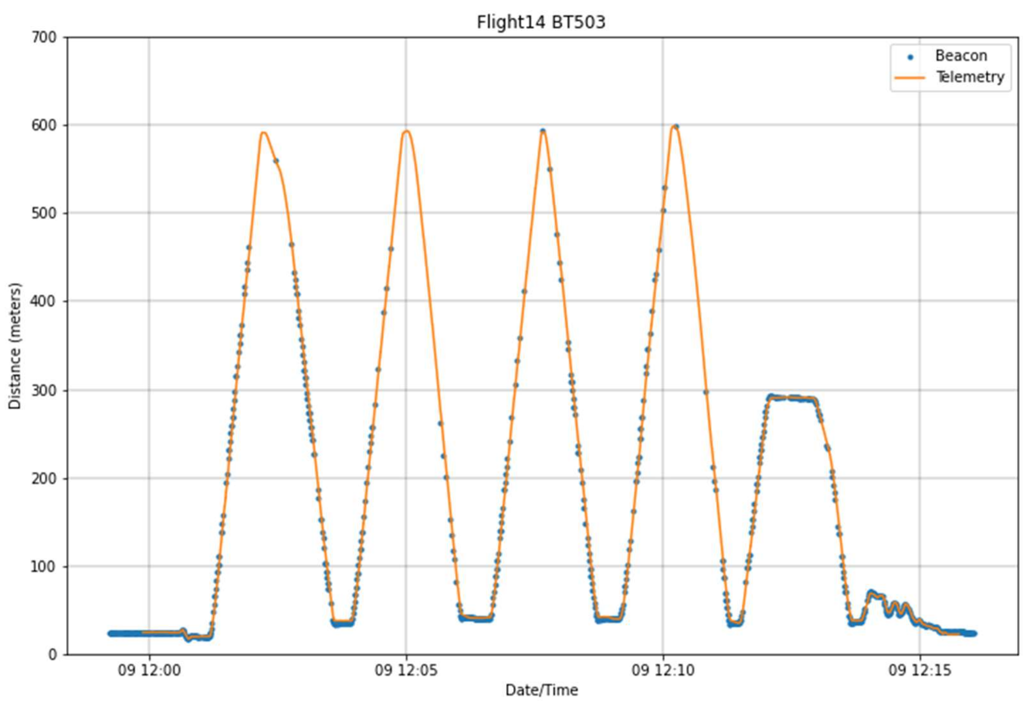

Flight10 BT833
Beacon
Telemetry
Distance (meters)
Date/Time
0
100
200
300
400
500
600
700
08 10:40
08 10:45
08 10:50

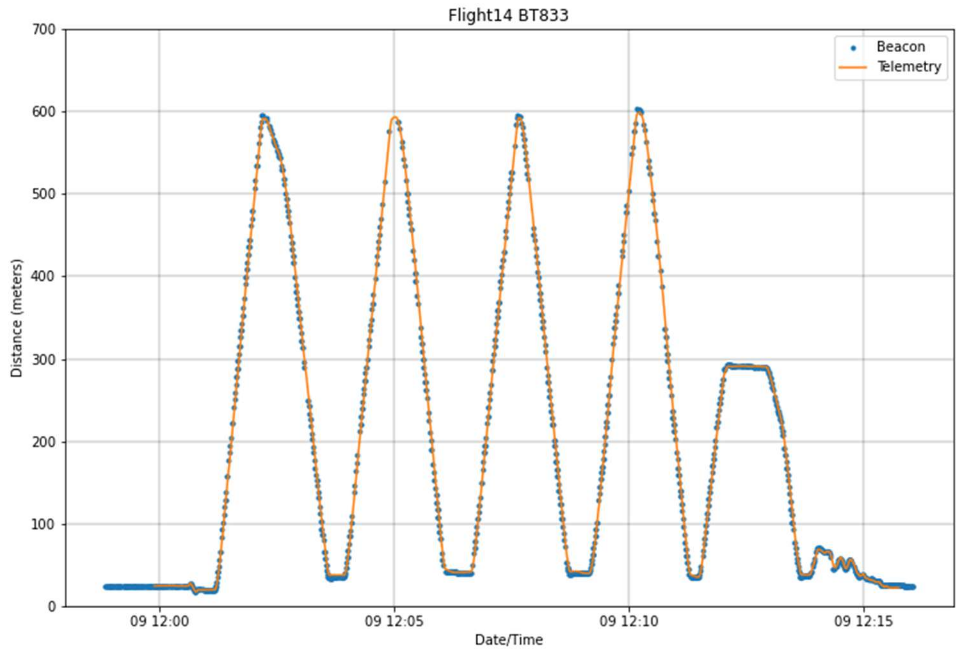

Flight11 BT503
Beacon
Telemetry
Distance (meters)
Date/Time
0
100
200
300
400
500
600
700
08 11:25
08 11:30
08 11:35

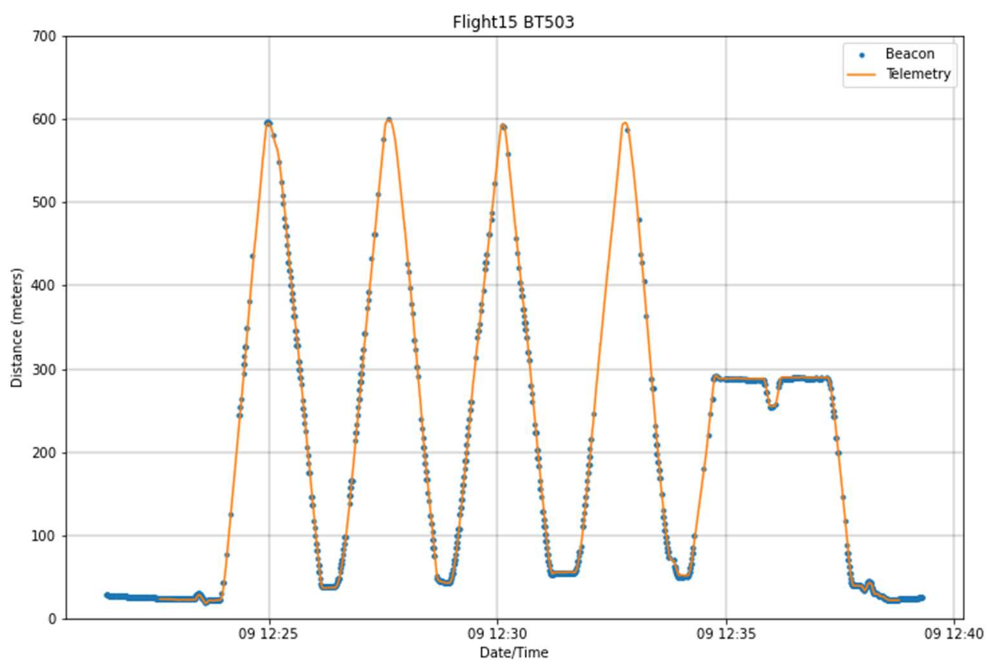

Flight11 BT833
Beacon
Telemetry
Distance (meters)
Date/Time
700
600
500
400
300
200
100
0
08 11:20
08 11:25
08 11:30
08 11:35

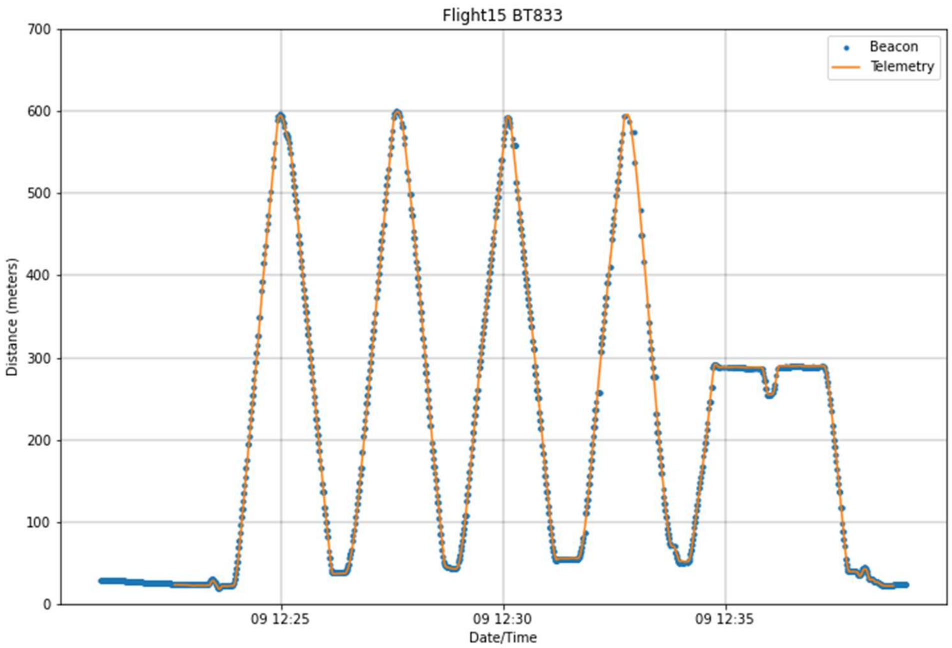

Flight12 BT503
Beacon
Telemetry
Distance (meters)
Date/Time
700
600
500
400
300
200
100
0
08 12:05
08 12:10
08 12:15
08 12:20

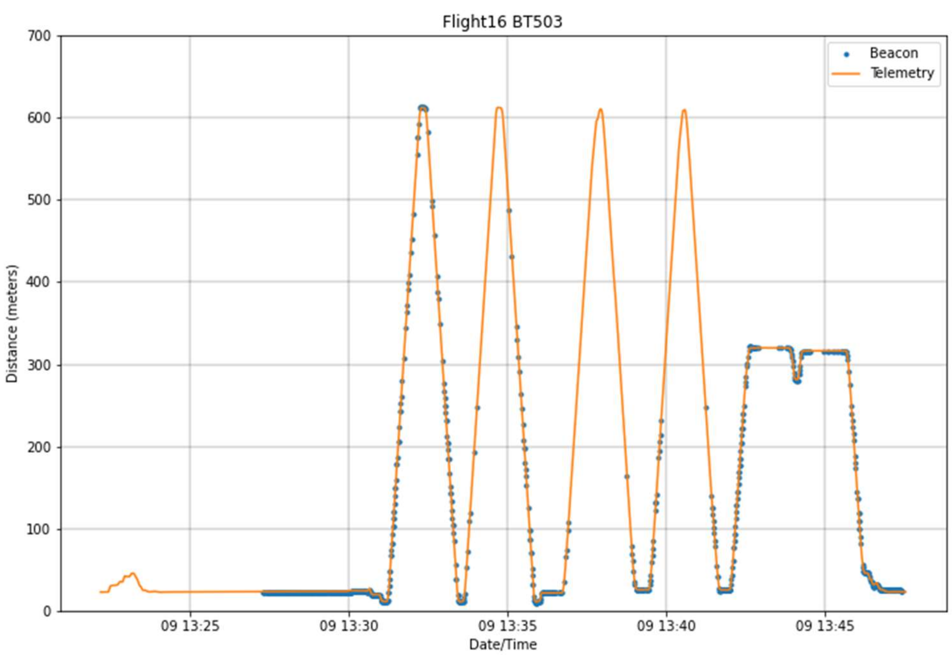

Flight12 BT833
Beacon
Telemetry
Distance (meters)
Date/Time
0
100
200
300
400
500
600
700
08 12:05
08 12:10
08 12:15
08 12:20

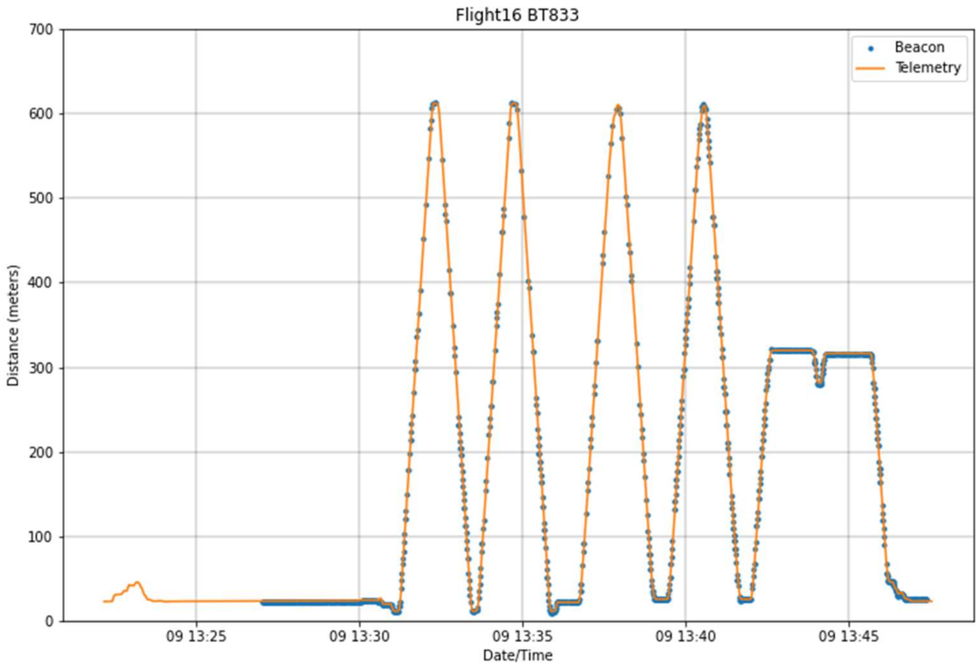

Flight14 BT503
Beacon
Telemetry
Distance (meters)
Date/Time
0
100
200
300
400
500
600
700
09 12:00
09 12:05
09 12:10
09 12:15


Flight14 BT833
Beacon
Telemetry
Distance (meters)
Date/Time
0
100
200
300
400
500
600
700
09 12:00
09 12:05
09 12:10
09 12:15


Flight15 BT503
Beacon
Telemetry
Distance (meters)
Date/Time
0
100
200
300
400
500
600
700
09 12:25
09 12:30
09 12:35
09 12:40


Flight15 BT833
Beacon
Telemetry
Distance (meters)
Date/Time
700
600
500
400
300
200
100
0
09 12:25
09 12:30
09 12:35


Flight16 BT503
Beacon
Telemetry
Distance (meters)
Date/Time
700
600
500
400
300
200
100
0
09 13:25
09 13:30
09 13:35
09 13:40
09 13:45



Flight16 BT833
Beacon
Telemetry
Distance (meters)
Date/Time
0
100
200
300
400
500
600
700
09 13:25
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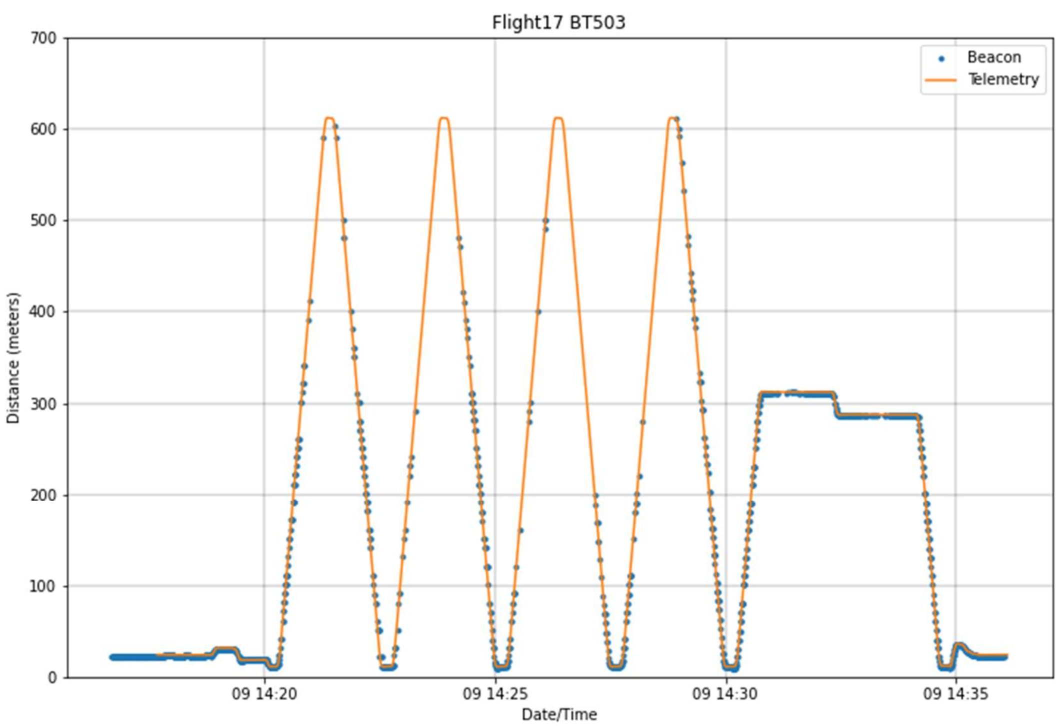
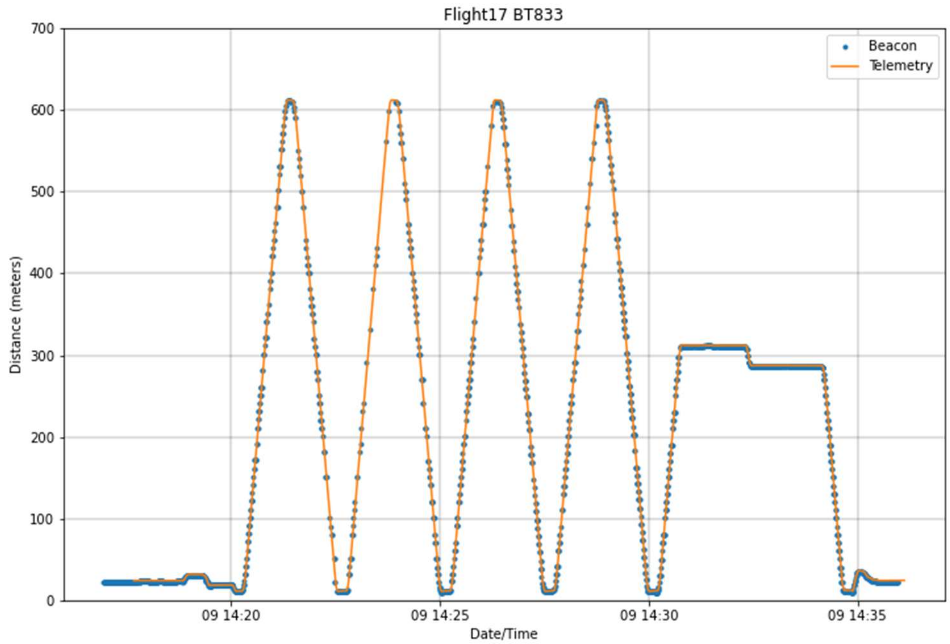
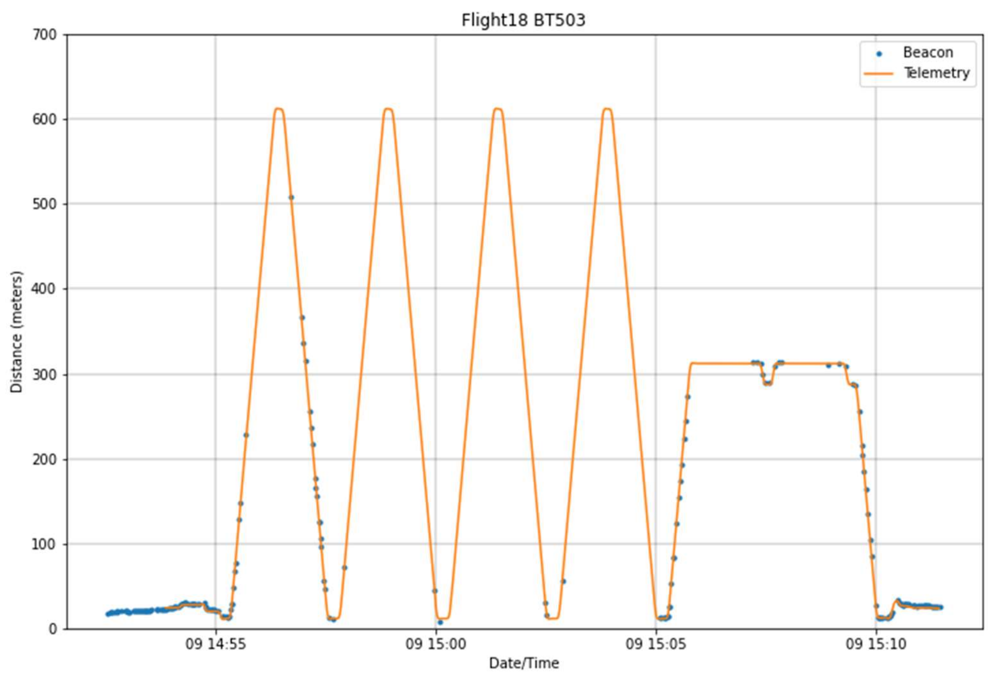
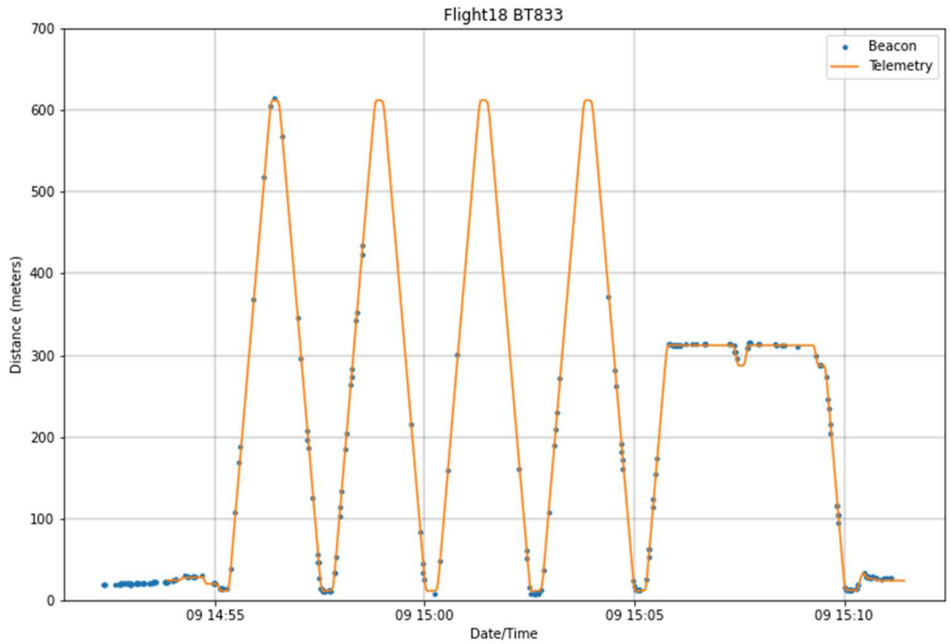
09 13:40
09 13:45



Flight17 BT503
Beacon
Telemetry
Distance (meters)
Date/Time
0
100
200
300
400
500
600
700
09 14:20
09 14:25
09 14:30
09 14:35


Flight17 BT833
Beacon
Telemetry
Distance (meters)
Date/Time
700
600
500
400
300
200
100
0
09 14:20
09 14:25
09 14:30
09 14:35


Flight18 BT503
Beacon
Telemetry
Distance (meters)
Date/Time
700
600
500
400
300
200
100
0
09 14:55
09 15:00
09 15:05
09 15:10


Flight18 BT833
Beacon
Telemetry
Distance (meters)
Date/Time
0
100
200
300
400
500
600
700
09 14:55
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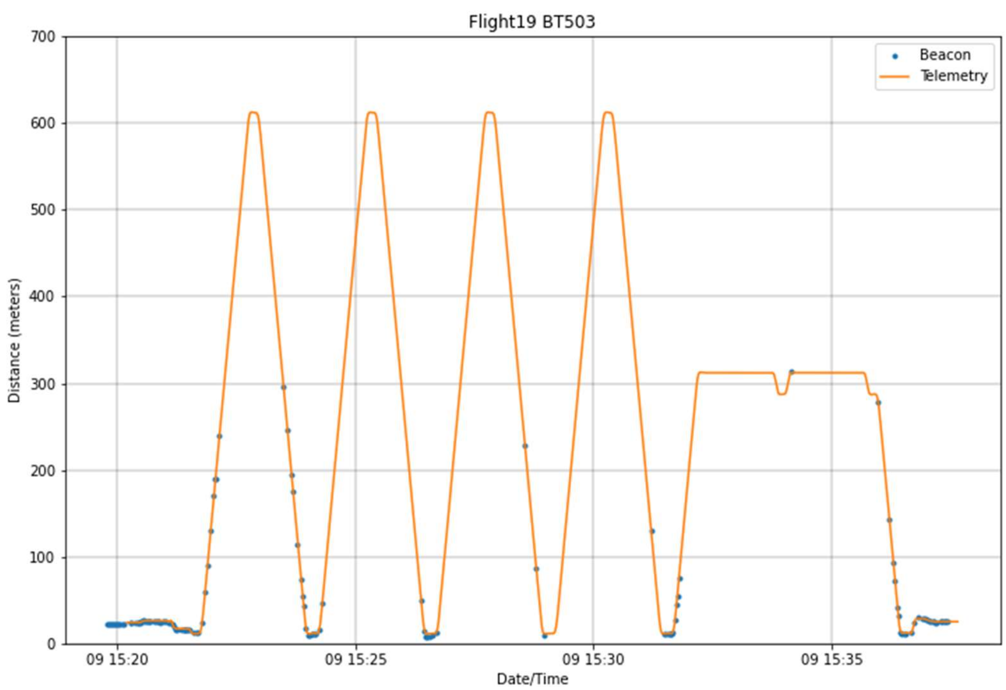
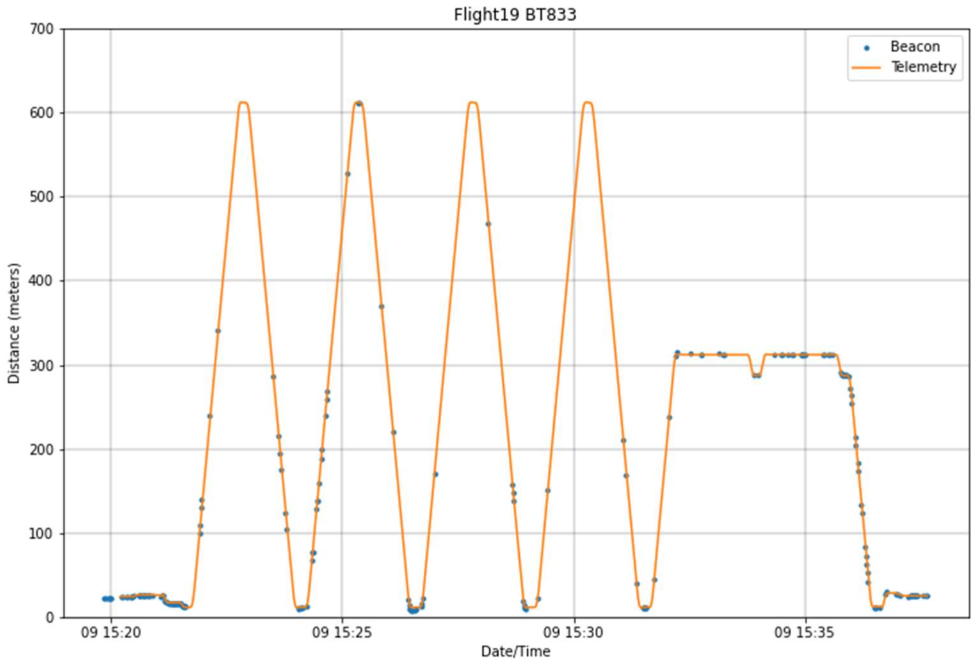
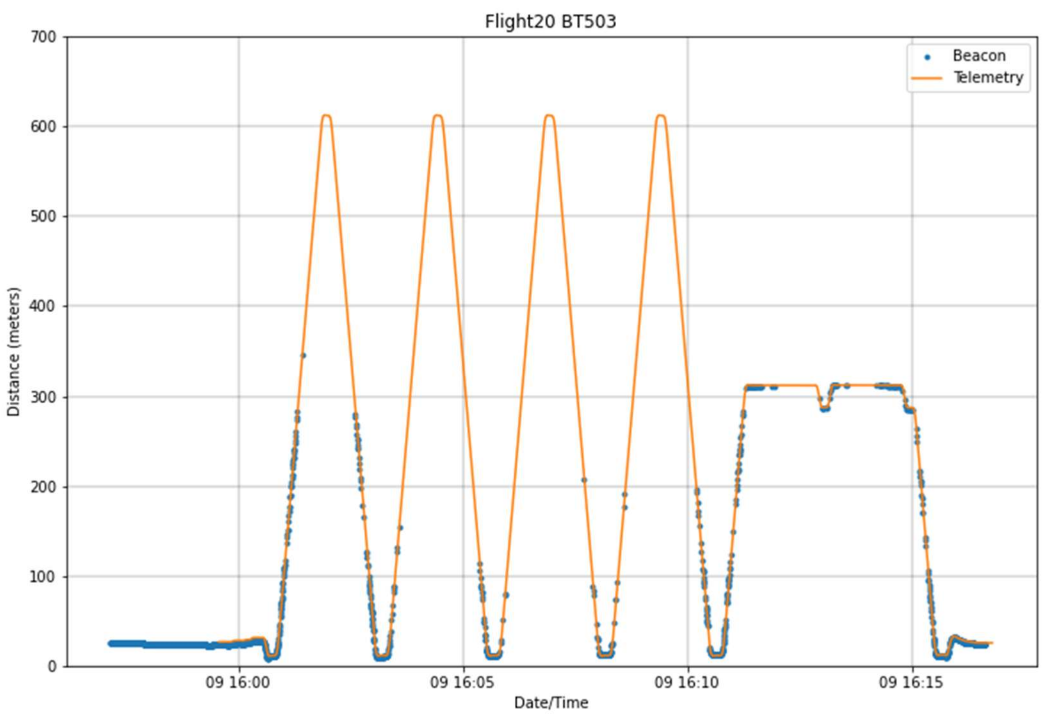
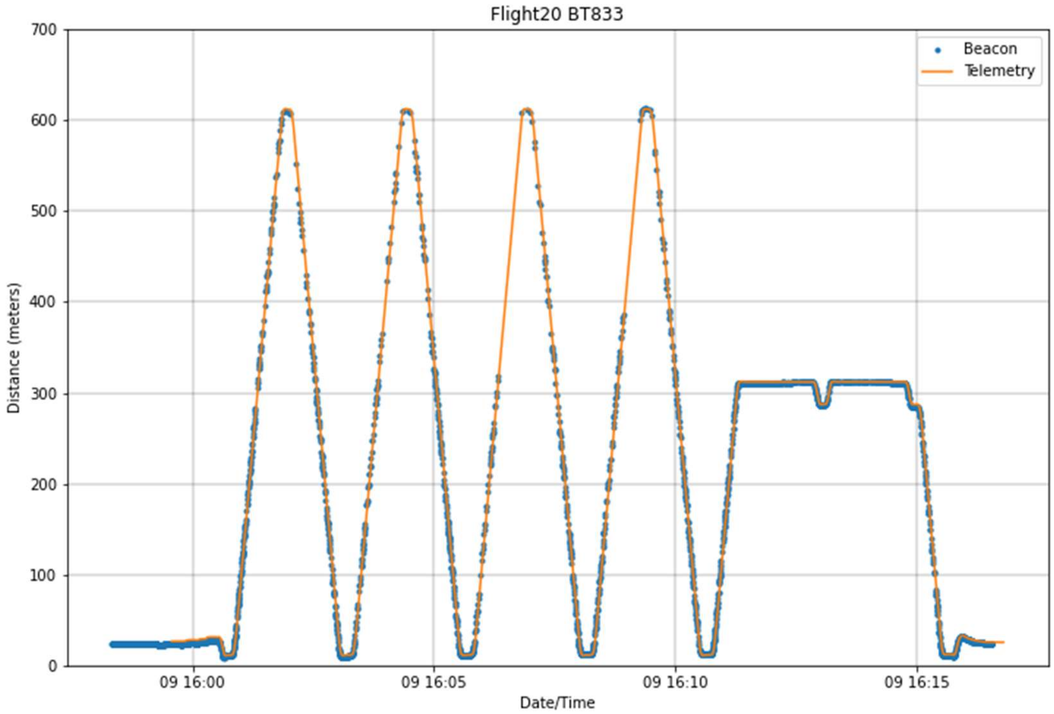
09 15:05
09 15:10

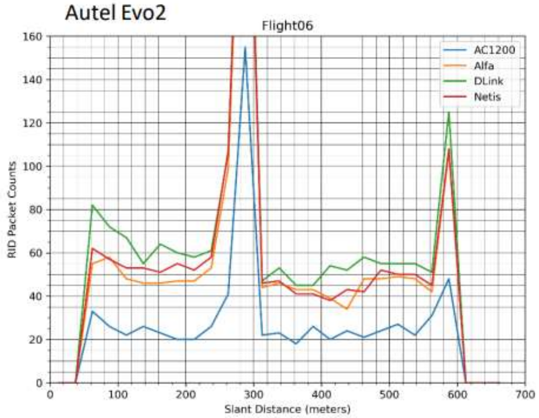

Flight19 BT503
Beacon
Telemetry
Distance (meters)
Date/Time
0
100
200
300
400
500
600
700
09 15:20
09 15:25
09 15:30
09 15:35


Flight19 BT833
Beacon
Telemetry
Distance (meters)
Date/Time
0
100
200
300
400
500
600
700
09 15:20
09 15:25
09 15:30
09 15:35

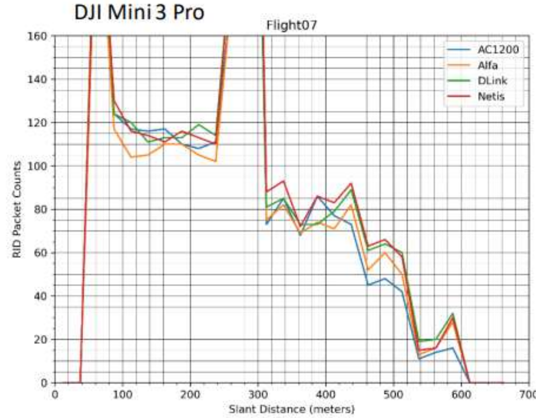

Flight20 BT503
Beacon
Telemetry
Distance (meters)
Date/Time
0
100
200
300
400
500
600
700
09 16:00
09 16:05
09 16:10
09 16:15


Flight20 BT833
Beacon
Telemetry
Distance (meters)
Date/Time
0
100
200
300
400
500
600
700
09 16:00
09 16:05
09 16:10
09 16:15

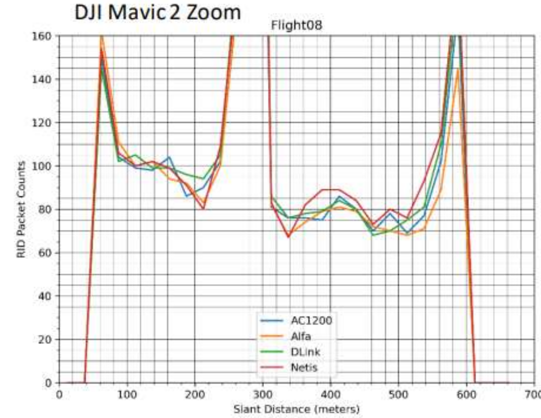
Autel Evo2



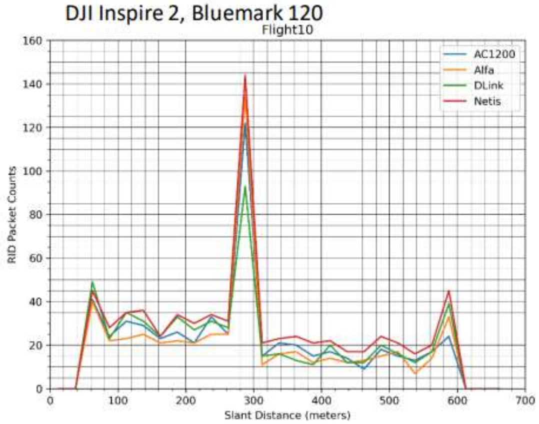
DJI Mini 3 Pro



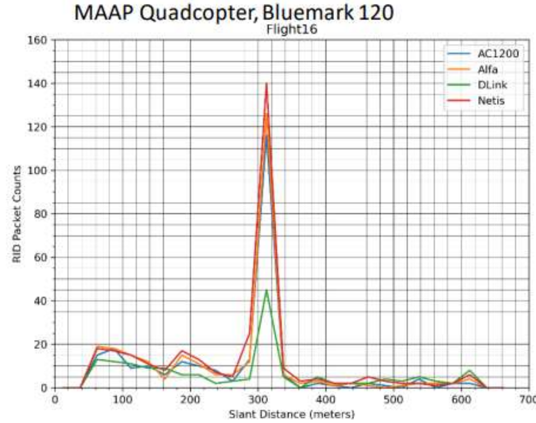
DJI Mavic 2 Zoom



DJI Inspire 2, Bluemark 120

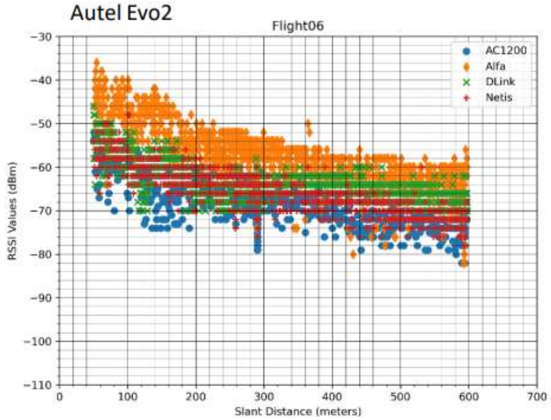


MAAP Quadcopter, Bluemark 120

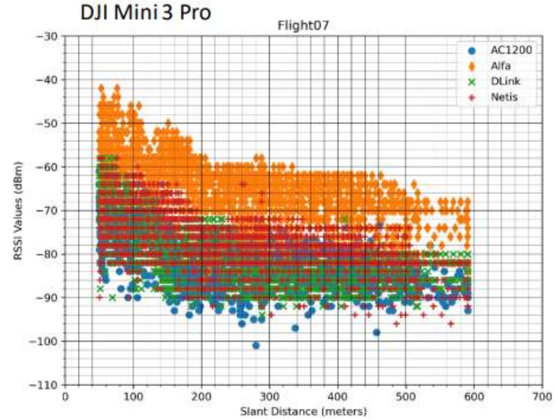


- Larger numbers of data packets from Autel Evo2, DJI Mini 3 Pro and Mavic 2 Zoom were received compared to Bluemark 120
- DJI Mini3 show significant drop in number of packets beyond 400 meters. This may be due to limits on flight distance (need to further investigation)
- The packet quantity difference may be due to differences in packet sending rate (need to further investigation)

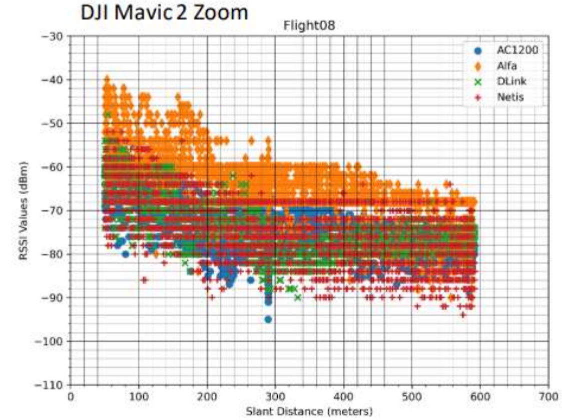
Autel Evo2



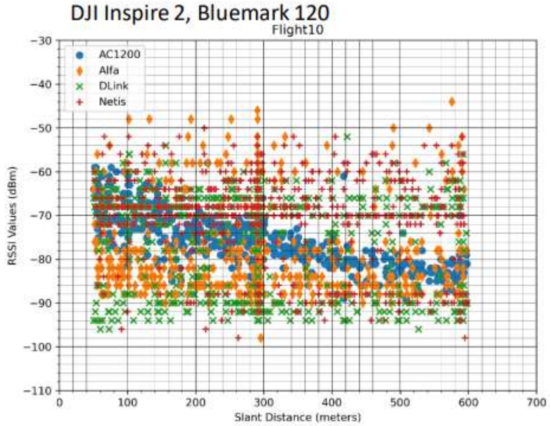
DJI Mini 3 Pro



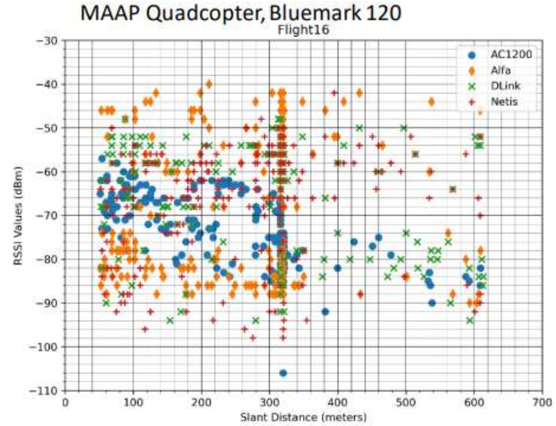
DJI Mavic 2 Zoom



DJI Inspire 2, Bluemark 120

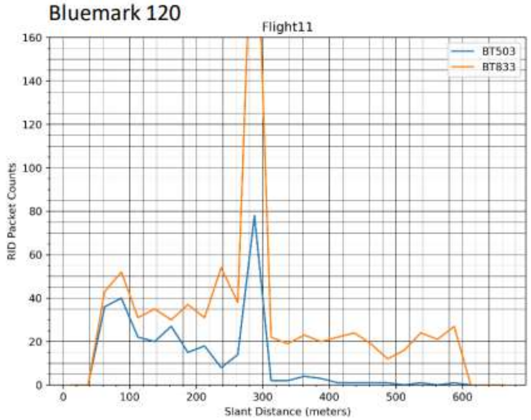


MAAP Quadcopter, Bluemark 120

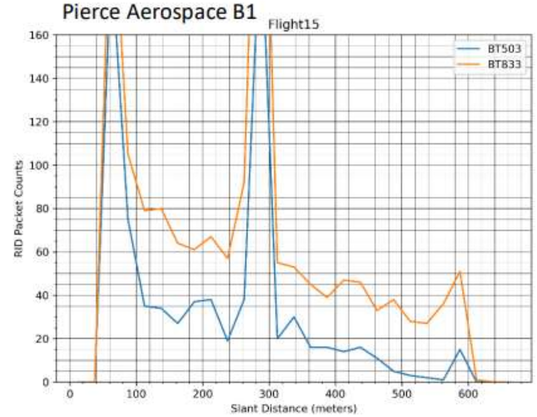


- Received signal strength (RSSI) values from Autel, DJI Mini, DJI Mavic are significantly larger than Bluemark 120
- Alfa recorded larger RSSI values than AC1200, Netis, or D-Link

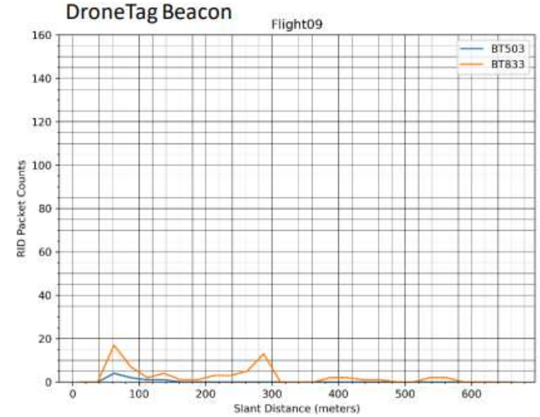
Bluemark 120



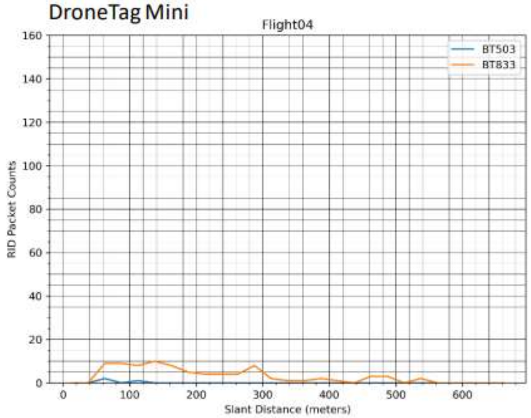
Pierce Aerospace B1



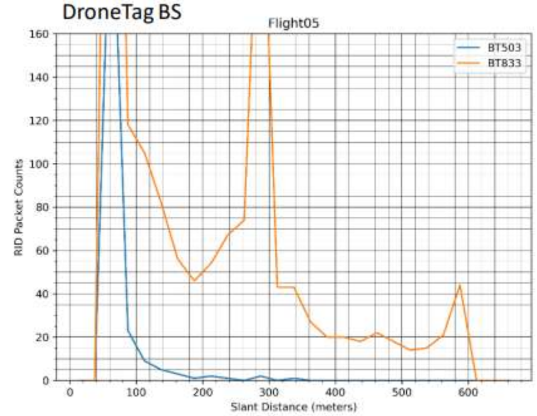
DroneTag Beacon



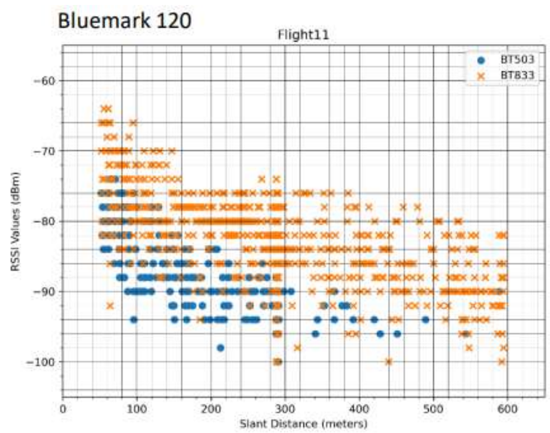
DroneTag Mini

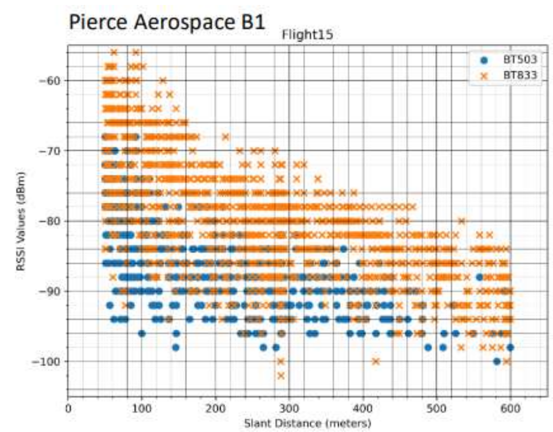


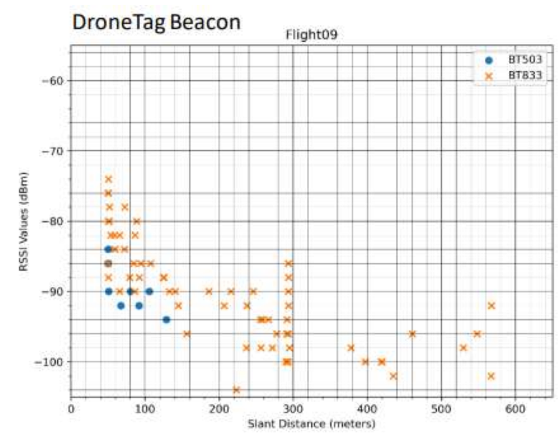
DroneTag BS

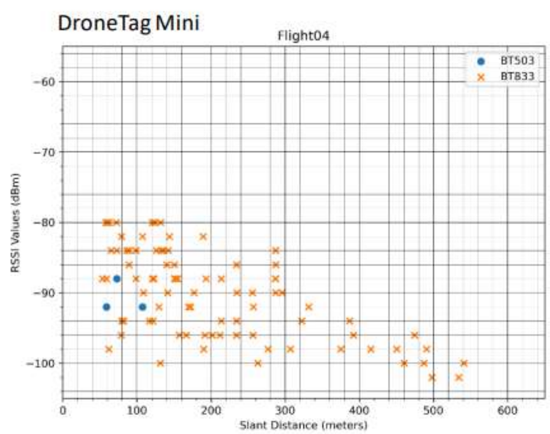


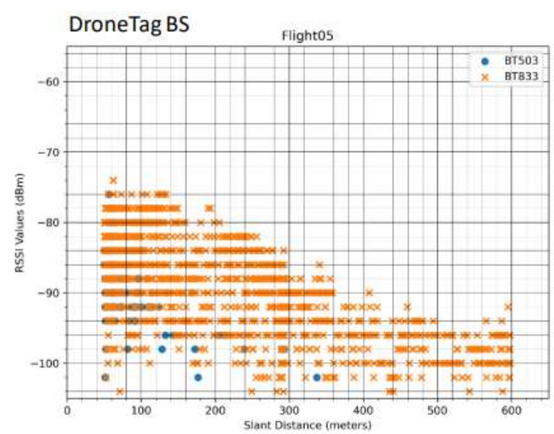
- Larger number of packets were recorded from Pierece Aerospace and DroneTag BS
- BT833 captured larger number of RID packets than BT503



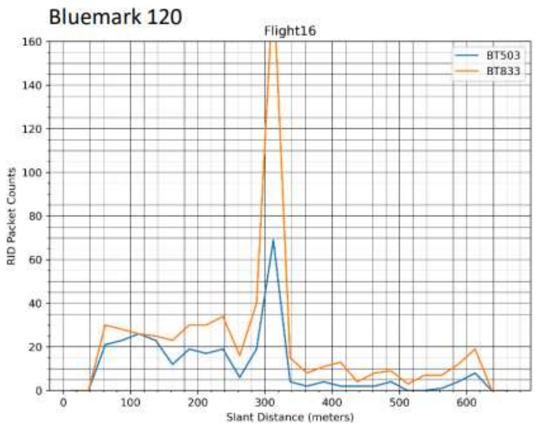


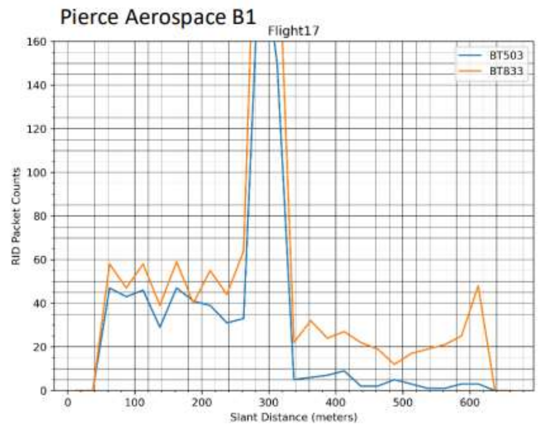


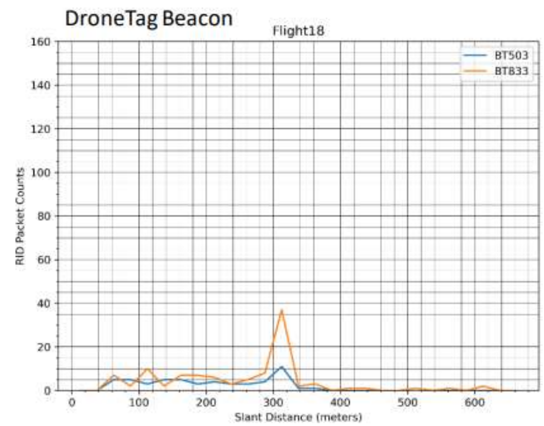


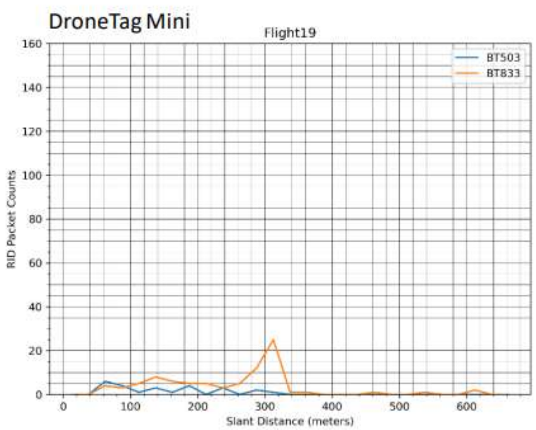


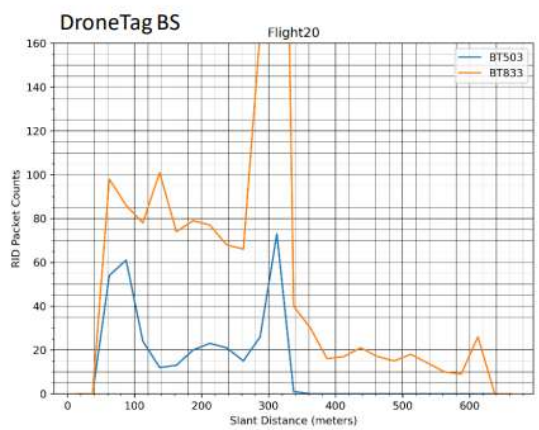
- Stronger RSSI values were recorded from Pierce Aerospace, Bluemark 120, and DroneTag BS
- BT833 show stronger RSSI values than BT503





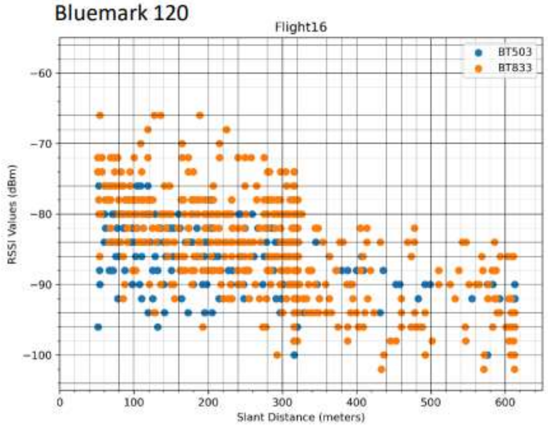




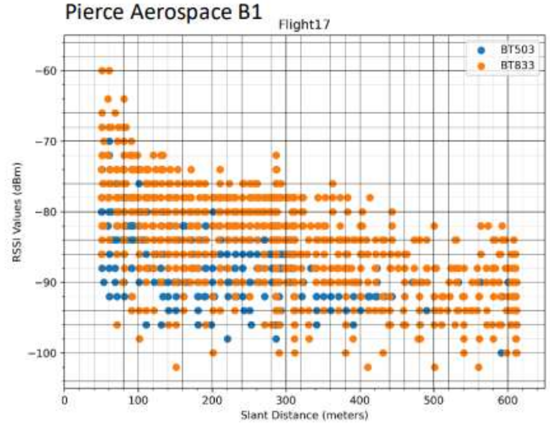


- Larger number of packets were recorded from Pierece Aerospace and DroneTag BS
- BT833 captured larger number of RID packets than BT503
- Trends on MAAP Quadcopter are similar to DJI Inspire 2

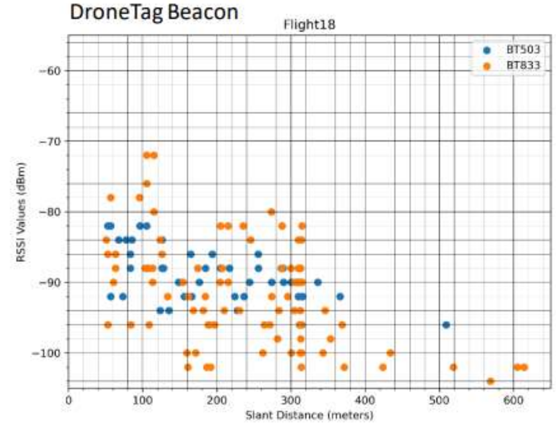
Bluemark 120



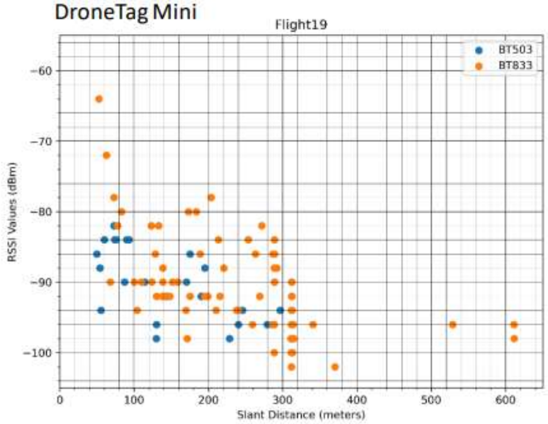
Pierce Aerospace B1



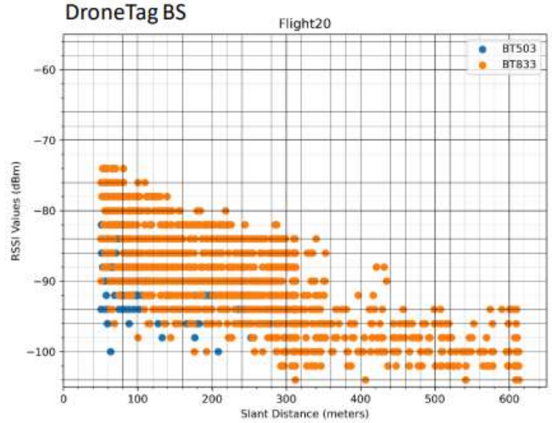
DroneTag Beacon



DroneTag Mini



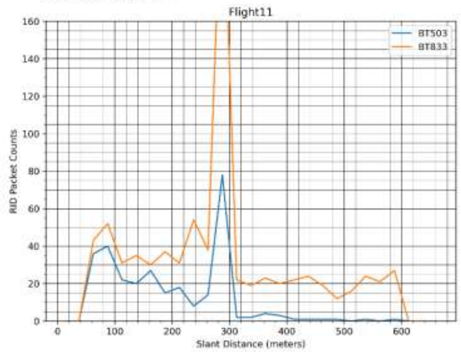
DroneTag BS



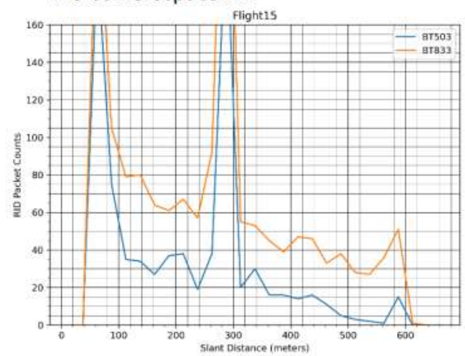
- Stronger RSSI values were recorded from Pierce Aerospace, Bluemark 120, and DroneTag BS
- BT833 show stronger RSSI values than BT503
- Trends on MAAP Quadcopter are similar to DJI Inspire 2

DJI Inspire 2

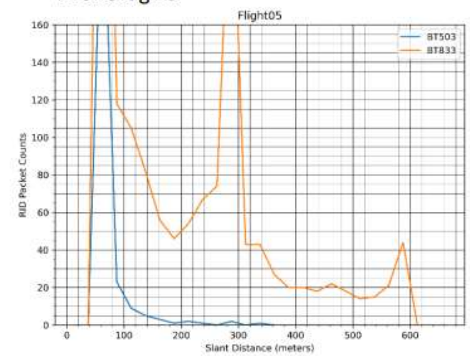
Bluemark 120



Pierce Aerospace B1

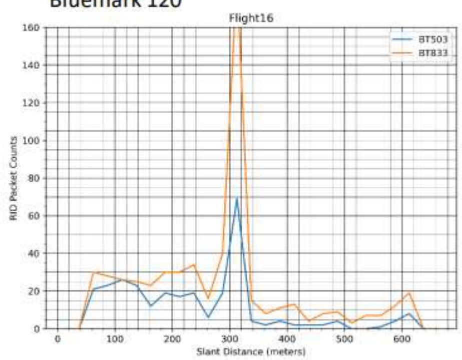


DroneTag BS

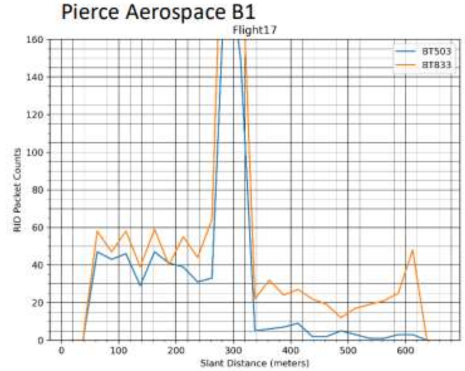


MAAP Quadcopter

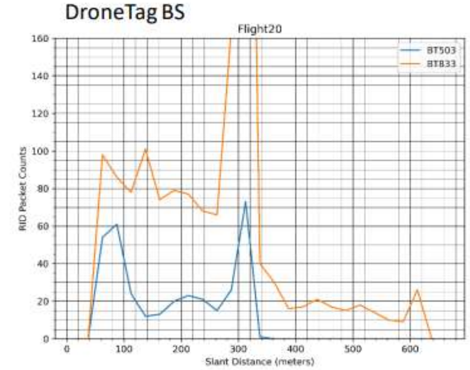
Bluemark 120



Pierce Aerospace B1

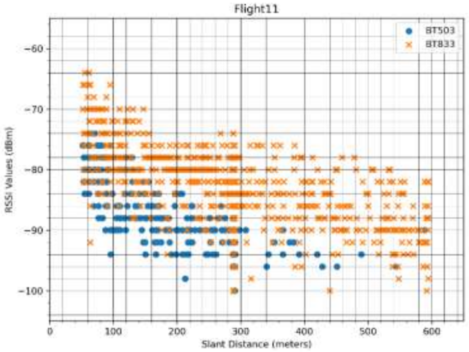


DroneTag BS

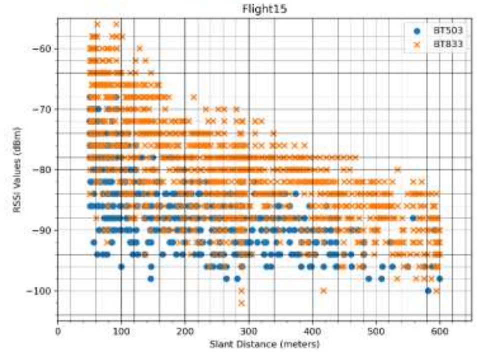


DJI Inspire 2

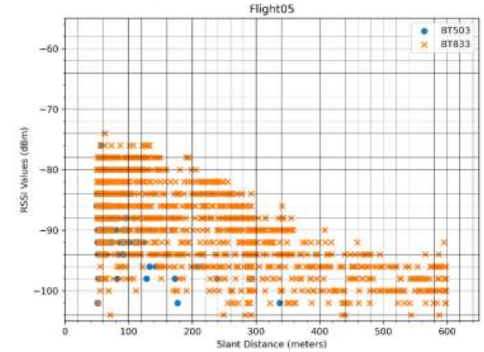
Bluemark 120



Pierce Aerospace B1

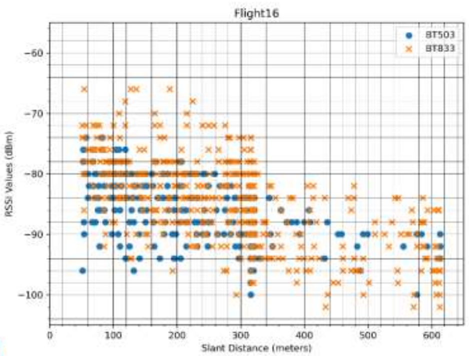


DroneTag BS

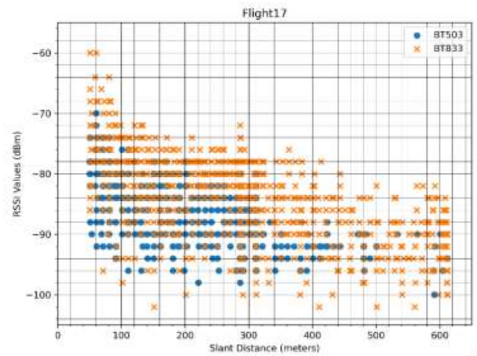


MAAP Quadcopter

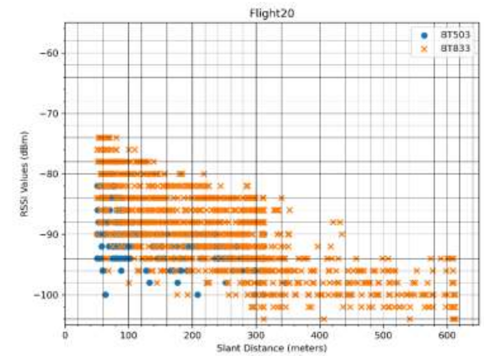
Bluemark 120

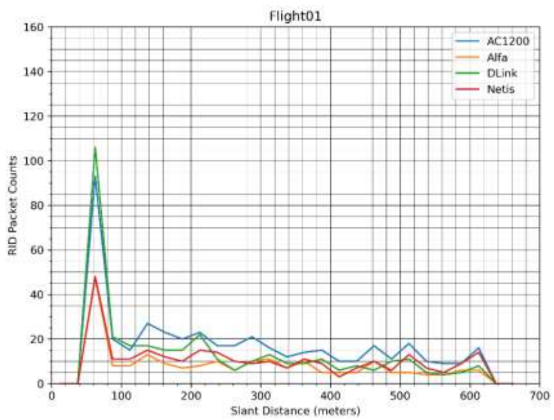


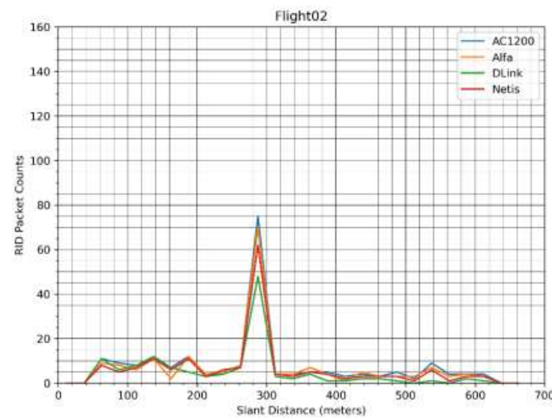
Pierce Aerospace B1

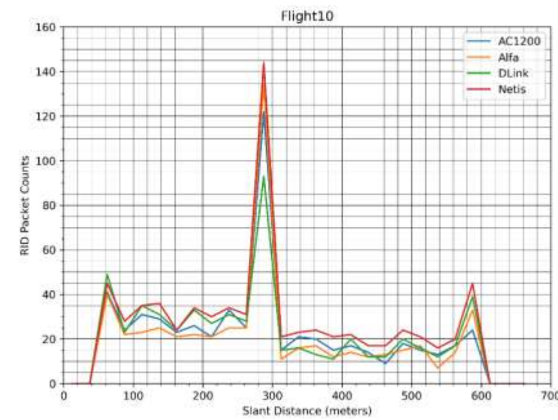


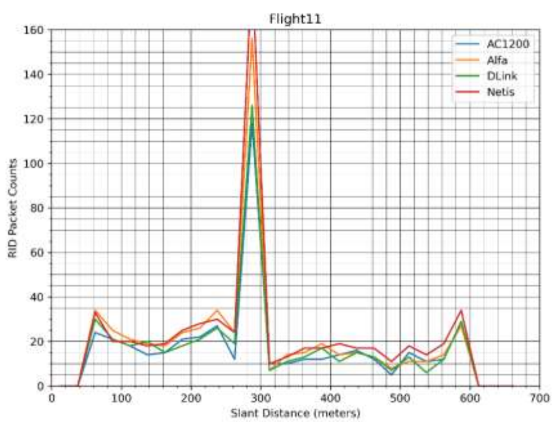
DroneTag BS

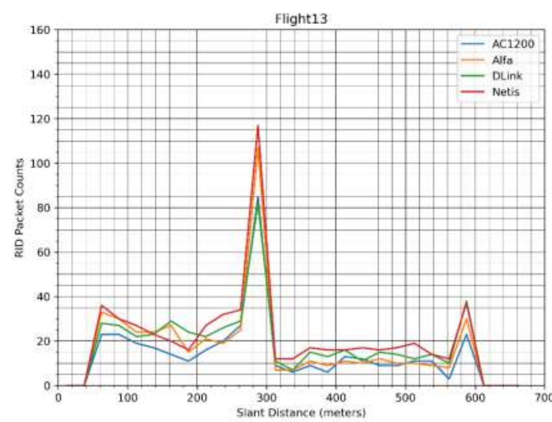


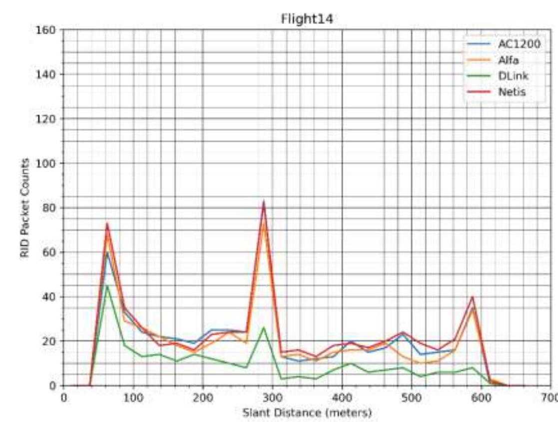

Flight01
RID Packet Counts
Slant Distance (meters)
0 20 40 60 80 100 120 140 160
0 100 200 300 400 500 600 700
AC1200
Alfa
DLink
Netis

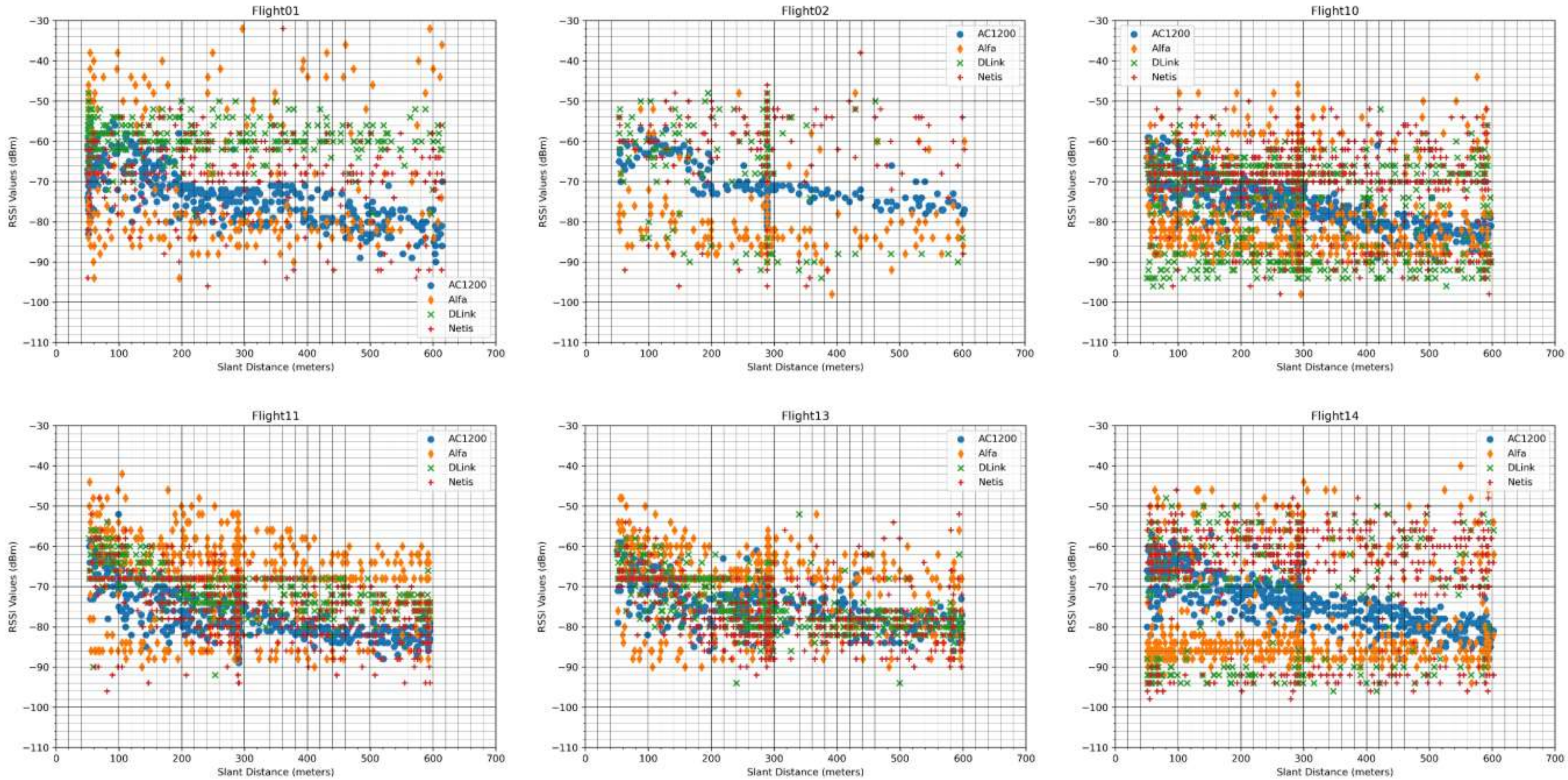

Flight02
RID Packet Counts
Slant Distance (meters)
0 20 40 60 80 100 120 140 160
0 100 200 300 400 500 600 700
AC1200
Alfa
DLink
Netis


Flight10
RID Packet Counts
Slant Distance (meters)
0 20 40 60 80 100 120 140 160
0 100 200 300 400 500 600 700
AC1200
Alfa
DLink
Netis

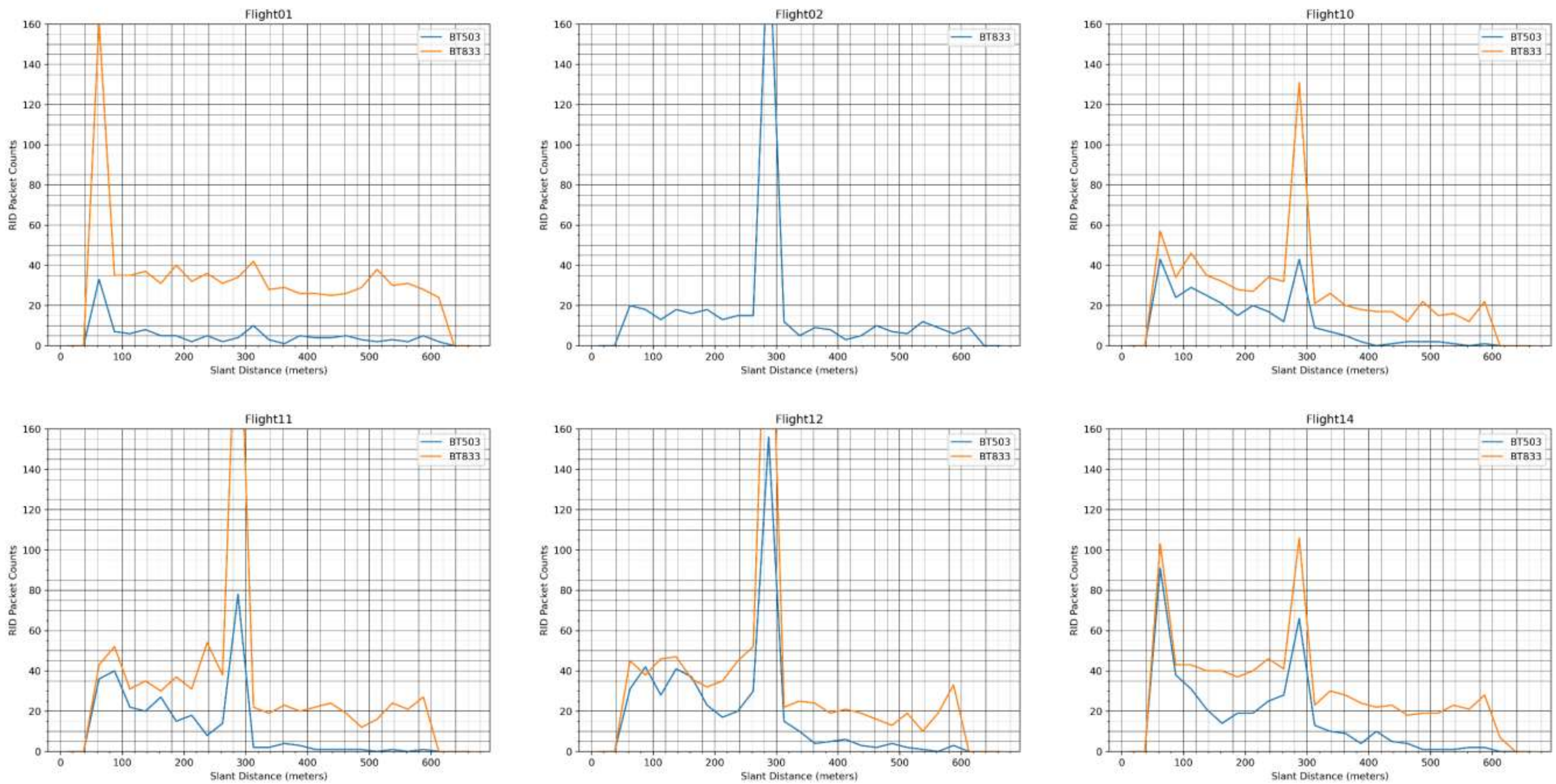

Flight11
RID Packet Counts
Slant Distance (meters)
0 20 40 60 80 100 120 140 160
0 100 200 300 400 500 600 700
AC1200
Alfa
DLink
Netis

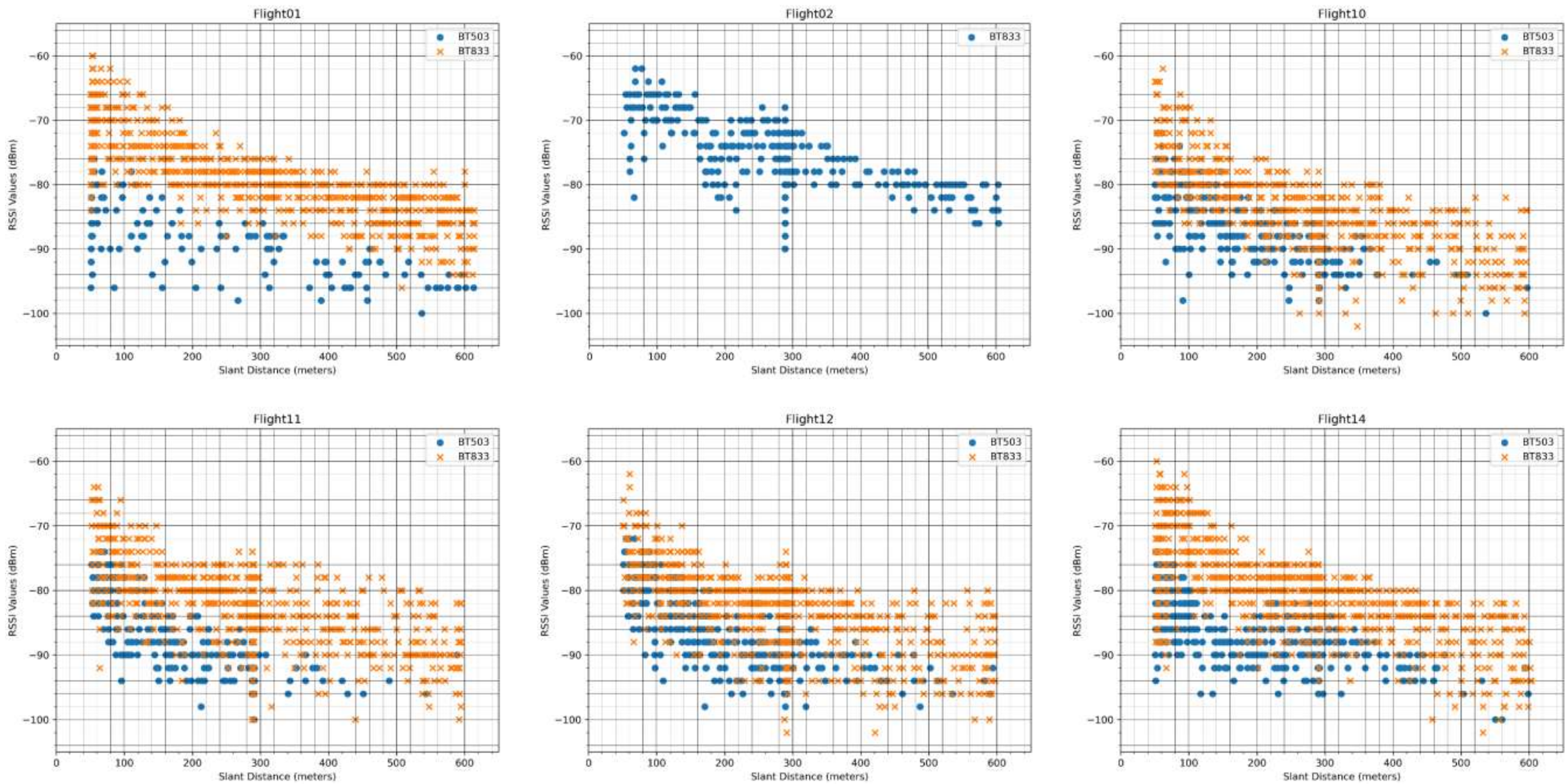

Flight13
RID Packet Counts
Slant Distance (meters)
0 20 40 60 80 100 120 140 160
0 100 200 300 400 500 600 700
AC1200
Alfa
DLink
Netis


Flight14
RID Packet Counts
Slant Distance (meters)
0 20 40 60 80 100 120 140 160
0 100 200 300 400 500 600 700
AC1200
Alfa
DLink
Netis



Flight01
Flight02
Flight10
Flight11
Flight13
Flight14
RSSI Values (dBm)
Slant Distance (meters)
AC1200
Alfa
DLink
Netis


Flight01
Flight02
Flight10
Flight11
Flight12
Flight14
BT503
BT833
RID Packet Counts
Slant Distance (meters)


Flight01
BT503
BT833
Flight02
BT833
Flight10
BT503
BT833
Flight11
BT503
BT833
Flight12
BT503
BT833
Flight14
BT503
BT833
RSSI Values (dBm)
Slant Distance (meters)

D. RID Sensor Model Probability of Detection Charts

The following RID sensor model probability of detection (POD) charts estimate the probability that an RID receiver can sense an RID transmitter by the slant range between the two antennas. The POD estimate is for a moment in time of about one second. That is, for this second, at this slant range, RID protocol, transmitter power, and operational area, what is the chance that the RID receiver receives an RID message from the RID transmitter. We should note that the team designed the RID sensor model using data collected from the two flight tests of the project. The team conducted both flight tests at VT MAAP's Kentland Farms UAS test site which is located in a semi-suburban and semi-rural area. Without any data collected in an urban environment, the POD charts below use EMI estimates gleaned from technical papers on EMI collected at altitudes much higher than sUAS operations. The team believes that the urban EMI impact is probably too conservative and therefore should not be as trusted as the rural and suburban estimates. The team recommends the FAA pursue further studies on the impact of EMI to the RID DAA concept, especially for urban use cases.

1. POD Without Self-Desense

The following two charts represent the expected probability of detection (POD) where the adverse effects of desense have been mitigated. As described above in the preamble of this appendix, the urban POD curve is most likely too conservative.

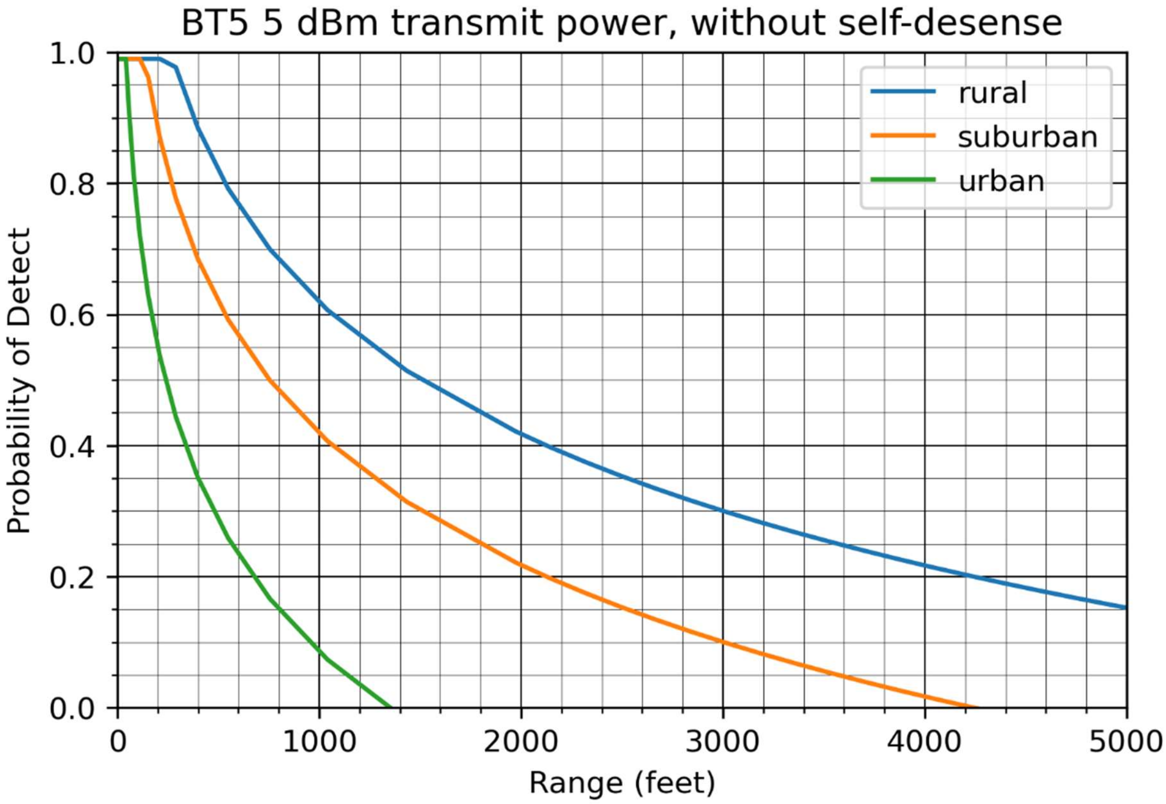


Figure 32. RID Sensor Model POD Chart – Bluetooth 5 (BT5) 5 dBm without Self-Desense.

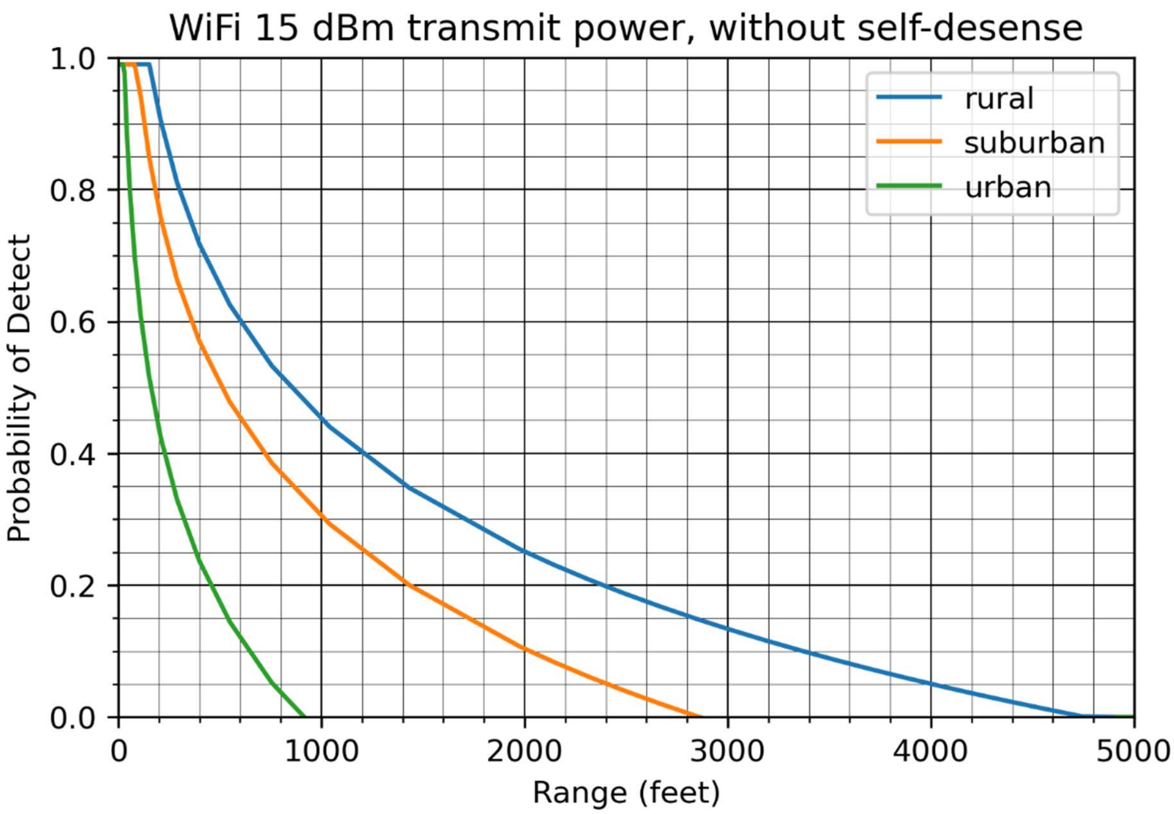


Figure 33. RID Sensor Model POD Chart – WiFi 15 dBm without Self-Desense.

2. POD With Self-Desense

The following two charts represent the expected probability of detection (POD) where the adverse effects of desense have **not** been mitigated. In other words, they represent what should be expected in the current – summer 2024 – operational environment. As described above in the preamble of this appendix, the urban POD curve is most likely too conservative.

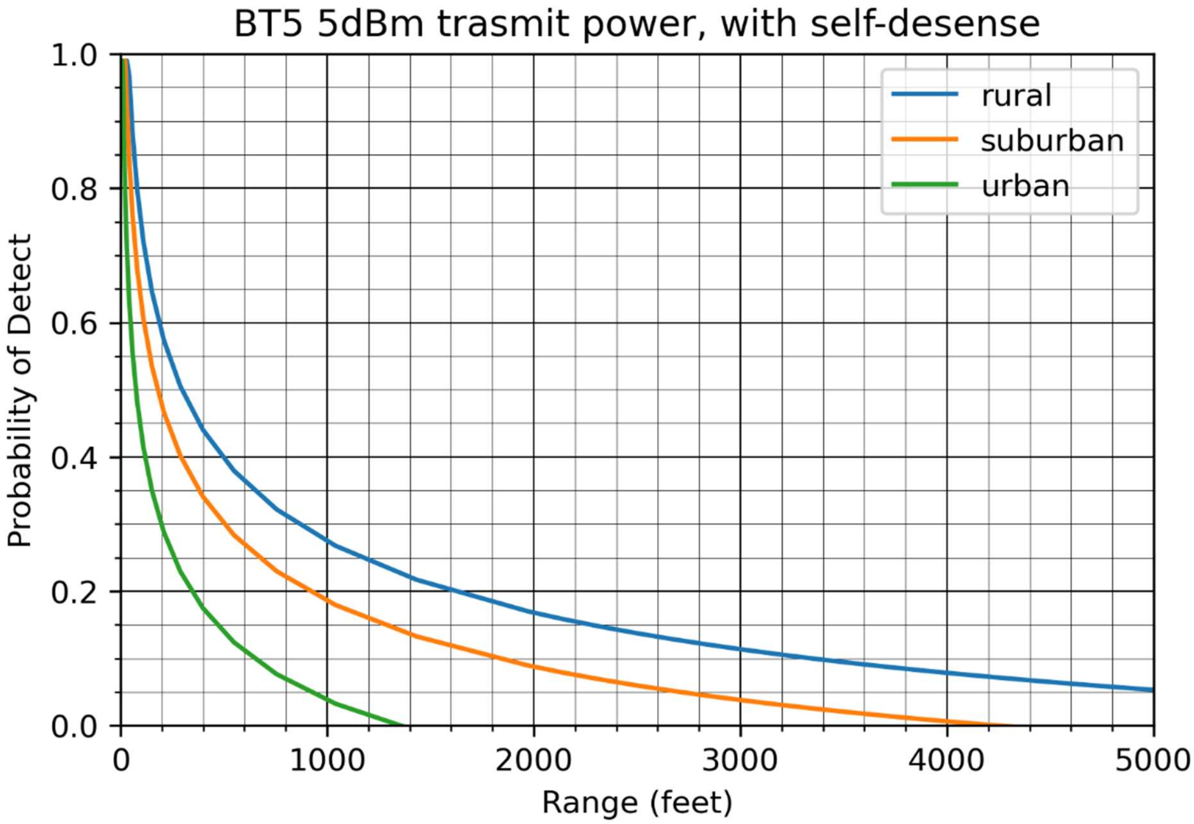


Figure 34. RID Sensor Model POD Chart – Bluetooth 5 (BT5) 5 dBm with Self-Desense.

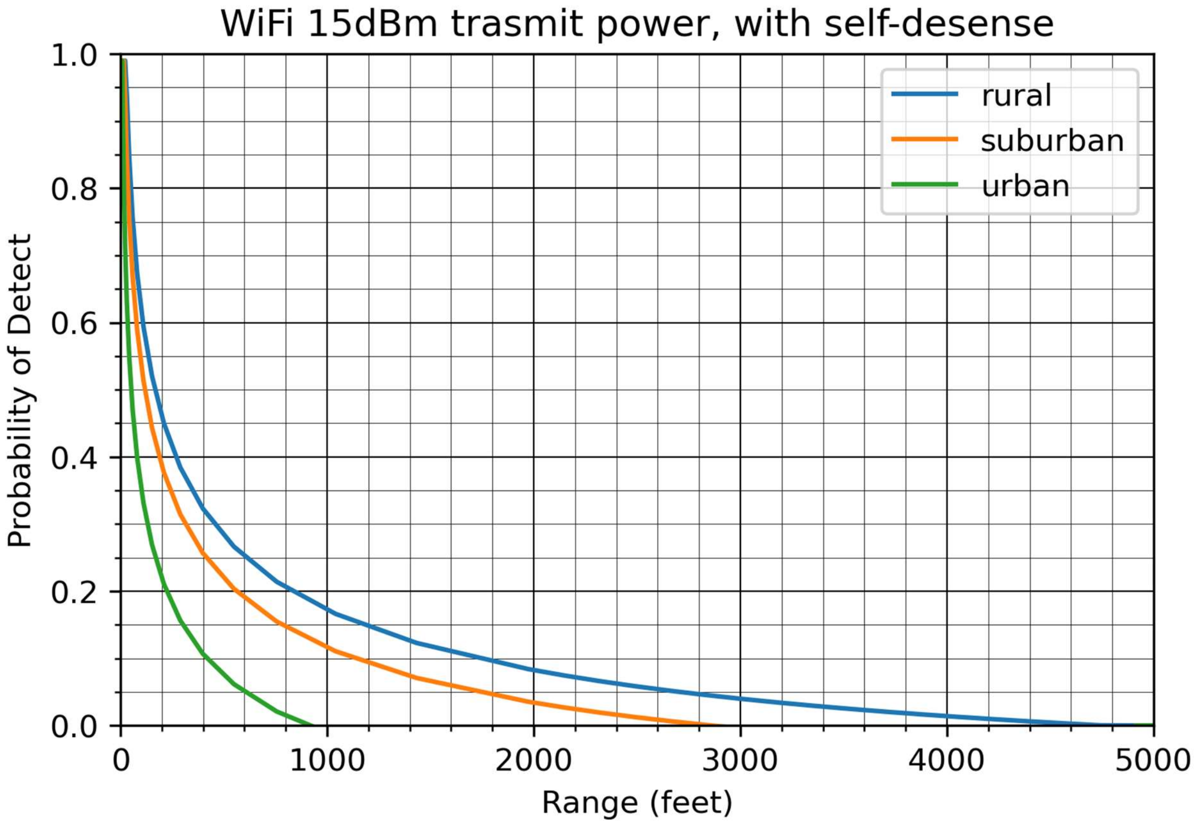


Figure 35. RID Sensor Model POD Chart – WiFi 15 dBm with Self-Desense.

3. POD With Self-Desense and Increased Transmit Power

The following two charts represent the expected probability of detection (POD) where the adverse effects of desense have **not** been mitigated but where the transmit power has been increased to just below the FCC 47 CFR Part 15C limits. In other words, they represent what should be expected in the current – summer 2024 – operational environment with the RID transmit power tweaked to the maximum legal level. As described above in the preamble of this appendix, the urban POD curve is most likely too conservative.

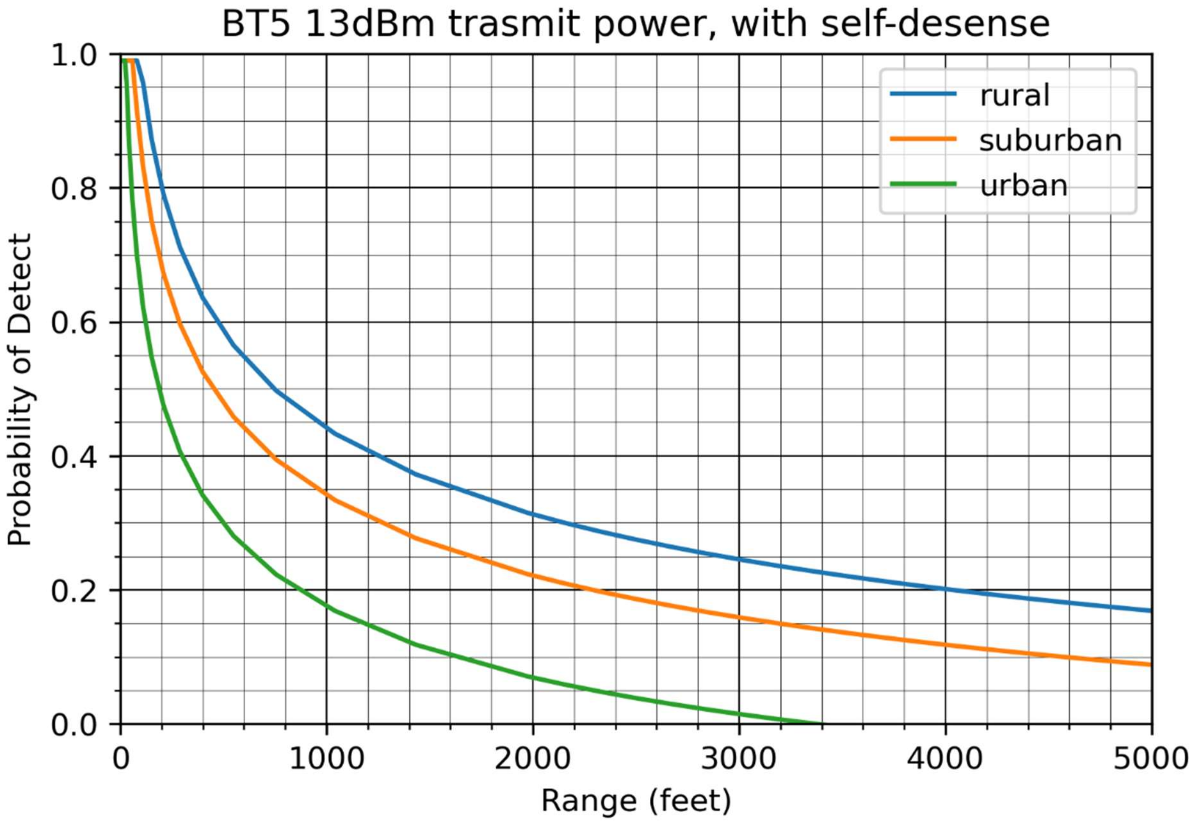


Figure 36. RID Sensor Model POD Chart – Bluetooth 5 (BT5) 13 dBm with Self-Desense.

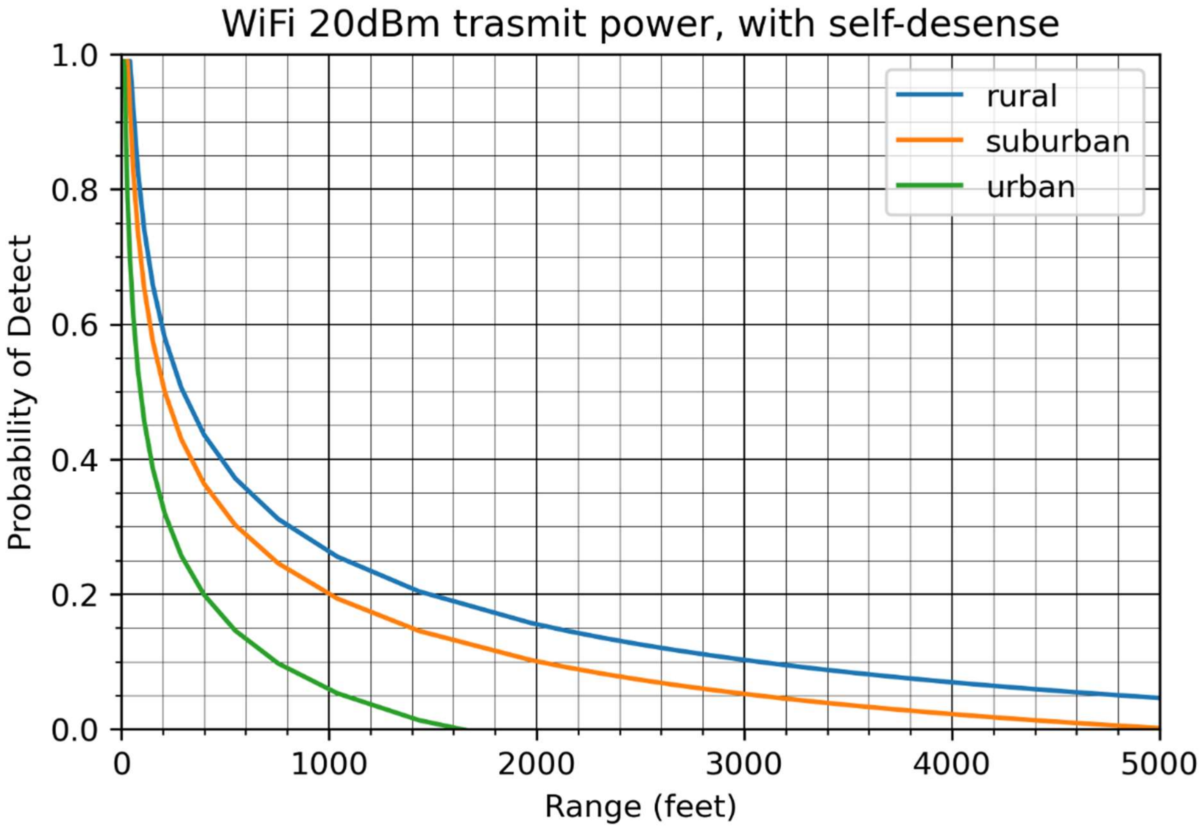


Figure 37. RID Sensor Model POD Chart - WiFi 20 dBm with Self-Desense.

4. POD With HereLink C2 Interference

The following chart is a special case to convey the expected performance when ownship is using a HereLink C2 system and trying to receive Wifi RID broadcasts. (Reception of BT broadcasts is relatively unimpacted by the HereLink C2 system.)

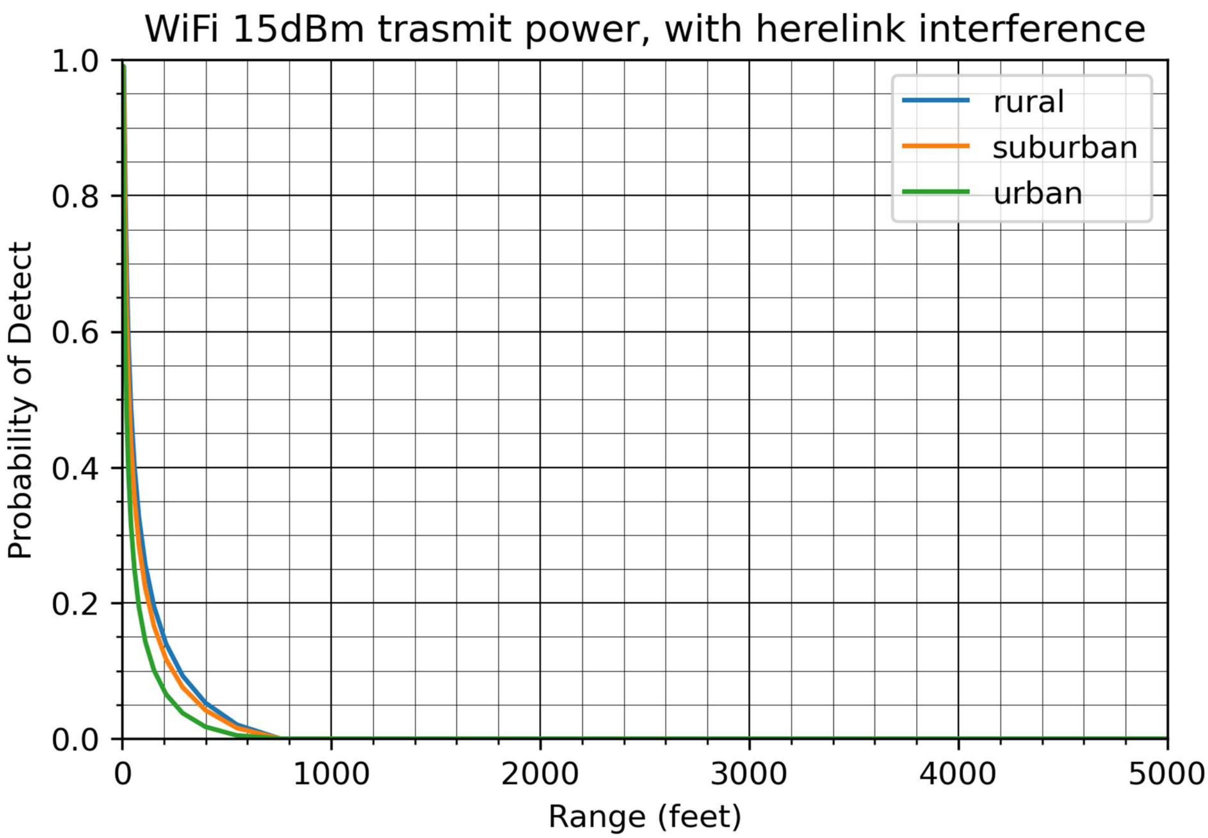


Figure 38. RID Sensor Model POD Chart - WiFi 15 dBm with HereLink Interference.

Funding Sources

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Acknowledgments

The team would like to acknowledge the contributions of Cesar Munoz, Principal Research Computer Scientist in the Safety Critical Avionics Systems Branch at the NASA Langley Research Center. Mr. Munoz is the primary research scientist responsible for the Detect and Avoid Alerting Logic for Unmanned Systems (DAIDALUS), a reference implementation of the DO-365 DAA logic that the team leveraged in its high-fidelity encounter simulation. Mr. Munoz proved to be an invaluable resource for expert advice on the application of DAIDALUS as well as for general DAA encounter simulation theory.

References

[1]

"14 CFR 89.310 -- Minimum performance requirements for standard remote identification unmanned aircraft." Accessed: Jul. 30, 2024. [Online]. Available: https://www.ecfr.gov/current/title-14/part-89/section-89.310

[2]

"14 CFR Part 89 Subpart D -- Requirements for Standard Remote Identification Unmanned Aircraft and Remote Identification Broadcast Modules." Accessed: Oct. 12, 2023. [Online]. Available: https://www.ecfr.gov/current/title-14/part-89/subpart-D

[3]

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