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Sense and Avoid Characterization of the ICAROUS Architecture

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Abstract

Independent Configurable Architecture for Reliable Operations of Unmanned Systems (ICAROUS) is a distributed software architecture developed by NASA Langley Research Center to enable safe autonomous UAS operations. ICAROUS consists of a collection of formally verified core algorithms for path planning, traffic avoidance, geofence handling, and decision making that interface with an autopilot system through a publisher-subscriber middleware. The ICAROUS Sense and Avoid Characterization (ISAAC) test was designed to evaluate the performance of the onboard Sense and Avoid (SAA) capability to detect potential conflicts with other aircraft and autonomously maneuver to avoid collisions, while remaining within the airspace boundaries of the mission. The ISAAC tests evaluated the impact of separation distances and alerting times on SAA performance. A preliminary analysis of the effects of each parameter on key measures of performance is conducted, informing the choice of appropriate parameter values for different small Unmanned Aircraft Systems (sUAS) applications. Furthermore, low-power Automatic Dependent Surveillance – Broadcast (ADS-B) is evaluated for potential use to enable autonomous sUAS-to-sUAS deconflictions as well as to provide usable warnings for manned aircraft without saturating the frequency spectrum.

Acronyms

ACAS-X	Advanced Collision Avoidance System
ADS-B	Automatic Dependent Surveillance - Broadcast
ATM	Air Traffic Management
cFS	Core Flight Systems
CPA	Closest Point of Approach
DAA	Detect and Avoid
DAIDALUS	Detect and Avoid Alerting Logic for Unmanned Systems
DTHR	Distance Threshold
FAA	Federal Aviation Administration
ISAAC	ICAROUS Sense and Avoid Characterization
MFD	Multi-function Display
MOPS	Minimum Operation Performance Standards
GA	General Aviation
GPS	Global Positioning System
HMD	Horizontal Miss Distance
ICAROUS	Independent Configurable Architecture for Reliable Operations of Unmanned Systems
PVS	Prototype Verification System
RF	Radio Frequency
SAA	Sense and Avoid
SARP	Sense and Avoid Science and Research Panel
SITL	Software in the Loop
sUAS	Small Unmanned Aircraft System
TAUMOD	Modified Tau Threshold used in TCAS alerting logic
TCAS	Traffic Collision Avoidance System
TCL	Technology Capability Level
TCPA	Time to Closest Point of Approach
TTHR	Time Threshold
UAS	Unmanned Aircraft System
UAT	Universal Access Transceiver
UAV	Unmanned Aerial Vehicle
UTM	Unmanned Aircraft Systems (UAS) Traffic Management System
WCV	Well Clear Volume

1 Introduction

Commercial applications of unmanned aircraft operating at low altitudes are likely to increase in the near future presenting both business incentives as well as huge airspace integration challenges. The full range of these low-altitude Unmanned Aircraft Systems (UAS) operations will likely include [1] "…those that are fully contained in uncontrolled airspace, to those that require transit across the boundary between controlled and uncontrolled airspace, and finally to those that originate and operate within controlled airspace …" As a result, scenarios in which UAS will operate in close proximity to each other or with other users of the airspace will be increasingly common, such as in the vicinity of terminal area.

Consequently, the ability of small UAS vehicles to sense traffic aircraft in the airspace and maintain a safe separation distance from other vehicles is a fundamental requirement for the integration of UAS into the National Airspace System. Research on sense and avoid (SAA) (also referred to as detect and avoid or DAA) for small UAS has focused mostly on development of separation assurance algorithms. Published research provides very little or no validation of these systems in a real-life setting. Furthermore, available sense and avoid algorithms for small UAS are often designed to provide traffic awareness to remote pilots to maintain well-clear, but do not consider the post-conflict maneuvers required to guide the vehicle back to the original path.

This paper details the results of the ISAAC (ICAROUS Sense and Avoid Characterization) tests. Tests include both simulations and flight tests conducted to evaluate and validate the sense and avoid capability of the Independent Configurable Architecture for Reliable Operations of Unmanned Systems (ICAROUS). ICAROUS was designed as a distributed publish-subscribe software architecture to enable the easy integration of mission-specific functionality and/or sensor technologies. Presently, ICAROUS runs onboard the vehicle on a companion computer but future instantiations of ICAROUS could be directly integrated with lower-level autopilot functions. Simulation testing enabled performance evaluation against a wide variety of well-clear parameters, initial conditions, and encounter geometries. Flight testing was used to validate simulation results and demonstrate ICAROUS as a practical, usable system for real world UAS applications. Flight tests were conducted against an unmanned fixed wing intruder aircraft to validate scenarios involving low closure rate encounters with other unmanned aircraft vehicles. A manned general aviation (GA) aircraft was used to validate the sense and avoid capability in a high closure rate scenario representative of encounters between UAS and GA aircraft in a terminal area setting.

An additional goal of this effort was to evaluate the efficacy of a representative Automatic Dependent Surveillance-Broadcast (ADS-B) receiver for sUAS to receive position reports for ICAROUS SAA as a source of cooperative traffic surveillance. A secondary goal of these tests was to investigate the use of ADS-B for UAS. There is concern that as ADS-B becomes a widespread method for SAA in UAS, total ADS-B transmissions will increase significantly, causing frequency congestion and negatively impact existing air traffic management (ATM) operations that use ADS-B.

One possible solution to minimize frequency congestion would be to use low-power ADS-B output on sUAS. To be a viable approach, ADS-B output power must be significantly reduced while maintaining the range and reception quality needed for small UAS operations in addition to providing useful warnings to manned aircraft. If the use of ADS-B does not provide useful alerts to manned aircraft, then there would be no justification for its use for UAS. Multiple levels of attenuated ADS-B output were tested during this effort with both UAS-to-sUAS as well as sUAS-to-manned aircraft to evaluate low power ADS-B as a solution to this problem.

This paper is organized as follows. Section 2 provides an overview of existing research related to sense and avoid. Section 3 provides background on the ICAROUS architecture and the Detect and Avoid Alerting Logic for Unmanned Systems (DAIDALUS) which is used by ICAROUS. This section also includes details on how ICAROUS performs avoidance and return to path maneuvers. Sections 4**Error! Reference source not found.** and 5 discuss methods used for simulation and testing of ICAROUS. Section 6 provides a detailed analysis of ICAROUS' performance with varied input parameters, and Section 7 provides analysis of the low power ADS-B used during testing. Finally, sections 8 and 9 provide a discussion of observed results, future work, and conclusions.

2 Related Work

Collision avoidance for manned aircraft has been an area of intense research since the advent of the Traffic Alert and Collision Avoidance System (TCAS). The TCAS system was developed to provide pilots with adequate information to make decisions regarding evasive maneuvers to mitigate risk due to an intruder in the airspace [2]. The TCAS system has seen several iterations and continues to be the backbone of collision avoidance in the civil commercial aviation community. Using transponders, TCAS I provides warnings (traffic advisories) of nearby intruders in the airspace. The TCAS II system also provides resolution advisories to the pilot in addition to the traffic advisories. In case of a resolution advisory, the pilot has the final authority and is required to implement these resolutions.

The Advanced Collision Avoidance System (ACAS-X), the next generation of collision avoidance algorithms was introduced in [3] with a view of replacing TCAS. Unlike TCAS, ACAS-X uses a model-based decision-theoretic framework where traffic resolutions and advisories are optimized using a reward function taking into account the encounter dynamics. However, the use of a decision-theoretic framework introduces multi-dimensional lookup tables thus making verification and validation a challenging task. Verification and validation of ACAS-X resolutions is an ongoing research activity [4].

Unlike manned aircraft operating at high altitudes, small UAS have different mission dependent performance constraints. Consequently, a straightforward translation of the collision avoidance algorithms used for manned aircraft may not be applicable. Collision avoidance algorithms for small UAS need to be cognizant of various constraints such as geofences and obstacles in low altitude airspace or an urban airspace environment. Integration of detect and avoid capability with path planning capability was discussed in [5].

For UAS, the final report of the Federal Aviation Administration (FAA) Sense and Avoid (SAA) Workshop [6] defines the concept of sense and avoid as "the capability of a UAS to remain well-clear from and avoid collisions with other airborne traffic." Based on this definition, the UAS Sense and Avoid Science and Research Panel (SARP) made a recommendation for a quantitative definition of UAS Well Clear that uses distance and time functions similar to those used in the TCAS II resolution advisory logic [7]. For large, remotely piloted UAS, the RTCA Special Committee 228 (SC-228) has developed minimum operational requirements for detect and avoid that uses SARP's well-clear definition [8]. DAIDALUS [9] is a NASA developed software library that serves as a reference implementation of the detect and avoid concept provided by the RTCA SC-228 MOPS. SARP recommendations are more suitable for large UAS operating around small UAS. These requirements are not practical for small Unmanned Aerial Vehicles (UAVs) operating in low altitude airspace.

Several researchers have investigated the sensing aspects of collision avoidance for small UAS. Surveillance performance of sensors required to perform SAA in small UAS with emphasis on risk was considered in [10]. That work provides a mapping between surveillance performance and collision risk. An analysis of the usage of radars for sense and avoid was provided in [11]. The use of ground-based radars to perform sense and avoid in a local area was investigated in [12]. Dolph et al. [13] used cameras to visually detect intruders in the vicinity. Acoustic sensors for intruder detection have also been used in [14]. Experimental evaluation of a rudimentary sense and avoid algorithm was conducted in [15]. A survey of various sense and avoid algorithms for small UAS can be found in [16].

3 Background

3.1 ICAROUS

ICAROUS is an architecture that integrates a collection of core algorithms for path planning, geofence handling, traffic avoidance, and decision-making capabilities to enable autonomous operation of UAS [17, 18]. ICAROUS was designed to run on a companion computer while consuming data from an autopilot system. It monitors the autopilot system, mission performance, and other mission and safety constraints. ICAROUS assumes control of the vehicle when a constraint violation is imminent and autonomously implements resolution maneuvers to prevent conflicts and mitigate risk.

Figure 1 provides an overview of the ICAROUS architecture, which uses NASA's core Flight Systems (cFS) middleware to coordinate communication between a suite of applications. Each app provides a different functionality, such as sending commands to an autopilot or implementing algorithms for geofence containment. New apps for new autonomous functionalities can be added to the system and share data with existing apps through cFS.

These flight tests focus specifically on the traffic avoidance app. This app relies on DAIDALUS to compute avoidance maneuvers based on available traffic surveillance data. ICAROUS selects a valid maneuver from DAIDALUS output and sends commands to the autopilot to implement the maneuver.

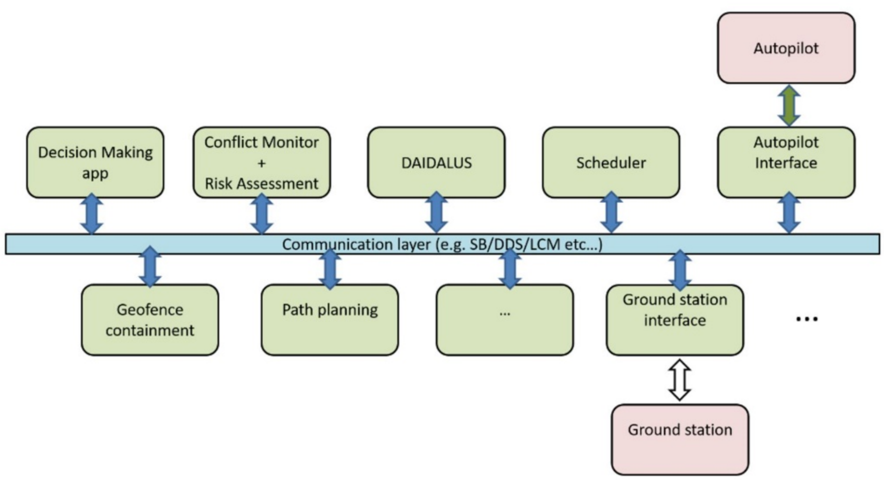

Figure 1 - ICAROUS architecture

3.2 DAIDALUS

DAIDALUS [9] provides the detect and avoid algorithms used by ICAROUS to compute valid traffic avoidance maneuvers. DAIDALUS is a software library that serves as the reference implementation of the detect and avoid (DAA) concept described in the RTCA DO-365 Minimum Operational Performance Standards for Unmanned Aircraft Systems. DAIDALUS source code is available in both C++ and Java under NASA's Open Source Agreement. The DAIDALUS software library consists of algorithms that predict well-clear violations between the ownship and traffic aircraft and provide maneuver guidance in the form of ranges of maneuvers (bands) for the ownship to follow in order to maintain or regain well-clear status with respect to traffic aircraft. These algorithms have been formally verified for logical correctness in the Prototype Verification System (PVS) [19].

Figure 2 illustrates DAIDALUS functionality on a notional encounter. The solid area represents the well-clear volume that the aircraft needs to avoid. This volume is defined by time and distance threshold parameters and is generated assuming ownship performance limits. In this notional encounter, the current ownship trajectory is not predicted to be in conflict, but if the ownship maneuvers to the right in the range of maneuvers denoted by γ, the aircraft will eventually lose well-clear. The range of maneuvers denoted by γ is called a conflict band.

A typical progression of conflict bands is illustrated in figure 3. In the figure, the well-clear volume (WCV) is the volume around the ownship that must be kept clear of traffic vehicles. For the ISAAC flight tests, this volume is defined by a well-clear radius. When a traffic vehicle enters the self-separation threshold (SST), the ownship begins performing DAA. For the ISAAC flight tests, this volume is defined by the alerting time and modified tau threshold parameters (see Section 3.3).

At time t_0, the aircraft are beyond SST limits and therefore no bands are computed. At time t_1, the aircraft are within SST limits and a peripheral conflict band is computed for the ownship. At time t_2, the intruder aircraft has maneuvered in the direction of the ownship and a conflict band appears in the current path of the ownship. At time t_3, the aircraft have lost well-clear. In this case, DAIDALUS computes recovery bands, which are represented by the dashed green range of maneuvers. Recovery bands enable the ownship to regain well-clear in a timely manner according to its performance limits.

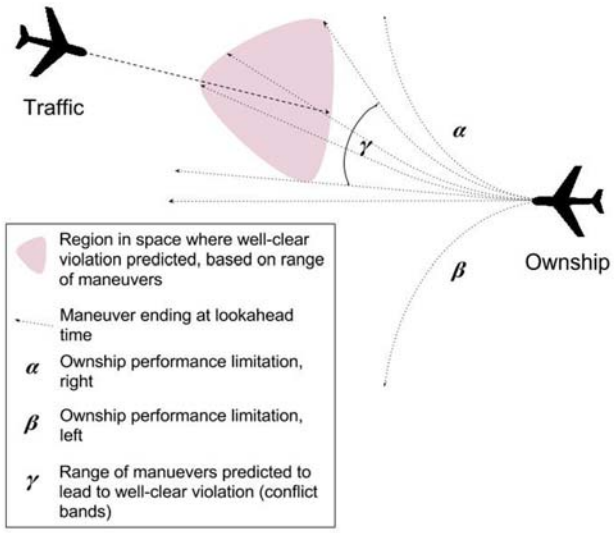

Figure 2 - Maneuver guidance

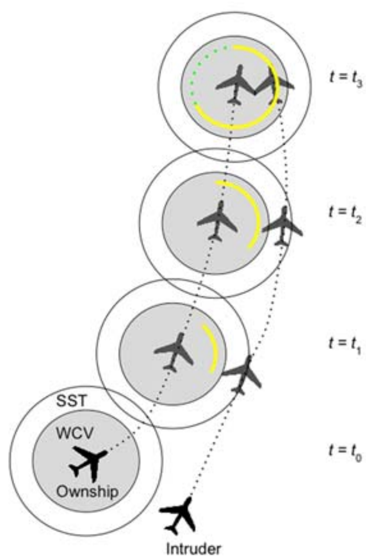

Figure 3 - Conflict progression

3.3 Well Clear Configuration

The DAIDALUS detect and avoid library is highly configurable and uses a list of parameters that govern its response to an intruder in the airspace. A list of all parameters used by DAIDALUS and detailed explanation of these parameters can be found in [9]. For the ISAAC tests, the effects of the following parameters were investigated:

- Alerting time – time before predicted well-clear violation to start avoidance maneuver

- Well-clear distance threshold (DTHR) – horizontal distance to be maintained between ownship and traffic aircraft
- Well-clear time threshold (TTHR) – This time threshold is related to the modified tau (TAUMOD) threshold used in the TCAS [2] alerting logic and it provides an estimate to time of closest point of approach

The time when a resolution maneuver is computed depends both on the alerting time and the well-clear time threshold. The sum of these time thresholds approximates the time prior to closest point of approach when the resolution maneuver is computed. In the present work, these times are varied in such a way that their sum remains constant. This way, tradeoffs between using the two parameters can be observed.

DAIDALUS computes many types of avoidance maneuvers, including changes to ownship ground track, speed, or altitude. This work evaluates only lateral resolutions provided by DAIDALUS. These lateral resolutions are in the form of track guidance and require the ownship to change its ground track, but not its altitude. Given the position and velocity of intruder aircraft in the airspace, DAIDALUS computes and outputs a range of track angles that could result in well-clear violation. These outputs are a function of the initial parameter set used to configure DAIDALUS.

3.4 Post Resolution Maneuvers to Return to Path

After commanding an avoidance maneuver, ICAROUS commands a maneuver to safely return to the original flight plan. Prior work on sense and avoid for manned aircraft have focused mostly on the avoidance maneuvers themselves. The pilot was responsible for returning to the original flight plan once clear of conflict. For small UAS however, this decision making has to be done onboard autonomously. When a conflict occurs, ICAROUS selects an avoidance maneuver from the guidance maneuver ranges computed by DAIDALUS and autonomously commands the autopilot to execute it. ICAROUS also constantly checks to see if the turn to intercept the original flight plan would cross a conflict track heading. ICAROUS initiates the return to path maneuver only when the vehicle is clear of a well-clear conflict and when returning to the original mission no longer results in loss of separation.

Return to path can be implemented in multiple ways depending on the mission. The vehicle could return to the next waypoint in the current flight plan or, alternately, it could return to the point on the flight plan where it initially deviated to avoid loss of separation. For this work, return to path is treated as returning to the next waypoint in the current flight plan.

3.5 Sensors for SAA in Small UAS

The limited payload carrying capability of small UAS poses significant restrictions on the type of onboard traffic surveillance sensors that can be used for SAA. Currently available off-the-shelf sensors suitable for SAA applications on small UAS include vehicle-to-vehicle communication devices and ADS-B for cooperative traffic, and airborne radars, LIDAR, vision-based sensors (cameras), and acoustic sensors for non-cooperative traffic. Ground based radars can also be used as a traffic surveillance source. Different sensor technologies have inherent capabilities and limitations as well as varying performance metrics and operational constraints. ICAROUS was designed to be sensor agnostic and configurable to adjust to different sensor performance and uncertainty ranges. Prior work conducted as part of the UTM Technology Capability Level 3 (TCL3) flight tests studied the suitability of vehicle to vehicle communication devices for sense and avoid [20].

This work specifically focuses on the usage of the pingRX ADS-B receiver (figure 4) manufactured by uAvionix [21] for providing intruder position data (UAS-UAS and GA-UAS). The pingRX is considered to be representative of the type of ADS-B receiver that could be used for sUAS applications. This receiver is very compact and weighs only 5 grams. The pingRX outputs received ADS-B information over a serial connection using the ADSB_VEHICLE message of the MAVLink protocol [22**Error! Reference source not found.Error! Reference source not found.**] containing information about aircraft call sign, ICAO address, GPS coordinates, altitude, and vehicle velocity. The use of the MAVLink protocol means the pingRX is easy to integrate with UAS flight controllers using MAVLink, such as the Pixhawk/Ardupilot [**Error! Reference source not found.**23].

Figure 4 - pingRX ADS-B receiver

The ISAAC tests rely on ADS-B technology to assess the performance of ICAROUS autonomous SAA capability since ADS-B performance and accuracy exceeds that of other sensor technologies. However, the use of ADS-B-based SAA for sUAS is usually not considered to be an acceptable solution since the increased volume of transmissions could overload and impair existing systems. M. Guterres et al. [24] found that the main factors that would impact ADS-B functionality are UAS fleet density and transmission power. To allow UAS fleet density to increase, reduced power ADS-B must be explored, or another frequency spectrum be allocated for UAS use. This work validates low power ADS-B for use in UAS applications as a potential solution to this problem

4 Simulation

The ArduPilot software in the loop (SITL) simulation tool [25] was used to study performance metrics of a large number of SAA configurations. The SITL integrates ICAROUS with a six degrees of freedom quad-rotor simulation model and an autopilot system through the MAVLink protocol. ICAROUS guidance commands are executed by the SITL simulator and relevant metrics are computed to characterize its performance. A wide range of SAA configurations were run, including well-clear distance thresholds ranging from 300 feet (91 m) to 2000 feet (610 m), and alerting time thresholds ranging from 0 to 25 seconds. In each simulation, the vehicles either approach each other head on, or at a 90-degree angle. Preliminary analysis of the results was used to guide and down select the SAA configurations used in the ISAAC flight test. Flight test results validate simulation tests and further characterize the performance of the algorithms with real sensor data, winds, and turbulence, amid various factors such as transmission latency, ADS-B packet dropouts and GPS errors.

5 Flight Tests

5.1 Flight Test Approach

The flight test was conducted in two phases. The first phase tested UAS-to-UAS encounters, where an ownship UAV running ICAROUS has to sense and avoid another UAV traffic vehicle flying a fixed route. The traffic aircraft for phase 1 was a Tempest UAV [26]. The second phase tested UAS-to-GA aircraft encounters, where the UAV traffic vehicle is replaced with a manned aircraft. The traffic aircraft for phase 2 was a Cirrus SR-22. Phase 1 examines low closure rate scenarios, while phase 2 looks at higher closure rates, similar to an airport terminal environment.

Tests were repeated using different well-clear volume definitions and timing parameters within ICAROUS. Scenarios included encounters with two different geometries, head-on and at 90-degree angle. All flight tests were conducted at the Beaver Dam Airpark located near Smithfield, VA, in the vicinity of multiple airports. As a result, ADS-B signals from multiple commercial planes were also present during testing.

Only lateral avoidance maneuvers are considered for this effort. Lateral maneuvers require the ownship to change heading, but not altitude, to maintain separation with the intruders. In both phases of flight testing, the intruders do not react to the ownship and continue on their respective flight plans. Additional maneuvers are being explored as part of ongoing work.

Flight safety requirements imposed several constraints on the encounter geometry whose impact warrants an explanation. Since both UAS had to be within visual-line-of-sight of the operators at all times, it was challenging to set up the test conditions with larger well clear distances and with encounters with high closure rate (as those involving a GA). Since in those cases the encounters start when the aircraft are in close proximity to the well-clear boundary, late detections are likely to occur. In those cases, the ownship may not have enough time to avoid the specified well-clear.

5.2 Test Aircraft

5.2.1 Ownship

A DJI S1000 octocopter with a PixHawk ArduPilot autopilot system is the ownship aircraft for these flight tests. An onboard Jetson TK1 companion computer hosts the ICAROUS architecture. The Jetson computer connects to the autopilot over the PixHawk's telem2 serial port. This setup is illustrated in figure 5. The S1000 is also equipped with a pingRX ADS-B in receiver (figure 6), which receives position data from traffic aircraft that are transmitting ADS-B out. The pingRX output connects to a serial port on the Pixhawk. The Pixhawk passes on received ADS-B messages to ICAROUS, along with data from the autopilot's GPS and IMU.

ICAROUS runs on the Jetson TK1 and monitors the sensor data it receives from the Pixhawk. When ICAROUS detects a potential loss of well-clear, it issues guidance commands to the autopilot via the MAVLink protocol. ICAROUS guides the ownship to deviate from its flight plan in order to avoid loss of well-clear.

The S1000 communicates with a Ground Control Station via RFD-900 radio and with a safety pilot via a Futaba transmitter. The pilot manually flies the vehicle to a starting position and controls the flight mode of the vehicle. When AUTO mode is set, the autopilot commands the S1000 to fly a set of programmed waypoints. Whenever ICAROUS issues guidance, the vehicle switches to GUIDED mode. In other modes, the pilot is in control of the vehicle. A research cutoff is installed between the Jetson and the Pixhawk so the safety pilot can take control of the vehicle during testing if necessary.

Data from testing is recorded in autopilot logs saved on the Pixhawk SD card, and in ICAROUS logs saved on the Jetson TK1. In addition, telemetry logs record all communication between the S1000 and the Ground Control Station.

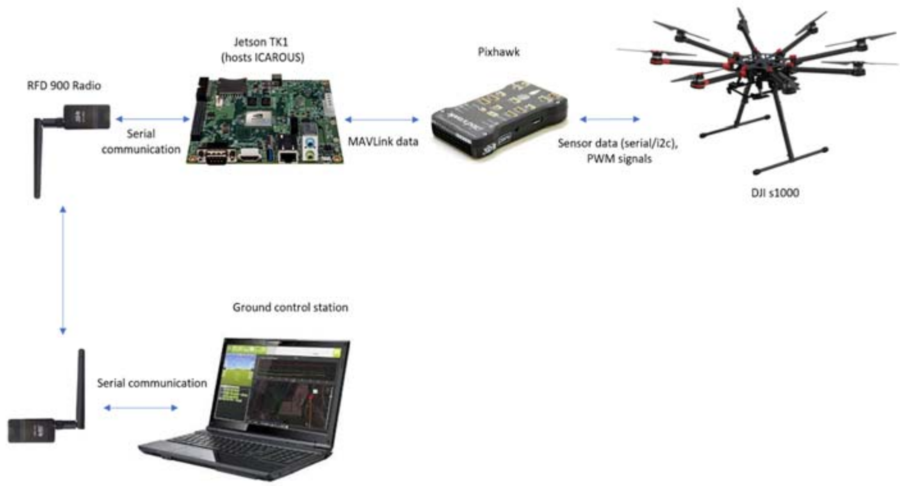

Figure 5 - Hardware setup

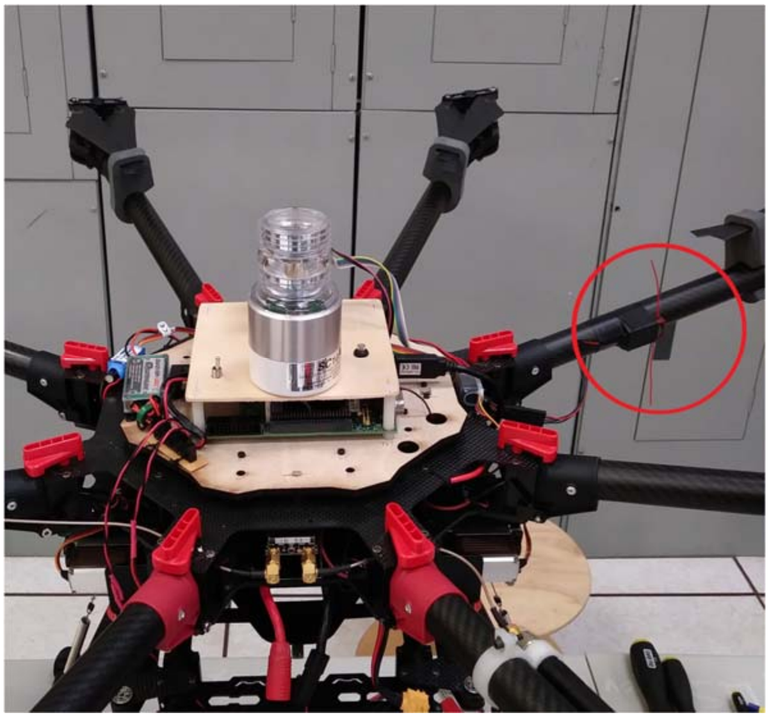

Figure 6 - pingRX ADS-B receiver unit (see figure 4) installed on DJI S1000

5.2.2 UAS Traffic Vehicle

The unmanned traffic vehicle for these tests is a Tempest, a fixed wing UAV with a span of 123 inches (figure 7). The Tempest uses a Pixhawk autopilot system and flies autonomously in all ISAAC tests.

A Bendix-King KGX-150 ADS-B transceiver (figure 8) is used to transmit ADS-B out, providing location data to the ownship. The configuration also includes an in-line attenuator that can be used to adjust the power of the ADS-B transmission (see Section 7**Error! Reference source not found.**).

Similar to the S1000 ownship, the Tempest communicates with a Ground Control Station and safety pilot. Flight data is recorded on the Pixhawk, and in telemetry logs from the Ground Control Station.

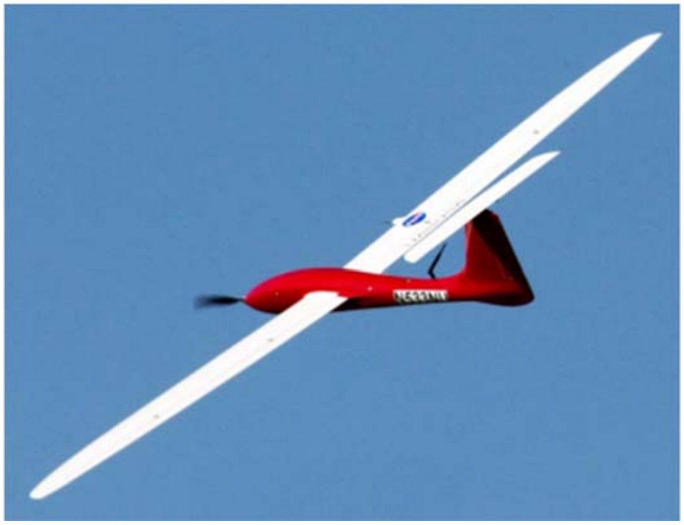

Figure 7 - Tempest UAV traffic vehicle

Figure 8 - Bendix King KGX-150 ADS-B unit provides ADS-B out on Tempest UAV traffic vehicle

5.2.3 Manned Traffic Vehicle

A Cirrus SR-22 serves as the manned traffic vehicle (figure 9). A Garmin GDL 90 Universal Access Transceiver (UAT) provides ADS-B in and out for the SR-22 (figure 10). The system has two antennae, one located on top of the aircraft, and one underneath. In addition to this system, a portable ADS-B transmitter was present on the SR-22 during testing. As a result, there were actually two ADS-B signals originating from the SR-22 during testing.

The SR-22's multi-function display (MFD) facilitated setting up the flight paths needed for the research encounters. During testing, researchers communicated with the SR-22 pilot using VHF radio. An ADS-B display also provided researchers with awareness of where in the flight plan the SR-22 was at any given time. Aircraft state and GPS position were recorded via the Baseline Research System.

Figure 9 - Cirrus SR-22, manned traffic vehicle

Figure 10 - Left: Garmin GDL 90 UAT. Right: UAT antenna mounted on bottom of Cirrus SR-22

5.3 Flight Test Setup for UAS Intruder (Phase 1)

Figure 11 illustrates the flight plans of the two aircraft for a head-on encounter. On the left (shown in blue) is the flight path of the fixed-wing intruder (Tempest) aircraft. On the right (shown in yellow) is the flight path of the ownship (DJI S1000) vehicle. Flight paths are chosen to maximize the likelihood of a predicted conflict between the two vehicles. In figure 11, a well-clear conflict should occur between the two vehicles during the southernmost leg of the flight plan since the vehicles are flying directly toward each other. Flight paths for a 90-degree encounter are shown in figure 12. These figures, and all figures in this report that depict flight paths, are oriented with North pointing up.

All flight paths are chosen so that the vehicles are 500 feet (152 m) apart at the closest point if no autonomous traffic deconfliction maneuvering is performed. This 500-foot boundary was established to separate the vehicles and mitigate risks of mid-air collisions. The two vehicles are set up to operate at roughly the same altitude.

The intruder aircraft maintains a constant speed of 20 m/s throughout all encounters. The ownship maintains a constant speed of 10 m/s. Thus, the relative closure rate between the two vehicles for the head-on encounters is 30 m/s (approximately 60 knots). This rate of closure is considered to be representative of nominal sUAS-to-sUAS encounters, but higher closure rates may be possible.

Once airborne, the Tempest intruder aircraft is flown up to its cruising altitude and its autopilot is engaged so that it continues to fly the programmed rectangular pattern. After the Tempest is established on its flight plan, the octocopter is launched and manually flown to waypoint X_1. Once at waypoint X_1, the octocopter loiters until the encounter can be initiated.

The encounter is initiated by engaging the Pixhawk autopilot, triggering it to fly the programmed flight plan. This should be done when the traffic vehicle is somewhere near waypoint Y_1 to ensure that a predicted conflict occurs between the two aircraft. An encounter initiated too soon can result in the octocopter completing the flight leg between waypoints X_1 and X_2 before observing a well-clear conflict. Similarly, an encounter initiated too late can result in the intruder completing its leg ahead of the ownship or the traffic deconfliction maneuver being initiated prior to reaching steady-state cruise conditions. An encounter initiated at the right timing resulted in the two vehicles approaching each other head on, leading to a well-clear conflict. Several trials were done to establish the timing to produce a well-clear conflict. The distance of the intruder from waypoint Y_1 can be used to time encounters consistently. The exact timing depends on the well-clear radius, alerting time of the detect and avoid configurations used by ICAROUS, and prevailing winds and needs to be adjusted throughout testing.

Figure 13 shows an example of detect and avoid response from a head-on encounter. The octocopter's autopilot is engaged at point t_1. The corresponding position of the intruder at this point is indicated by t_1 on the intruder's flight path. Once the ownship's autopilot is engaged, it starts accelerating towards its next waypoint, X_2. At point t_2 a well-clear conflict is predicted and ICAROUS assumes control of the ownship's autopilot. ICAROUS issues guidance commands to direct the ownship away from the well-clear conflict. ICAROUS continues this heading guidance until it is safe to return to the mission. The computation of the return to path maneuver is discussed in Section 6.3**Error! Reference source not found.**. At point t_3, the ownship is safe to return to the original mission and ICAROUS starts guiding the aircraft towards the next waypoint, X_2.

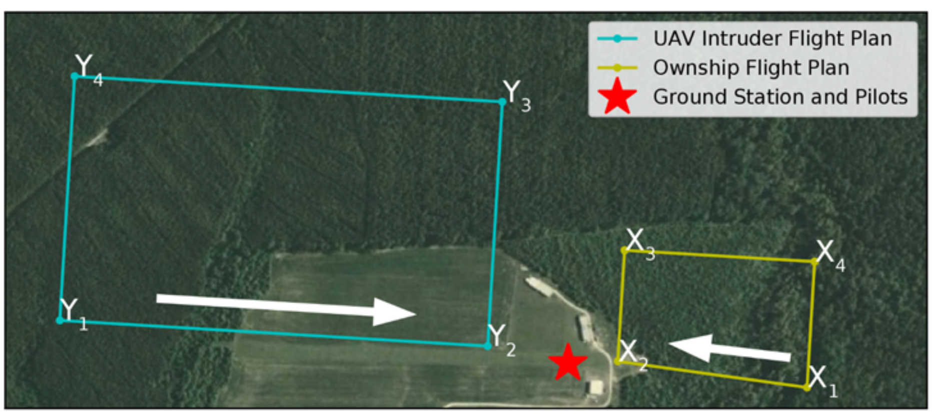

Figure 11 - Head-on encounter flight plan

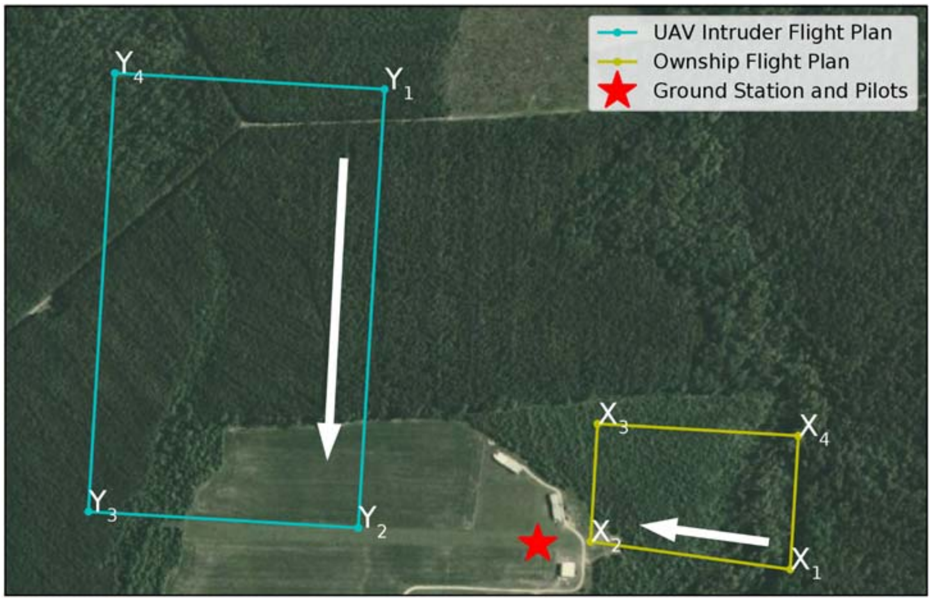

Figure 12 - 90-degree encounter flight plan

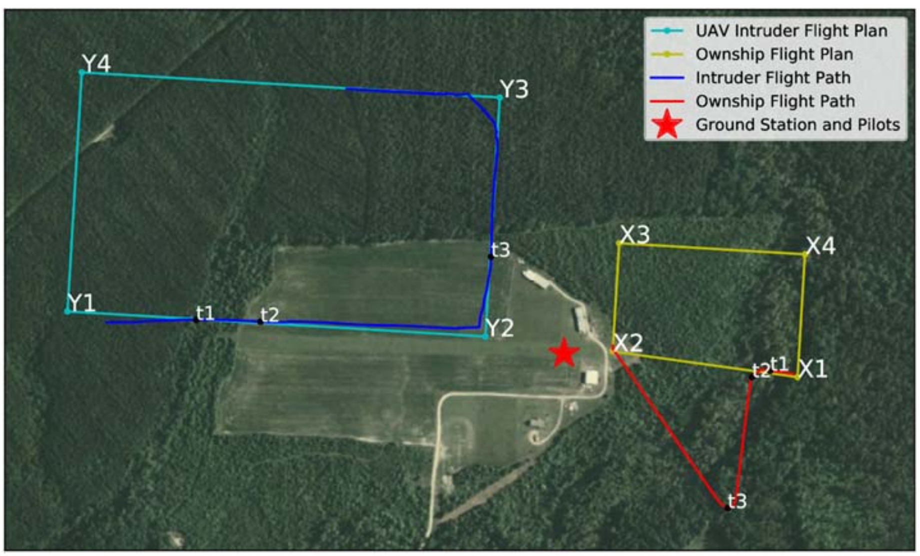

Figure 13 - Example encounter

5.4 Flight Test Setup for Manned Intruder (Phase 2)

The flight paths for the manned aircraft are shown in figure 14. For tests involving a well-clear radius of 2000 feet (610 m), the flight path of the GA aircraft is offset by 1000 feet (305 m). This is mainly to restrict the deviations of the UAS to be within 1000 feet (305 m) in the pilot's line of sight. In these tests, the GA aircraft maintains a constant airspeed of 100 knots (51 m/s). The ownship maintains a constant speed of 10 m/s. This setup results in a relative closure rate of 60 m/s in head-on encounters. Timing for encounter initiation is similar to the flight tests with a UAV intruder. Following the GA plane position on an ADS-B monitor helps to get the timing right.

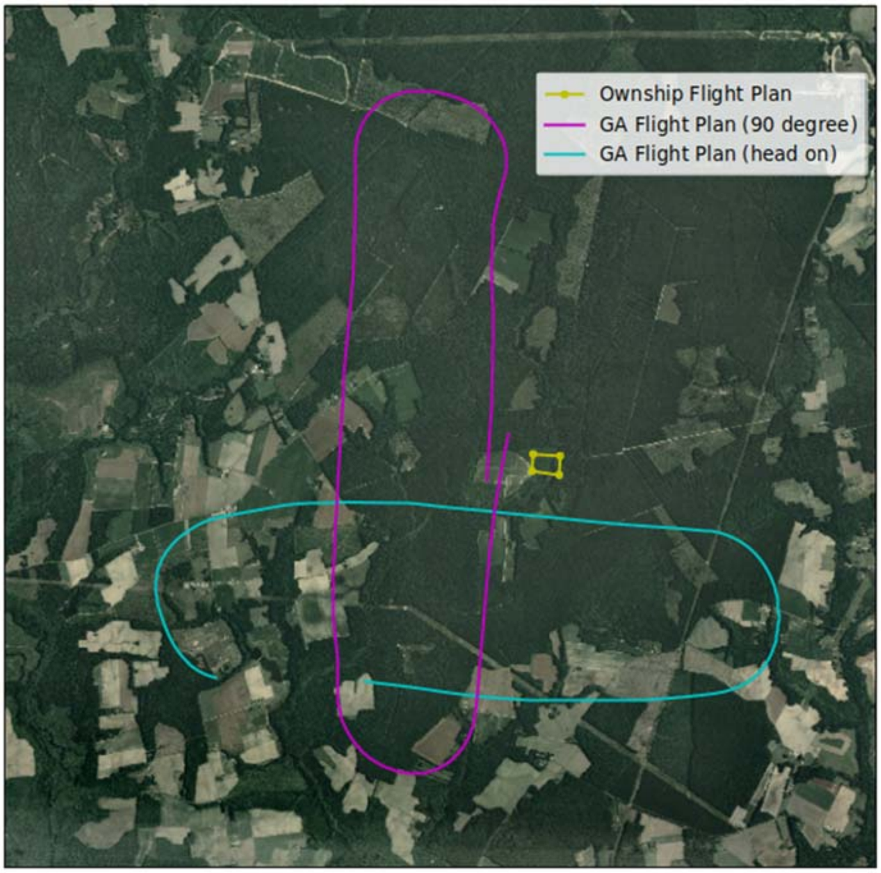

Figure 14 - Flight plans for manned intruder

5.5 Tests with Geofences

Flight tests also included scenarios with a simple keep-out geofence added either to the north or south of the ownship's flight plan to force deviations in specific directions. An example geofence is shown in figure 15. These geofences can be static, i.e., known before flight, or dynamic, i.e., provided during flight (also referred to as "dynamic restrictions"). In this setup, the ownship is expected to deviate away from the geofence while executing a traffic avoidance maneuver. These additional conditions were included to demonstrate ICAROUS integrated SAA and geofence containment capabilities.

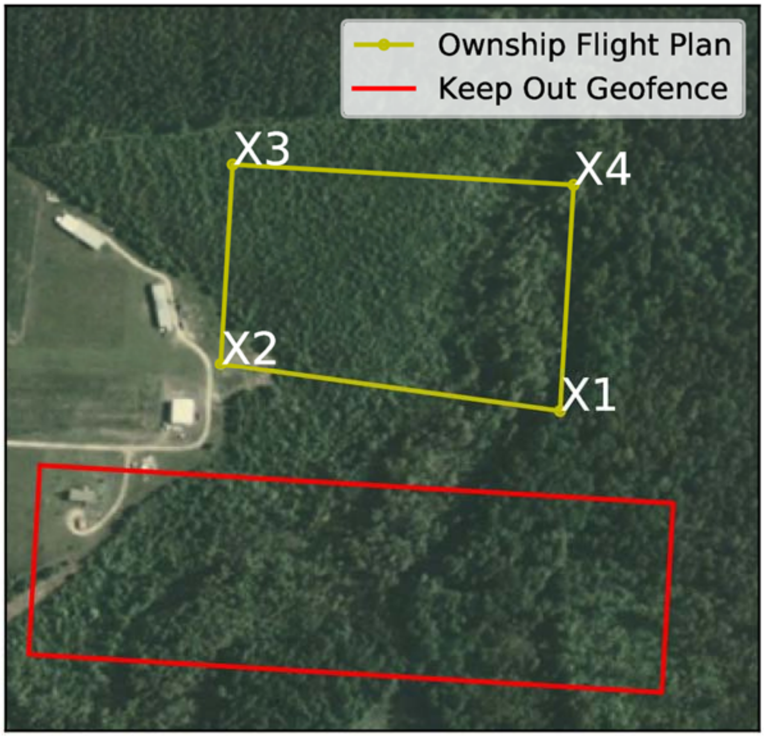

Figure 15 - Example geofence

5.6 Test Conditions

The ISAAC test conditions were designed to evaluate the impact of different well-clear volumes and alerting times used by the core avoidance logic. Table 1 enumerates the test conditions for both the UAS-UAS and UAS-GA encounters.

Each condition is repeated several times (runs) for different well-clear configurations. As explained earlier, the encounter geometries were constrained by the flight safety requirements as well as the test site limits. Hence, only 1000 feet (305 m) and 2000 feet (610 m) of horizontal separation were tested. Also, at most 20 seconds of total alerting time + TTHR time were tested. The choice of alerting time (i.e., time at which maneuver guidance is first computed prior to well-clear violation) and TTHR (i.e., well-clear time threshold based on aircraft closure rate) values was informed by simulation results.

Table 1 - Test Matrix

Intruder type	DTHR (ft)	Alerting time (s)	TTHR (s)	Encounter type	Number of Runs
UAS	1000	20	0	Head on	9
UAS	1000	10	10	Head on	2
UAS	1000	0	20	90 deg	3
UAS	2000	10	10	Head on	2
UAS	2000	10	10	90 deg	5
GA	1000	20	0	Head on	3
GA	1000	20	0	90 deg	2
GA	1000	10	10	Head on	2
GA	1000	10	10	90 deg	4
GA	2000	20	0	Head on	2
GA	2000	20	0	90 deg	3
GA	2000	10	10	Head on	3
GA	2000	10	10	90 deg	3
GA	2000	0	20	Head on	3
GA	2000	0	20	90 deg	3

6 Results

Figures 16 and 17 summarize the impact of alerting time, well-clear radius, and time threshold on the horizontal miss distance at the closest point of approach during the different encounters. Each point on the plot represents one encounter between the ownship and the traffic vehicle. The color and shape of each point indicates whether the encounter was 90 degrees or head on, and whether the traffic vehicle was a UAV or GA aircraft. In the graphs, a horizontal miss distance smaller than the horizontal well-clear radius indicates a loss of separation, while a separation distance greater than the well-clear radius indicates a successful avoidance maneuver.

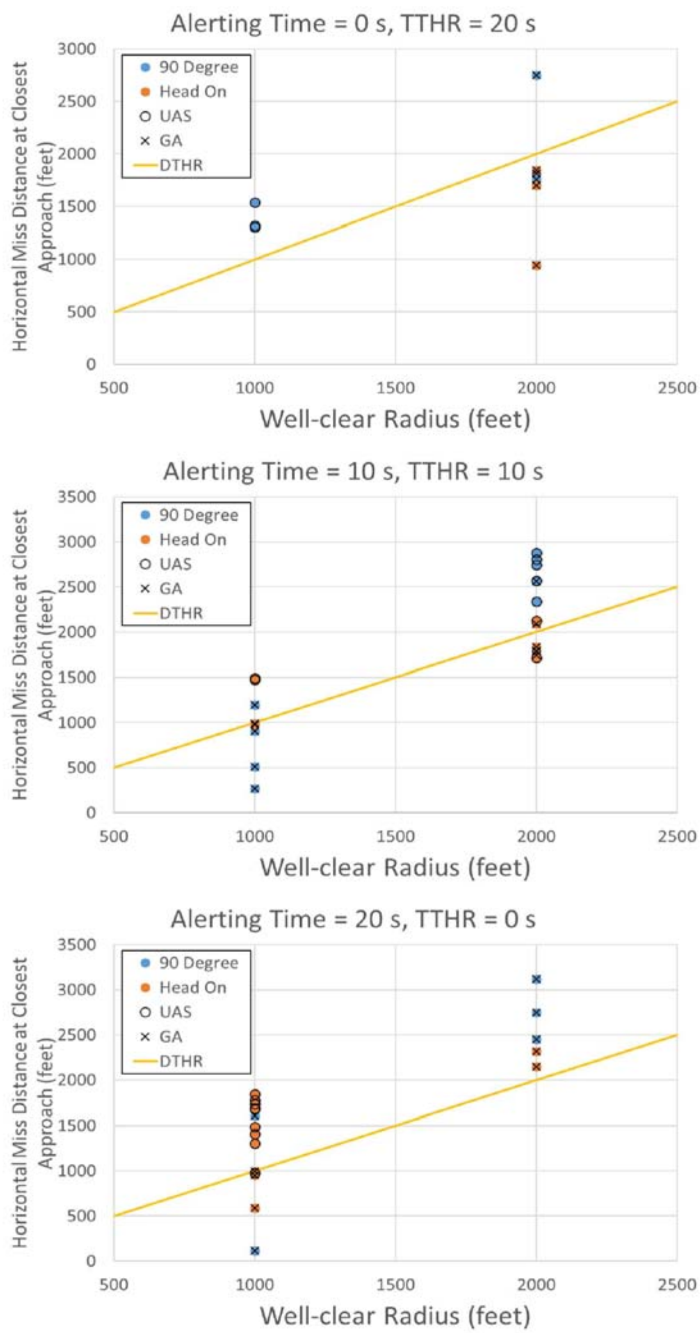

Figure 16 - Horizontal Miss Distance (SAA.6.12) versus alerting time and time threshold

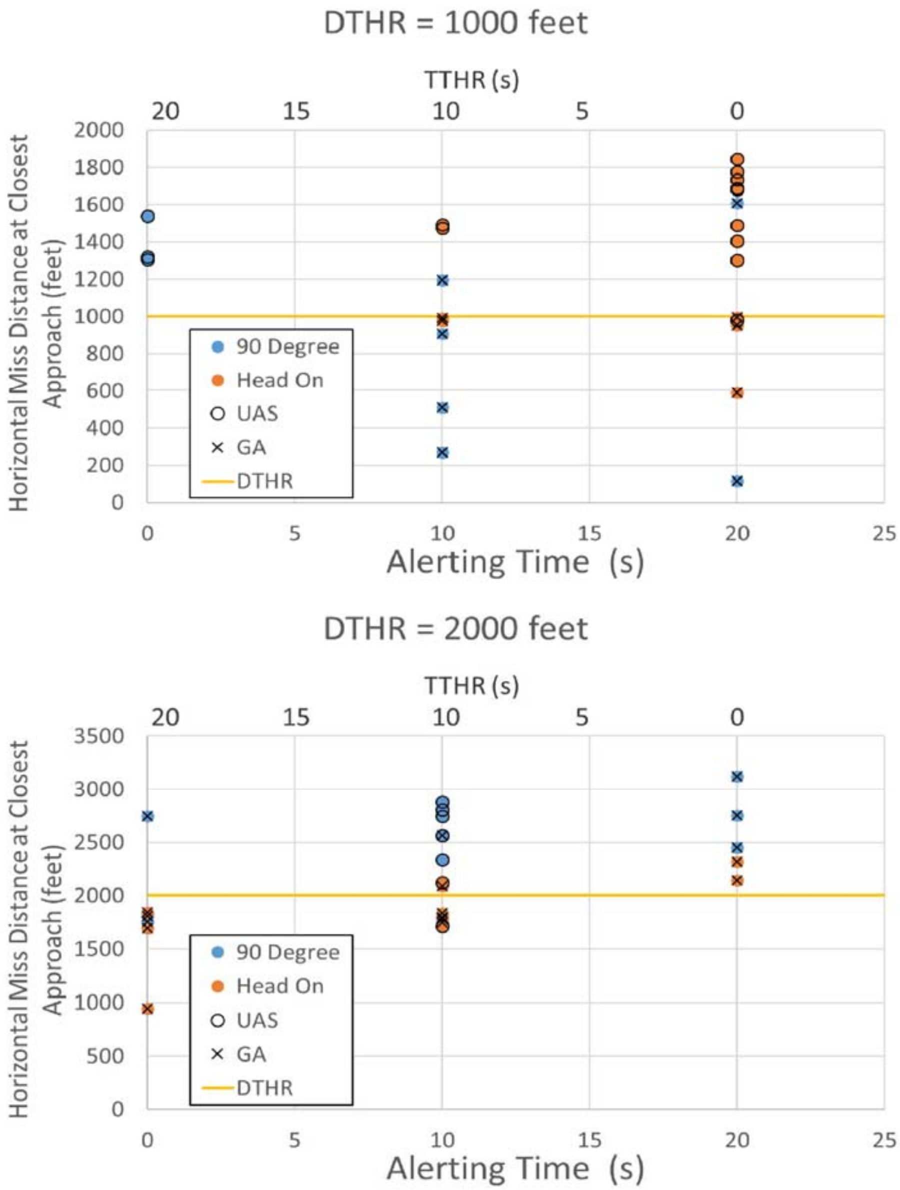

Figure 17 - Horizontal Miss Distance (SAA.6.12) versus well-clear radius

There were 42 successful runs, including 16 UAS-UAS encounters and 26 UAS-GA encounters. The UAS-UAS encounters experienced only two losses of separation. One of these losses of separation was by an intrusion distance of only 20 feet (6 m). The other was an unusual encounter where ICAROUS was forced to perform a secondary encounter because the Tempest completed its loop too quickly. This kind of unusual encounter is a good test of realistic flight scenarios. ICAROUS showed resilience by maneuvering to avoid this secondary encounter and only violating the 2000 foot well-clear volume by 15%. For the rest of the UAS-UAS flights, separation criteria were maintained regardless of horizontal separation or combination of alerting and threshold time parameters used. This may indicate that for low closing speeds (<30 m/s) the configurations chosen are safe and possibly overly conservative.

Of the 28 UAS-GA encounters there were 18 losses of separation, with intrusion distances ranging from 7 feet (2 m) to 1000 feet (305 m). The data shows that all but one of the losses was related to the test site constraints and the choice of parameters that proved to be insufficient for the closing speeds of the GA-UAS encounters. In those cases, the SAA equipped UAS was initialized too close to the well clear boundary or in some cases, already in a loss of separation. However, the data seems to indicate that the alerting time component is more consequential than TTHR resulting in fewer losses of separation. The most successful set of runs corresponds to 2000 feet (610 m) of horizontal separation and 20 seconds of alerting time.

Analysis of the remaining case shows an anomaly in the system, possibly related to an autopilot condition that caused the UAS to slow down as the encounter progressed. After the UAS reaches the commanded speed of 10 m/s in autonomous mode, it unexpectedly and abnormally decreases the speed to 0.53 m/s. The GA aircraft is flying in the direction of the UAV at a speed of 54.5 m/s (106 knots). According to configuration parameters, maneuver guidance is computed by ICAROUS 21 seconds prior to CPA when the aircraft have a horizontal separation of 3763 feet (1147 m). Given the performance limits of the UAS, ICAROUS does not find a track resolution for the UAS. It does find ground speed and vertical resolutions, but they are not currently integrated into the decision-making logic. The UAS, still in autonomous mode, slowly accelerates. The first track resolution autonomously implemented by the UAS is computed by ICAROUS 16 seconds prior to CPA. At this time the aircraft have a separation of 2827.7 feet (862 m). The UAS does not have enough time to avoid a loss of separation and passes 758.7 feet (231 m) from the GA aircraft.

6.1 Maneuver Initiation

ICAROUS commands a maneuver to avoid a conflict whenever certain threshold parameters are met. For the ISAAC tests, these thresholds are the distance threshold (DTHR) and time threshold (TTHR). If the value of modified tau is less than TTHR, or if the projected range between the vehicles is less than DTHR (within the alerting time) then ICAROUS identifies a conflict and issues guidance. Modified tau is an approximation of time to closest point of approach (tcpa). When the two aircraft are horizontally diverging the value of modified tau has no real meaning. This work defines the value of modified tau as -1 in this case.

Figure 18 presents the threshold conditions at the time ICAROUS first identified a conflict in each encounter. This plot reveals which threshold value caused ICAROUS to engage and start issuing guidance.

Each dot on the plot represents an encounter between the ownship and traffic vehicle. The dots are color coded to show the value of TTHR during that test encounter. The blue dots represent encounters where TTHR = 20s, and alerting time = 0s. Since there is no alerting time for these runs, the maneuver could not be initiated by the DTHR criterion and must have been initiated when the value of modified tau fell below TTHR (beneath the blue line). The orange dots represent encounters with TTHR = 10s, and alerting time = 10s. For these runs, the maneuver could have been initiated by either criteria (beneath the orange line or left of the yellow line). The green dots represent runs with TTHR = 0s and alerting time = 20s. Since there is no TTHR for these runs, the maneuver could not have been initiated by the TTHR criterion and must have been initiated when the separation distance (projected into the future by the alerting time) fell below DTHR (left of the yellow line).

Note that the flights labeled A through D on this plot do not meet the criteria described above. Each of these encounters was with a GA traffic vehicle. For points B, C, and D, the discrepancy is due to the GA traffic vehicle having a second ADS-B transmitter on board, as described in Section 7.1**Error! Reference source not found.**. This second transmitter sent ADS-B updates less frequently and occasionally reported its location a significant distance away from the primary ADS-B transmitter. During the runs shown in points C and D, the secondary ADS-B signal reported a position 1000 feet (305 m) ahead of the more reliable primary signal, which triggered ICAROUS to maneuver. The computations for the plots were done using data from the primary ADS-B signal, which causes the discrepancy in the plot. On closer inspection of the flight logs, the conflicts in flights A and B were triggered by the secondary ADS-B signal meeting the TTHR criterion. Avoidance maneuvers in flights C and D were triggered by the secondary ADS-B signal meeting the DTHR criterion.

6.2 Closure Rate

As discussed above, the encounters against GA intruders suffered many more losses of separation than the encounters against UAS intruders. The major difference between the two sets of encounters is the closure rate. The UAS-to-UAS flights had closure rates of 20-30 m/s, while the UAS-GA flights had closure rates of 50-70 m/s. Figure 19 shows that the higher closure rate flights generally resulted in a smaller horizontal separation distance between the two vehicles at their closest point of approach. However, this may also be due to other differences between the UAS-UAS and UAS-GA flights.

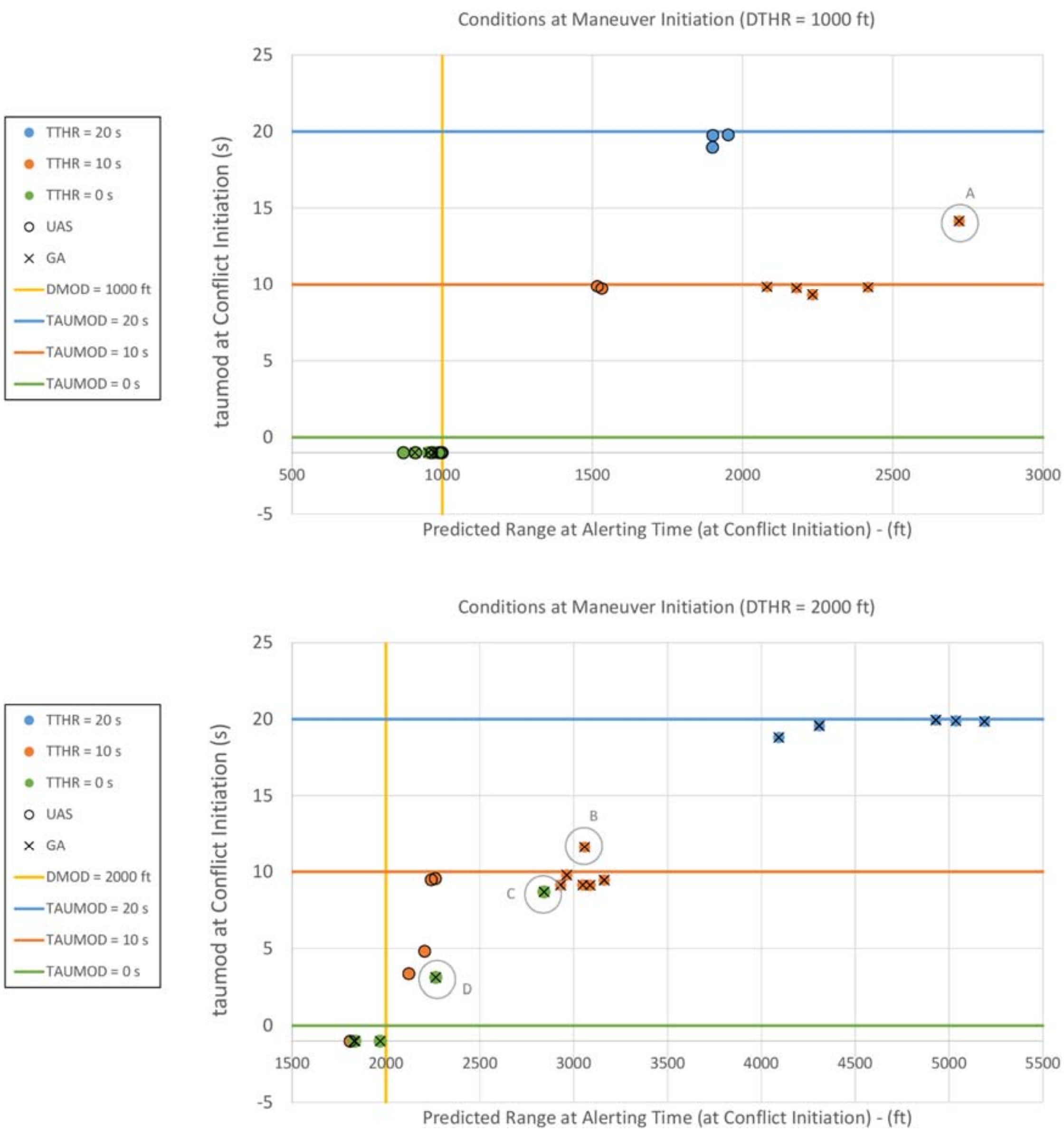

Figure 18 - Conditions that triggered ICAROUS maneuver initiation

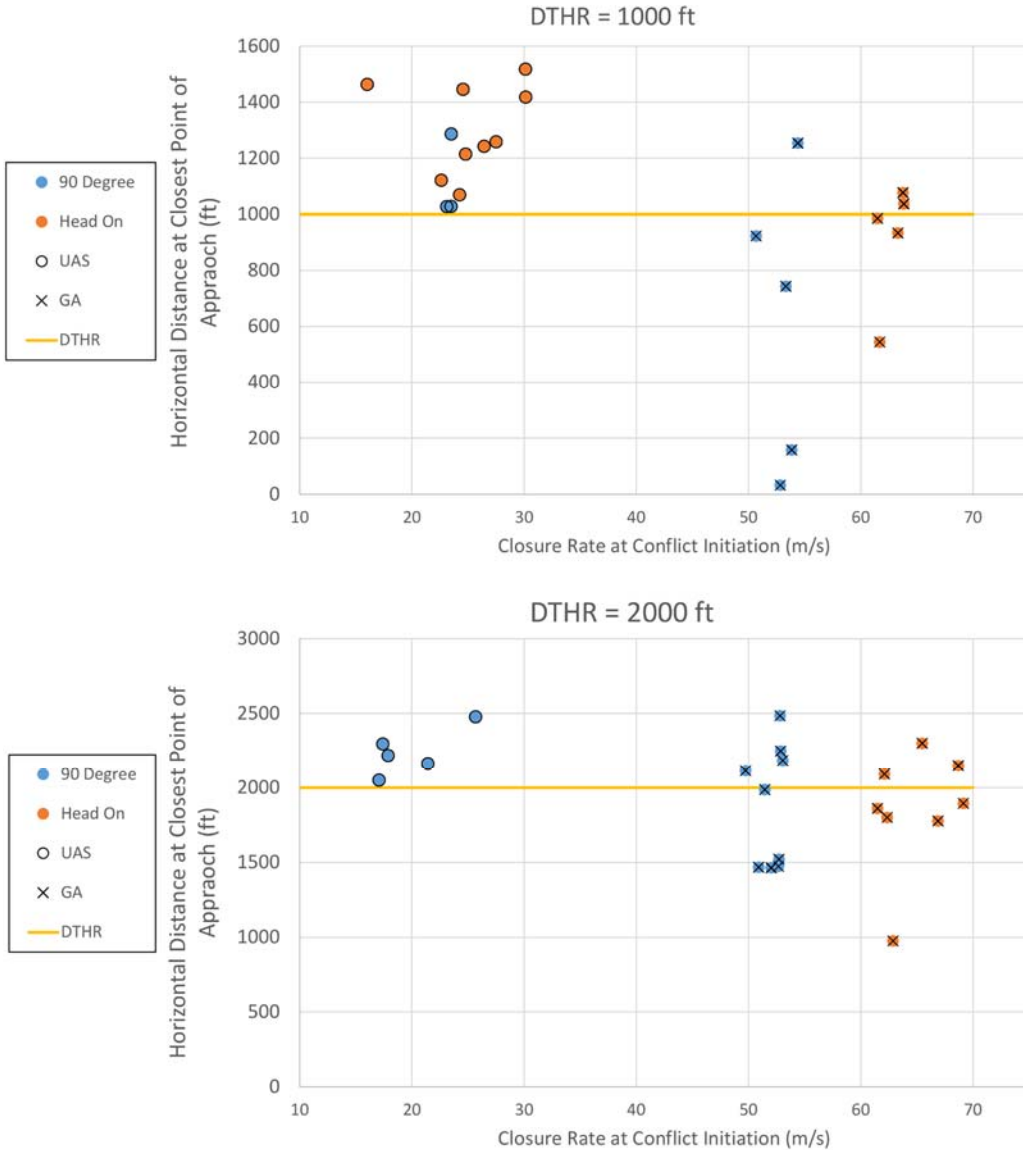

Figure 19 - The effect of closure rate on minimum horizontal distance

6.3 ICAROUS Return to Path

Once a potential conflict with an intruder vehicle has been avoided, ICAROUS must command the ownship to return to its original path. An example of this behavior is shown in figure 20. At time t_0 the ownship begins its automated flight plan from waypoint X1 to X2. At time t_1, ICAROUS detects a conflict with the intruder vehicle and commands a deviation to the North. By time t_2, the ownship's new trajectory is sufficient to avoid the intruder, and no conflict is predicted. However, if the ownship were to attempt to return to its flight plan, it would immediately be in conflict again. Instead, ICAROUS maintains the avoidance trajectory until it detects that it is safe to turn back towards the flight plan without causing a conflict. At time t_3 ICAROUS determines that it is safe to return to the flight plan and guides the ownship back to waypoint X2.

This ability of ICAROUS to return to the original path is important so that a predicted conflict does not derail the autonomous ownship's mission. In a fully autonomous situation, ICAROUS must be able to decide when and how to return to the flight plan after an avoidance maneuver without any input from a pilot.

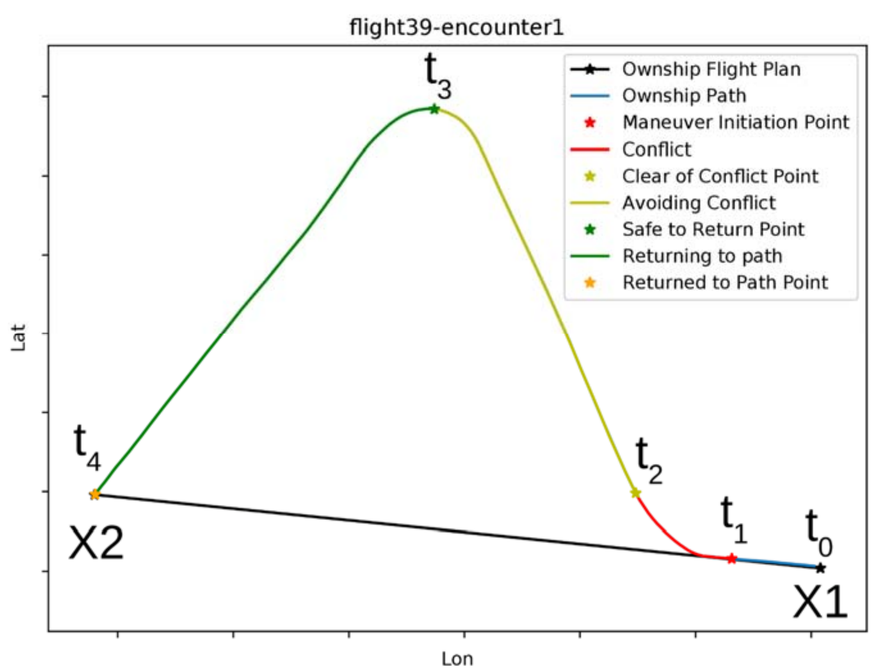

Figure 20 - ICAROUS avoidance maneuver and return to path

6.4 Secondary Conflicts

During a head-on encounter, ICAROUS could command a maneuver to the North or South to avoid conflict with the oncoming traffic vehicle (figure 21). Either direction is an equally valid avoidance maneuver to get out of the intruder's path. However, due to the design of these experiments, an avoidance maneuver to the North presents an additional challenge to ICAROUS.

As shown in figure 11, once the traffic vehicle reaches waypoint Y2, its programmed route turns to the North. If the ownship chose to deviate to the North, then it is confronted with a second conflict because the traffic vehicle has turned directly toward its chosen path. As shown in figures 21 and 22, ICAROUS is able to handle these scenarios and adjusts the avoidance maneuver to keep well-clear of the traffic vehicle. At time t_1, the vehicles are traveling directly toward each other, creating a head on conflict. ICAROUS commands an avoidance maneuver to the North. At time t_2, the traffic vehicle turns North as part of its programmed loop, causing a new predicted conflict. In response, ICAROUS commands a second deviation, traveling further East to avoid the conflict. At time t_3 all conflict has passed. At this time, it is safe to return to the original flight plan, continuing from waypoint X2. This is an important result, as it demonstrates the ability of ICAROUS to perform effective avoidance maneuvers beyond nominal simple encounters. Traffic vehicle trajectories are not fixed and can potentially change during an avoidance maneuver. Any practical SAA system needs to continue monitoring for violations while conducting a maneuver.

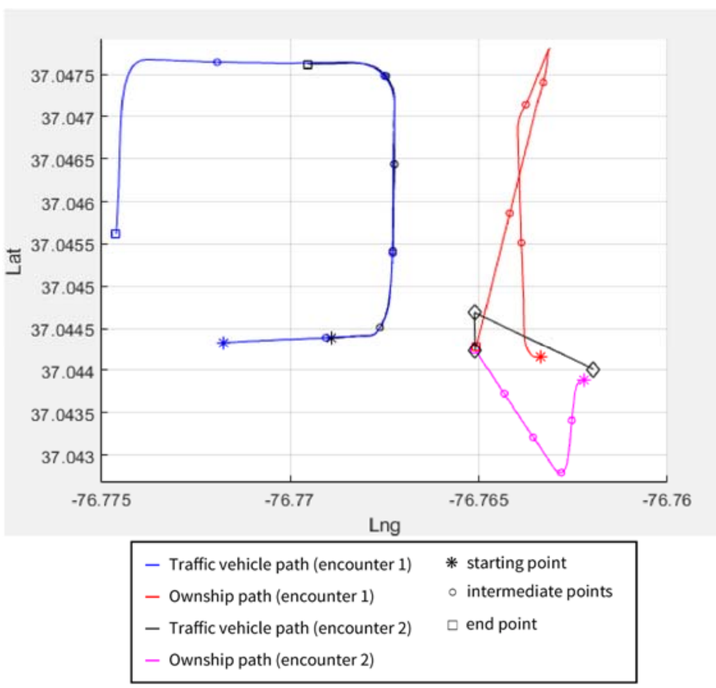

Figure 21 - ICAROUS deviations for two encounters - first encounter avoidance is to the North, second encounter avoidance is to the South

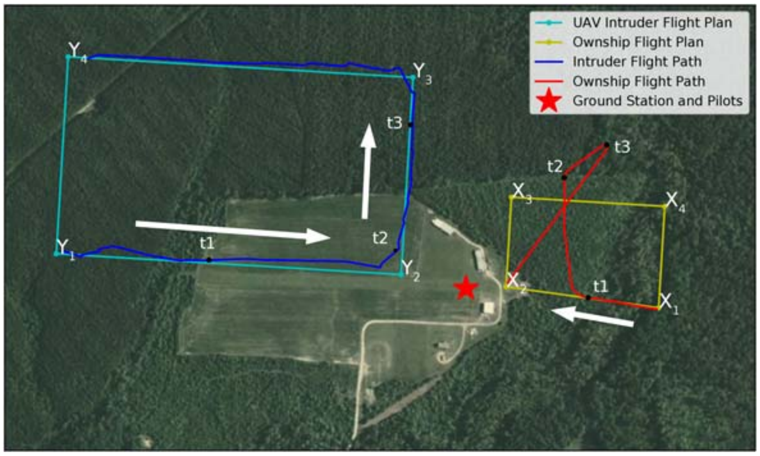

Figure 22 - ICAROUS performs a secondary deviation when the traffic vehicle turns towards the initial avoidance maneuver, creating a second conflict

6.5 Geofence Avoidance

Of 23 head-on encounters conducted without any geofences, ICAROUS commanded a deviation to the North in 14 encounters, and to the South in 9 encounters. This roughly equal division is expected, since either direction is equally acceptable.

Of 4 head-on encounters conducted with a keep-out geofence located directly north or south of the flight plan, ICAROUS commanded a traffic avoidance maneuver away from the geofence in all 4 encounters. In these 4 encounters, ICAROUS successfully maintained well-clear with the traffic vehicle while avoiding the keep-out geofence. When selecting from possible avoidance maneuvers, ICAROUS prefers maneuvers that do not lead to a geofence breach. This result demonstrates ICAROUS' ability to perform SAA and monitor for geofence violation simultaneously.

6.6 Data Collection

Special care was taken to ensure that the necessary data was collected to assess ICAROUS' sense and avoid performance against defined SAA Measures of Performance.

For each ISAAC flight, ICAROUS recorded a log file containing the details of each encounter from ICAROUS' point of view. This log can be used to determine when ICAROUS first identified a conflict with an intruding aircraft, the specific maneuver that ICAROUS commanded to avoid the conflict, and the time when the conflict has been successfully cleared by deviating from the flight plan. These logs also show where ICAROUS believes the intruders are located based on received ADS-B messages.

In addition to the logs from ICAROUS, Pixhawk data flash logs are stored for each UAS flight. These logs contain the recorded GPS locations from directly onboard the vehicles. This can be compared to the positions recorded within ICAROUS to assess sensor performance. The Baseline Research System onboard the SR-22 manned aircraft records the aircraft state and GPS position in a kml format.

In addition to these logs, the MissionPlanner ground control station recorded telemetry logs (tlogs), which contain all of the messages the ground station received during the flight, including position updates, and status messages.

7 ADS-B Sensor Performance

During the flight tests described above, three levels of UAS ADS-B output power were tested:

- 40 Watts (full power)
- 1.3 Watts (15 decibel attenuation)
- 0.4 Watts (20 decibel attenuation)

The different output power levels were produced by adding a 50 Watt RF in-line attenuator to the ADS-B transmitter on the UAV intruder (Tempest). By swapping out the attenuator between flights, different transmission powers were achieved. The output power for each scenario is estimated based on the 40 Watts nominal output of the antenna.

Flight tests were conducted at Beaver Dam Air Park near Smithfield, VA, in the vicinity of multiple airports. As a result, ADS-B signals from multiple commercial planes were also present during testing.

7.1 PingRX Performance

The pingRX ADS-B receiver used in these tests provides a simple practical way to incorporate ADS-B data into UAS sense and avoid operations and is considered to be representative of future devices that could be used for commercial UAS operations. In our tests, the pingRX was able to successfully receive and decode greater than 90% of the ADS-B messages sent by the intruder UAV aircraft at full transmission power (40 W). Slightly better results were seen from the GA plane, with greater than 95% of ADS-B messages successfully received. Since this analysis was performed using telemetry logs from the ownship ground station, some of these missed updates could be attributed to lost packets in the telemetry link, which would not affect the amount of ADS-B data available to ICAROUS. However, analysis shows that fewer than 2% of packets were dropped over the telemetry link. In addition, packets lost due to drops out of the telemetry link would be assumed to affect all ADS-B transmission power levels and aircraft types (UAS vs GA).

With our flight test configuration, the pingRX passed ADS-B data to the Pixhawk autopilot, which in turn passed those messages on to ICAROUS. The Pixhawk has parameters designed to limit how many ADS-B messages are passed on. It is important to properly set Pixhawk parameters such as the ADS-B range filter (ADSB_LIST_ RADIUS) and maximum number of ADS-B targets tracked (ADSB_LIST_MAX) for each application. Otherwise, messages from the target intruder aircraft may be dropped due to the Pixhawk being overloaded with data from other aircraft in the general vicinity. During testing it was observed that the pingRX was receiving ADS-B data from aircraft more than 50 miles away. With the ADS-B maximum range set to the default 100,000 meters, ADS-B reception was inconsistent, especially when there were many other ADS-B targets passing by within range. Figure 23 compares the traffic vehicle GPS track with the track estimated by ICAROUS using the ADS-B data it received. The upper plot was generated using the GPS data recorded directly by the Pixhawk. This should be considered the true path of the traffic vehicle. The lower plot was generated using ICAROUS logs, where the source for the traffic vehicle path is the received ADS-B messages, representing the position data from the traffic vehicle that was available to ICAROUS for sense and avoid. The path is too erratic and inaccurate for ICAROUS to perform successful sense and avoid. Setting the ADS-B filtering parameters to 10,000 meters of range and 25 maximum ADS-B targets filtered out the unwanted ADS-B messages and resulted in much more consistent ADS-B updates from the target traffic vehicle. These are the parameter values used for the reception rates given in this report. With the parameters set to these new values, ADS-B reception using the pingRX was reliable and provided good data for sense and avoid.

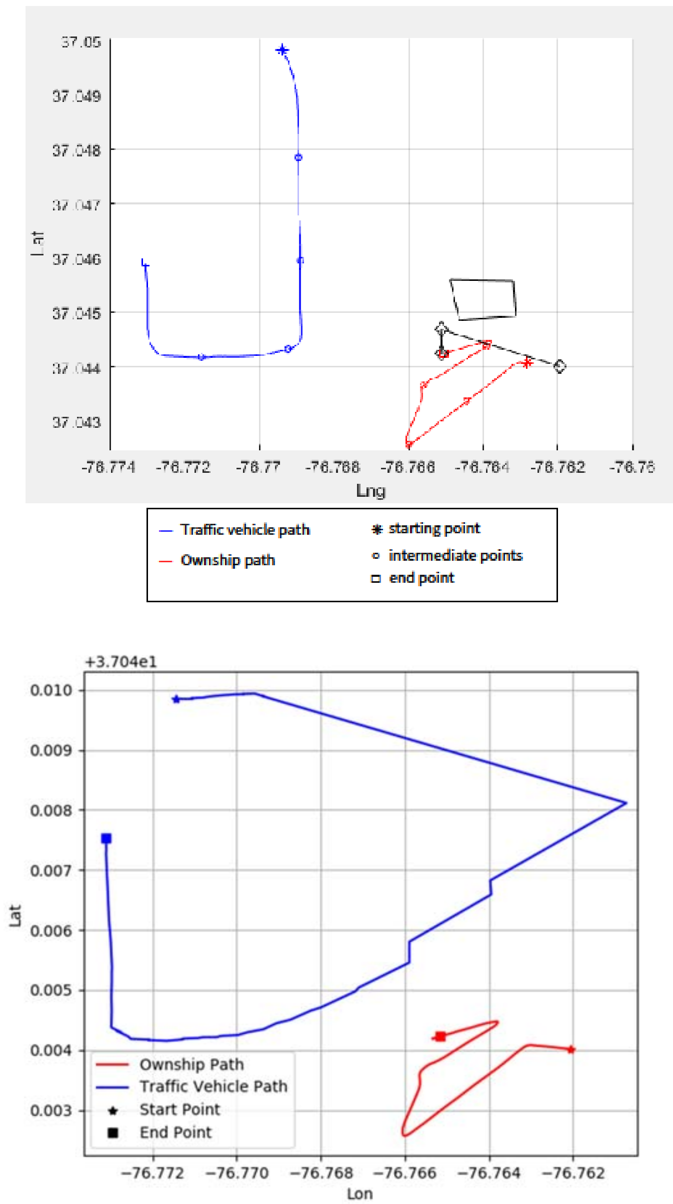

Figure 23 - Above: GPS tracks recorded directly by the Pixhawks. Below: Traffic vehicle path received by ICAROUS over ADS-B

ICAROUS performed successful SAA maneuvers using ADS-B input from the pingRX for more than 30 flight tested encounters. The range of full power ADS-B has no effect on small UAS operations, as the lookahead time and alerting time parameters in ICAROUS limit the monitored range to be much smaller than the actual range of ADS-B reception. The few encounters where ICAROUS failed to maintain well clear were not caused by ADS-B errors (once ADS-B filtering parameters were properly set). The failures were due to well-clear definition and timing parameters that were inappropriate for the scenario being tested. For example, alerting time was not adequate for ICAROUS to generate and execute the required maneuver before the loss of well-clear occurred.

In addition to the standard ADS-B system transmitting at 1 message per second, the Cirrus SR-22 traffic vehicle had a portable secondary transmitter onboard that sent less frequent updates. This additional transmitter was not part of the experiment design, but its unexpected inclusion created a more challenging and realistic scenario for ICAROUS SAA. From ICAROUS' perspective, this second signal appeared as a second traffic vehicle trailing close behind the SR-22. In most scenarios, this was not an issue for ICAROUS' avoidance, since the two signals were in almost the same location. However, because the secondary signal had a lower transmit rate, it often appeared to be in an inaccurate location, especially when the aircraft executed a turn. In the absence of an updated position message, ICAROUS projects the traffic vehicle's path linearly, which causes a large error when the aircraft executes a turn. In some test cases, this second signal caused an extra challenge and confusion for ICAROUS. If the secondary signal was significantly offset from the primary signal, then ICAROUS tried to avoid what was effectively a much larger well-clear volume. In some scenarios ICAROUS found itself "surrounded," and believed there was an aircraft on both sides and no safe path to take. This issue would not occur when traffic vehicles only transmit one regular, accurate ADS-B signal, or if ICAROUS knew beforehand which signal could be safely ignored. Ideally, ICAROUS would be able to prioritize the regularly updating signals, rather than giving equal trust to a traffic message that was received several seconds ago.

These tests validate the use of ADS-B for UAS in scenarios involving both unmanned and manned aircraft. Any ADS-B receiver needs to be carefully integrated and tested before use in safety critical applications.

7.2 Attenuated ADS-B Performance

ICAROUS performed successful detect and avoid maneuvers at three different ADS-B output power levels. Even with the lowest power (0.4 Watt) signal, 83% of ADS-B messages were received by the pingRX unit within the 0-1200 meters separation range tested. This reception rate proved sufficient for ICAROUS avoidance maneuvers within this range. Attenuated ADS-B performance during the ISAAC flight tests is discussed in more detail in [27].

Figure 24 shows a logistic regression between the probability of ADS-B message reception and separation range between the two vehicles. The regression shows how increasing distance between the two vehicles reduces the probability that a transmitted ADS-B message will be successfully received by the ownship. Each received message is associated with the distance between the two vehicles at the time the message was sent, based on ownship GPS position and intruder ADS-B data. The missed messages are estimated based on the standard once per second broadcast rate and associated with the approximate distance between the two vehicles at the time of expected transmission. For the full power signal, the range between vehicles does not significantly affect the probability of message reception ($p = 0.125 > 0.05$) within the tested range. For the 1.3-Watt signal, the range significantly affects the probability of message reception (p =

0.015<0.05). For the 0.4-Watt attenuated signal, the effect is highly significant (p<0.0001<0.05). This is expected for reduced power transmissions.

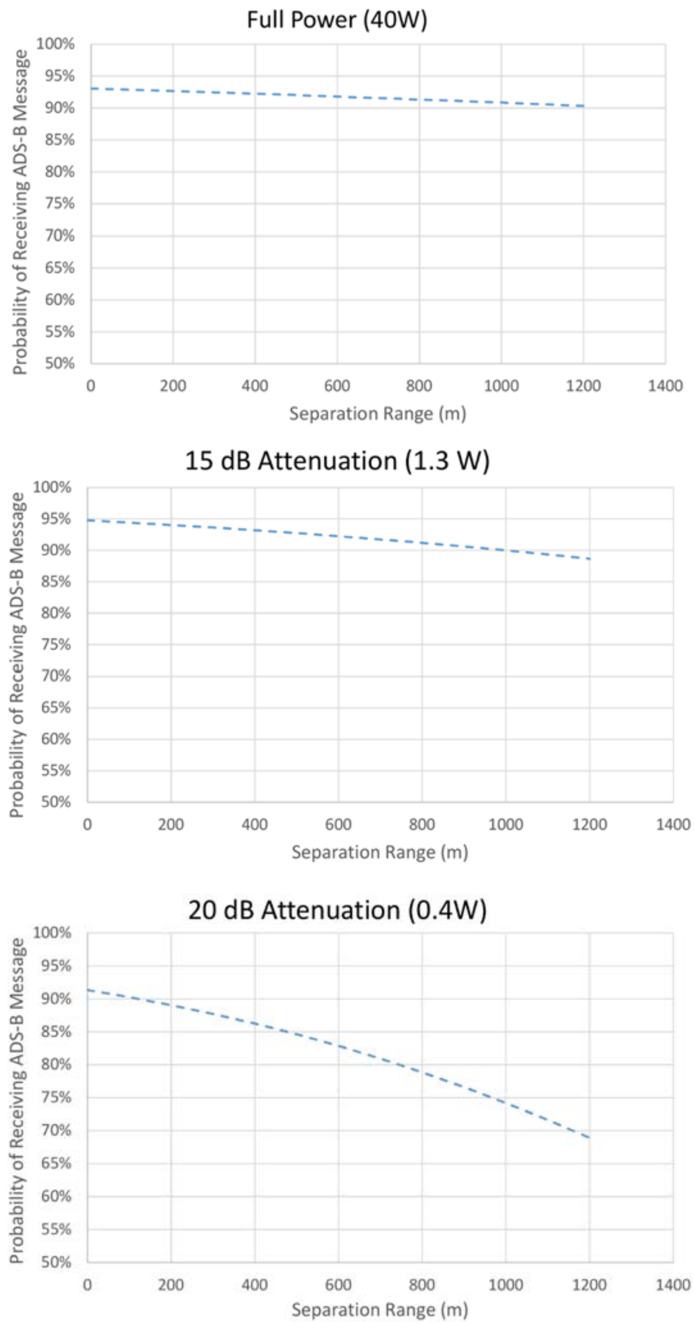

Figure 24 - Probability of pingRX successfully receiving an ADS-B message, dependence on separation range for three different output power levels

The average ADS-B message reception rate for the 0.4-Watt transmission was 83%, corresponding to an expected 2 seconds between messages. This reception rate is higher when the vehicles are closer together. The ISAAC tests indicate that these message reception rates may be sufficient for UAS avoidance maneuvers, as ICAROUS was able to perform multiple successful sense and avoid maneuvers using the 20 dB attenuated ADS-B signal. M. Guterres et al. [24] concluded that UAV ADS-B transmit power within 0.01-0.1 Watts, coupled with a fleet density less than 5 UAVs per square kilometer is required to sufficiently reduce frequency congestion and maintain acceptable ATM message reception rates of greater than 80%. The current test evaluated only single aircraft and testing of multiple aircraft in higher-density operations is required to establish the actual upper power limit. The lowest output power tested in this effort was 0.4 Watts which is above the suggested criteria yet provides minimum required performance. It is feasible that the sensitivity of the pingRX unit could be improved, but that was beyond the scope of the current effort. Lower transmission powers that fall within this range should be tested in future efforts.

In addition to achieving adequate performance for UAS-to-UAS applications, results for UAS-to-GA aircraft were also adequate. Observations from the manned GA SR-22 aircraft revealed that for the mid-power level the position of the intruder Tempest aircraft was observed more than 15 miles away. When the Tempest ADS-B power output was attenuated to 400 milliwatts, its location was observed consistently by the GA aircraft from at least 8 miles away. This distance is equivalent to approximately 4 minutes warning time for the GA aircraft.

8 Discussion

A successful maneuver to avoid a well-clear conflict is largely a function of the performance of the aircraft and position communication link. Factors such as the speed and turn rate of the vehicle play a significant role in maneuvering to avoid an approaching intruder and also impact the effective range for required position communication link performance. Consequently, careful consideration of the parameters chosen for well clear is crucial. These parameters must be chosen to handle the fastest intruder in a given airspace.

The phase 1 flight tests with the Tempest aircraft resulted in closure rates of 30 m/s during head-on encounters and 22 m/s during the 90-degree encounters. With a turn rate of 10 degrees/second, and a top speed of 10 m/s, the octocopter was able to maneuver fast enough to avoid a well-clear violation defined by the configuration parameters.

Proper selection of parameters depends on many factors including intruder speed, desired separation radius, and ownship limitations in turn rate and speed. Conservatively chosen parameters will reduce the risk of a well-clear violation but consume more time and fuel as the ownship executes long maneuvers that are not necessarily required to maintain safe separation. On the other hand, if parameters are chosen to maximize efficiency, the ownship may lose well clear during encounters with higher speed vehicles. Figure 25 shows how increasing the alerting time parameter can increase the total path deviation. Well-clear definition and parameters must be chosen carefully for each application and be based on actual assessments of the risk of vehicle collisions. Values evaluated herein were considered nominal and appeared very conservative to ground observers. The results of these tests characterize ICAROUS' performance under different configurations and inform the effective selection of parameters for future operations.

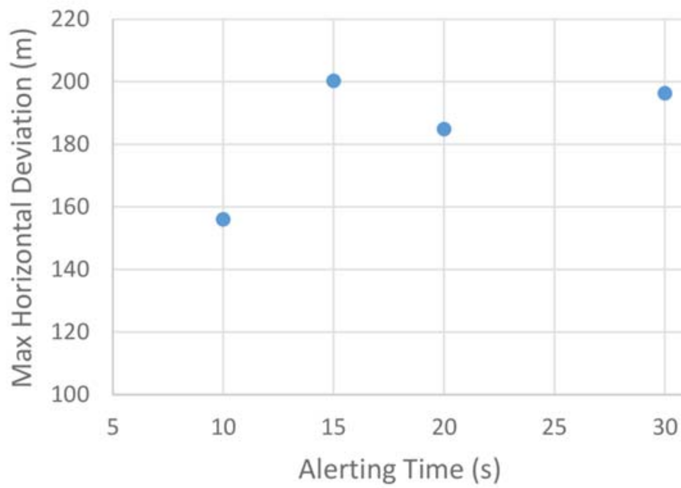

Figure 25 - Maximum path deviation vs alerting time

9 Conclusions and Future work

9.1 Development of ICAROUS

The ICAROUS capability for autonomous SAA was designed as a distributed software architecture based on well-established communication protocols and developed using formally verified SAA algorithms. ICAROUS has been undergoing extensive simulation evaluations as well as flights to evaluate its performance in real flight conditions.

The ISAAC flight test was designed to explore the performance of the autonomous SAA functionality in conflict encounters between a UAS and both another UAS and a GA aircraft. The flights were conducted on days with mild wind conditions. Performance was measured in terms of horizontal miss distance as a function of well clear horizontal separation, alerting, and threshold times.

Results from this test indicate that ICAROUS autonomous SAA capability was very effective in maintaining separation between two UAS in mild wind conditions, with closing speeds not exceeding 30 m/s, and for all combination of alerting and threshold times and distance parameters used. Results from the UAS-GA encounters were impacted by the constraints of the ISAAC test design that did not allow some of the test conditions to be initialized properly, causing late detections and losses of separation. However, within the limits of the test conditions, results seem to indicate that at closing speeds in the order of 100 knots an alerting time of 20 seconds and a separation threshold of 2000 feet (610 m) was effective for all tested encounters.

The ISAAC test was the first flight test designed to investigate this complex and wide-ranging problem and, clearly, there remains work to be done. Future flight studies are needed to explore the parameter space beyond the ISAAC limits and to characterize the performance of other sensor technologies for SAA to determine if it can support such applications.

9.2 Attenuated ADS-B

These tests validate low powered 0.4-Watt ADS-B transmission as a practical option for UAV to UAV applications. The output powers tested provided sufficient quality and range for ICAROUS to perform consistent detect and avoid encounters. Reduced power should decrease the risk of frequency congestion that would interrupt normal ADS-B use but may require lower transmit powers than tested here.

Future tests should assess the 0.01 to 0.1-Watt transmission power suggested by [23]. Tests should also be conducted over larger separation distances and examine the impact that several UAVs transmitting at this low power would have on ATM ADS-B operations, especially the impact of a fleet of UAVs operating at or near an airport.

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Appendix A: Flight Run Log

Date	Ownship Vehicle	Own-ship Flight #	Intruder Ve-hicle	Intruder type	Intruder Flight #	Intruder ADSB attenuation	WC ra-dius (ft)	Alerting time (s)	Tau thresh-old (s)	Geofence	Encoun-ter type	Number of Suc-cessful SAA En-counters
10/16/18	S1000	22	Tempest	UAS	31	full power	1000	20	0	No geofence	Head on	2
10/16/18	S1000	24	Tempest	UAS	33	full power	1000	20	0	Geofence to the South	Head on	3
10/23/18	S1000	27	Tempest	UAS	35	full power	2000	10	10	No geofence	90 deg	1
10/23/18	S1000	29	Tempest	UAS	36	full power	2000	10	10	No geofence	90 deg	3
10/23/18	S1000	31	Tempest	UAS	38	15 dB	2000	10	10	Geofence to the North	90 deg	1
10/25/18	S1000	32	Tempest	UAS	39	full power	1000	10	10	No geofence	Head on	2
10/25/18	S1000	33	Cirrus SR-22	GA	NA	NA	2000	20	0	No geofence	Head on	2
10/25/18	S1000	35	Cirrus SR-22	GA	NA	NA	2000	10	10	No geofence	Head on	3
10/25/18	S1000	36	Cirrus SR-22	GA	NA	NA	2000	20	0	No geofence	90 deg	3
10/25/18	S1000	37	Cirrus SR-22	GA	NA	NA	2000	0	20	No geofence	90 deg	1
10/30/18	S1000	39	Tempest	UAS	42	full power	1000	0	20	No geofence	90 deg	3
10/30/18	S1000	42	Cirrus SR-22	GA	NA	NA	2000	0	20	No geofence	90 deg	2
10/30/18	S1000	43	Cirrus SR-22	GA	NA	NA	2000	10	10	No geofence	90 deg	3
10/30/18	S1000	44	Cirrus SR-22	GA	NA	NA	2000	0	20	No geofence	Head on	3
10/30/18	S1000	45	Cirrus SR-22	GA	NA	NA	1000	20	0	No geofence	Head on	3
10/30/18	S1000	46	Cirrus SR-22	GA	NA	NA	1000	10	10	No geofence	Head on	2
10/30/18	S1000	48	Cirrus SR-22	GA	NA	NA	1000	10	10	No geofence	90 deg	3
11/20/18	S1000	50	Tempest	UAS	68	20 dB	1000	20	0	No geofence	Head on	2
11/20/18	S1000	51	Cirrus SR-22	GA	NA	NA	1000	20	0	No geofence	90 deg	1
12/4/18	S1000	58	Tempest	UAS	45	20 dB	NA	NA	NA	NA	NA	NA
12/4/18	S1000	59	Tempest	UAS	45	20 dB	NA	NA	NA	NA	NA	NA
12/4/18	S1000	60	Tempest	UAS	46	15 dB	NA	NA	NA	NA	NA	NA
12/4/18	S1000	61	Tempest	UAS	46	15 dB	NA	NA	NA	NA	NA	NA
12/4/18	S1000	62	Tempest	UAS	47	full power	NA	NA	NA	NA	NA	NA
12/4/18	S1000	63	Tempest	UAS	47	full power	NA	NA	NA	NA	NA	NA

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14. ABSTRACT Independent Configurable Architecture for Reliable Operations of Unmanned Systems (ICAROUS) is a distributed software architecture developed by NASA Langley Research Center to enable safe autonomous UAS operations. ICAROUS consists of a collection of formally verified core algorithms for path planning, traffic avoidance, geofence handling, and decision making that interface with an autopilot system through a publisher-subscriber middleware. The ICAROUS Sense and Avoid Characterization (ISAAC) test was designed to evaluate the performance of the onboard Sense and Avoid (SAA) capability to detect potential conflicts with other aircraft and autonomously maneuver to avoid collisions, while remaining within the airspace boundaries of the mission. The ISAAC tests evaluated the impact of separation distances and alerting times on SAA performance. A preliminary analysis of the effects of each parameter on key measures of performance is conducted, informing the choice of appropriate parameter values for different small Unmanned Aircraft Systems (sUAS) applications. Furthermore, low-power Automatic Dependent Surveillance – Broadcast (ADS-B) is evaluated for potential use to enable autonomous sUAS-to-sUAS deconflictions as well as to provide usable warnings for manned aircraft without saturating the frequency spectrum.

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