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Final Report – Evaluation of PANCAS and TASA in Support of UAS Operations Near Shielded Airspace

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

SARA Inc., in collaboration with the Northern Plains UAS Test Site, has evaluated for the FAA UAS Integration Office the feasibility of using Detect and Avoid (DAA) systems to augment the safety of UAS operations Beyond Visual Line of Sight (BVLOS) in and around shielded areas, and in so doing, safely extend the UAS operational limits. SARA provided two DAA systems for evaluation, the Passive Acoustic Noncooperative Collision Avoidance System (PANCAS), and the Terrestrial Acoustic Sensor Array (TASA). Through flight testing and analysis described herein, SARA concluded that either PANCAS or TASA individually, or both concurrently, can perform their intended functions effectively enough to replace visual observers and extend the allowable UAS operational ranges beyond current limits.

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Acronyms

AGL = *Above Ground Level*

ARC = *UAS BVLOS Aviation Rulemaking Committee*

BVLOS = *Beyond Visual Line of Sight*

DAA = *Detect and Avoid*

FAA = *United Stated Federal Aviation Administration*

LoWC = *Loss of Well Clear*

LR = *LoWC Risk Ratio for noncooperative aircraft, per ASTM F3442*

ML = *Machine Learning*

NMAC = *Near Midair Collision*

NPUASTS = *Northern Plains UAS Test Site*

PANCAS = *Passive Acoustic Noncooperative Collision Avoidance System*

RPIC = *Remote Pilot in Command*

RR = *NMAC Risk Ratio for noncooperative aircraft, per ASTM F3442*

TASA = *Terrestrial Acoustic Sensor Array*

UAS = *Unmanned Aerial System or Uncrewed Aerial System*

VO = *Visual Observer*

Executive Summary

SARA Inc., in collaboration with the Northern Plains UAS Test Site, has evaluated for the FAA UAS Integration Office the feasibility of using Detect and Avoid (DAA) systems to augment the safety of UAS operations Beyond Visual Line of Sight (BVLOS) in and around shielded airspace, and in so doing, safely extend the UAS operational limits. SARA provided two DAA systems for evaluation, the Passive Acoustic Noncooperative Collision Avoidance System (PANCAS), and the Terrestrial Acoustic Sensor Array (TASA). Through flight testing and analysis described herein, SARA concluded that either PANCAS or TASA individually, or both concurrently, can perform their intended functions effectively enough to replace visual observers and extend the allowable UAS operational ranges beyond current limits. SARA has developed a methodology by which PANCAS and TASA users can quickly derive UAS operating limits and provide the FAA a level of confidence that their proposed operations will be safe when applying for a BVLOS waiver to 14 CFR § 107.31.

1. Introduction

A special category of unmanned aerial system (UAS) operations are those conducted within shielded areas. The UAS BVLOS Aviation Rulemaking Committee (ARC) defined shielded areas as "a volume of airspace that includes 100 feet above the vertical extent of an obstacle or critical infrastructure and is within 100 feet of the lateral extent of the same obstacle or critical infrastructure as defined in 42 U.S.C. § 5195c. A Shielded Operation is an operation within a Shielded Area." Manned aircraft tend to avoid shielded areas, creating an opportunity for UAS operations within those spaces. With appropriate safety measures in place, some UAS operators have received FAA waivers to 14 CFR § 107.31, allowing these UAS to operate beyond visual line of sight (BVLOS) of the remote pilot in command (RPIC) while conducting shielded operations. Authority to fly BVLOS is a critical long-term goal and key milestone for many UAS-related businesses. The value proposition for many of these businesses is to provide low-cost UAS services to replace existing, more expensive, services. BVLOS operations are often required to achieve these low costs. The FAA UAS Integration office, in line with their mission to promote the integration of UAS into the National Airspace System, funded a 12-month effort for SARA and the Northern Plains UAS Test Site (NPUASTS) to evaluate two Detect and Avoid (DAA) systems for their ability to support shielded operations. Furthermore, SARA and NPUASTS were to evaluate if these DAA systems could enable safe UAS operations beyond shielded areas, providing the airspace surveillance and advance warning necessary for a UAS to return to a shielded area to avoid a crewed aircraft.

1.1. Detect And Avoid

Just as the pilot onboard a crewed aircraft is responsible to see and avoid other crewed aircraft, a UAS operating BVLOS of the remote pilot must detect and avoid crewed aircraft. This may be accomplished in multiple ways, including restricting operation to within visual line of sight (VLOS) of the remote pilot, or extending VLOS through a network of visual observers (VOs) scanning the airspace and reporting back to the remote pilot. However, the cost of employing a team of VOs can eliminate the cost benefit of using UAS, making it an unattractive solution for most businesses. Recognizing this, companies like SARA have developed DAA systems that can replace VOs.

There are many technological challenges faced when developing a DAA system. Without complete knowledge of the airspace surveillance picture, UAS operations pose a credible risk towards aviation safety. While most aircraft are required to broadcast their location using ADS-B, not all aircraft are required to do so, and some ADS-B equipped aircraft will have non-functioning equipment. Aircraft using ADS-B out or a transponder are called cooperative aircraft and are relatively easy to detect. In contrast, noncooperative aircraft do not transmit their position information and can be difficult to detect. DAA systems generally detect noncooperative aircraft using optical, radar, or acoustic technologies. These systems must reliably detect noncooperative aircraft at operationally suitable ranges with low false alarm rates across a wide range of environments, visibility conditions, and weather conditions. If the DAA system is carried onboard the UAS, it must have extremely small size, weight, and power. Because most UAS are much slower than crewed aircraft, there is a risk of collision from any direction and the airspace must be monitored in all directions around the UAS. For this research, SARA provided two acoustic DAA systems for evaluation, PANCAS and TASA. These systems are described in the following sections.

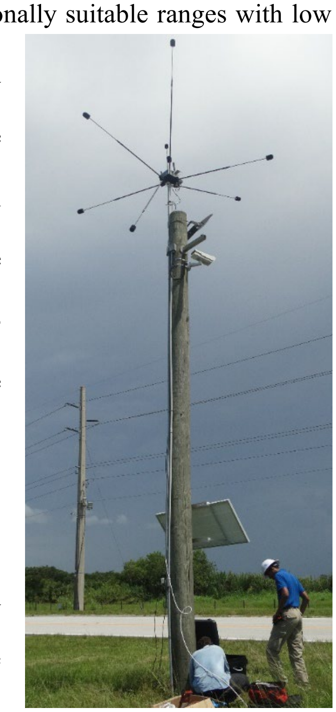

Fig. 1 TASA DAA System

1.2. TASA

SARA's Terrestrial Acoustic Sensor Array (TASA) is a novel ground based Detect and Avoid (DAA) system. Shown in Fig. 1, each TASA node consists of an array of passive acoustic probes and an edge processor. Aircraft detections are processed locally and transmitted to the cloud. Users can access real time detections for each TASA node in a network on a combined display, which uses sensor fusion algorithms to track aircraft and reject clutter. This approach allows a TASA network to flexibly scale to cover any operational area. Each TASA node provides long range detection, a 360° field of regard, and reliable performance in all visibility conditions. Because passive acoustics do not require line of sight, TASA node placement is very flexible.

1.3. PANCAS

The Passive Acoustic Noncooperative Collision Avoidance System (PANCAS) is a novel onboard DAA system developed by SARA. By using passive acoustic sensing, PANCAS detects collision threat aircraft with no cooperation or communication with the threat aircraft and no reliance on data links outside the UAS platform. An example integration of PANCAS on an AeroVironment RQ-20 Puma UAS is shown in Fig. 2. A PANCAS system consists of an onboard, real-time processor, an array of acoustic probes, and a harness connecting the probes to the processor. The number and location of microphones can be varied as needed and a flexible software architecture allows for alert range to be tuned to the user's needs. A simple operator display is provided which allows for fully automatic avoidance or human-in-the-loop operation.

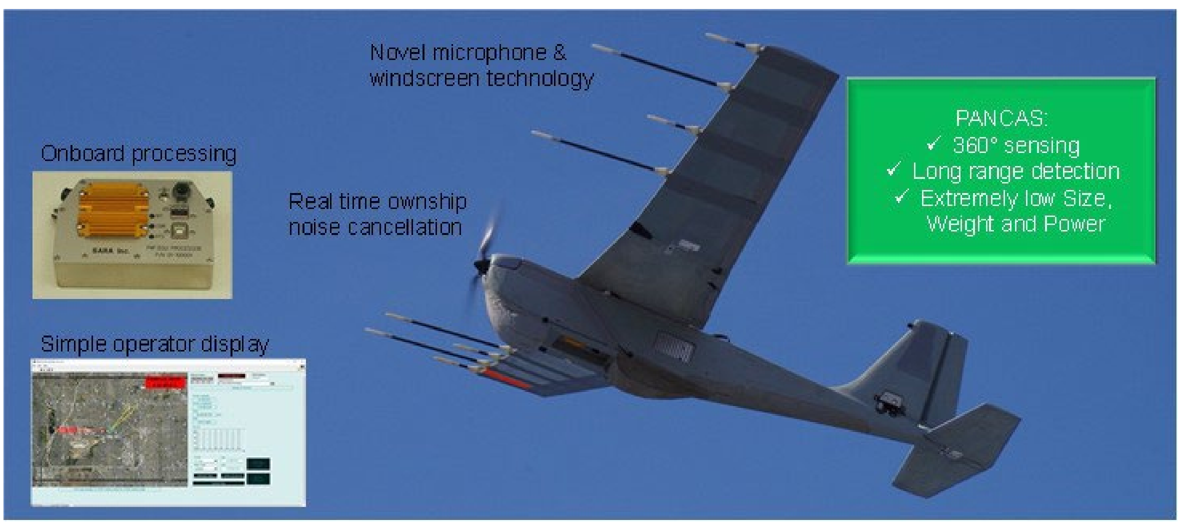

Fig. 2 PANCAS DAA System flown on Puma UAS

1.4. DAA Requirements

Shielded area operations most naturally fit the use case for UAS categorized as small. According to 14 CFR Part 107, small UAS are those weighing less than 55 pounds and may operate from the surface to 400 feet above ground level. Shielded areas are naturally below 400 feet. The FAA has issued no performance requirements for small UAS DAA systems, but ASTM has released standard F3442 "*Standard Specification for Detect and Avoid System Performance Requirements*". F3442 is a performance-based standard with the primary requirement being a set of Risk Ratios. It also requires UAS to avoid near midair collision (NMAC) and prevent a loss of well clear (LoWC) with crewed aircraft. In turn, both requirements apply to cooperative and noncooperative aircraft.

Table 1 Risk Ratio Requirements

	NMAC Risk Ratio (RR)	LoWC Risk Ratio (LR)
Cooperative	≤0.18	≤0.40
Noncooperative	≤0.30	≤0.50

F3442 defines NMAC as two aircraft coming within 100 feet vertically and 500 feet horizontally of each other while in flight and LoWC as two aircraft coming within 250 feet vertically and 2000 feet horizontally of each other while in flight.

1.5. Test Objectives

While the FAA has granted a small number of Part 107 waivers allowing trusted operators to fly UAS BVLOS within shielded areas, such operations are still generally not allowed under Part 107. One objective of this research was to measure how much additional safety PANCAS and/or TASA can bring to shielded BVLOS operations. Furthermore, this research evaluated if PANCAS and/or TASA could mitigate the risk of a mishap with a crewed aircraft enough that the UAS could safely venture beyond shielded areas and return to a shielded area if a crewed aircraft approached. To answer these questions, flight testing sought to measure the amount of time TASA and PANCAS afforded a UAS to conduct either a descent or a lateral maneuver.

The team was also interested in comparing TASA and PANCAS performance to visual observers (VOs). Visual observer performance varies based on numerous factors, such as training, experience, level of fatigue, visibility conditions, and viewshed. Visual observers also perform multiple functions, including aircraft detection, estimating aircraft position, course, altitude, and conflict potential, and relaying information to the remote pilot. To right-size the effort, VO testing focused on their ability to detect aircraft and communicate with the RPIC. VOs did not attempt to determine if detected aircraft posed a collision hazard to the UAS or not.

2. Methodology

2.1. Visual Observer Testing

NPUASTS provided experienced, trained visual observers for four rounds of evaluation. PANCAS and TASA data were gathered concurrently during these tests. Table 2 shows the flight test dates, locations, and systems under evaluation. When a table entry indicates a system was used actively, it means the system (VO, PANCAS, or TASA) issued alerts and guidance which the RPIC used to maneuver the UAS to safety. If a system was used passively, alerts and guidance were logged but not communicated to the RPIC.

Table 2 Flight Testing Completed

Test No.	Dates	Location	VO Used?	PANCAS Used?	TASA Used?
1	1/9/2024 1/11/2024 1/12/2024	Barstow, CA	Actively	NO	Passively
2	1/30/2024 1/31/2024	Simi Valley, CA	Actively	Passively	Passively
3	5/14/2024 5/16/2024	Simi Valley, CA	Passively	Actively	Passively
4	5/19/2024 5/22/2024	Barstow, CA	Passively	NO	Actively

2.1.1. Barstow

Tests were conducted at the Burlington Northern Santa Fe (BNSF) intermodal facility at the edge of Barstow, a small city in the Mojave Desert with approximately 25,000 residents. Two TASA nodes were installed; one North of the facility and one South. A VO stood below each TASA node. The TASA and VO locations are depicted on a satellite image in Fig. 3. Each VO had a radio, as did the test conductor and the remote pilot in command (RPIC). The north VO position had an unobstructed view of the horizon, apart from occasional blockages to the South when double-stack train cars were passing. The south VO position featured a slight hill and low perimeter fence to the south that blocked the true horizon. Based on analysis of north and south VO detection range, we believe physical obstructions were not a factor. VOs were instructed to radio the RPIC when they spotted the test aircraft and report its direction, heading, and recommended course of action for the UAS. VOs could hear each other over the radio, so the first VO sighting helped the second VO acquire the same target. The RPIC kept the UAS within the intermodal facility at all times, which represented the shielded area for this test. Beyond the safety afforded by operating in a shielded area, the UAS maneuver, either lateral or descent, aimed to further increase the safety of the UAS operation by increasing the lateral separation from the crewed aircraft or by landing the UAS. The UAS flight path nominally followed the southernmost rail line, then crossed the facility and returned following the northernmost rail line before crossing back to the southernmost rail line. This rough rectangle was flown either clockwise or counterclockwise. For test runs where the UAS was to maneuver laterally, it flew at 100 feet above ground level (AGL), within the typical confines of shielded areas. When descent maneuvers were tested, the UAS began at 400 feet AGL. This enabled the UAS accelerations and decelerations during descent to be better resolved than if the descent had begun at 100 feet AGL.

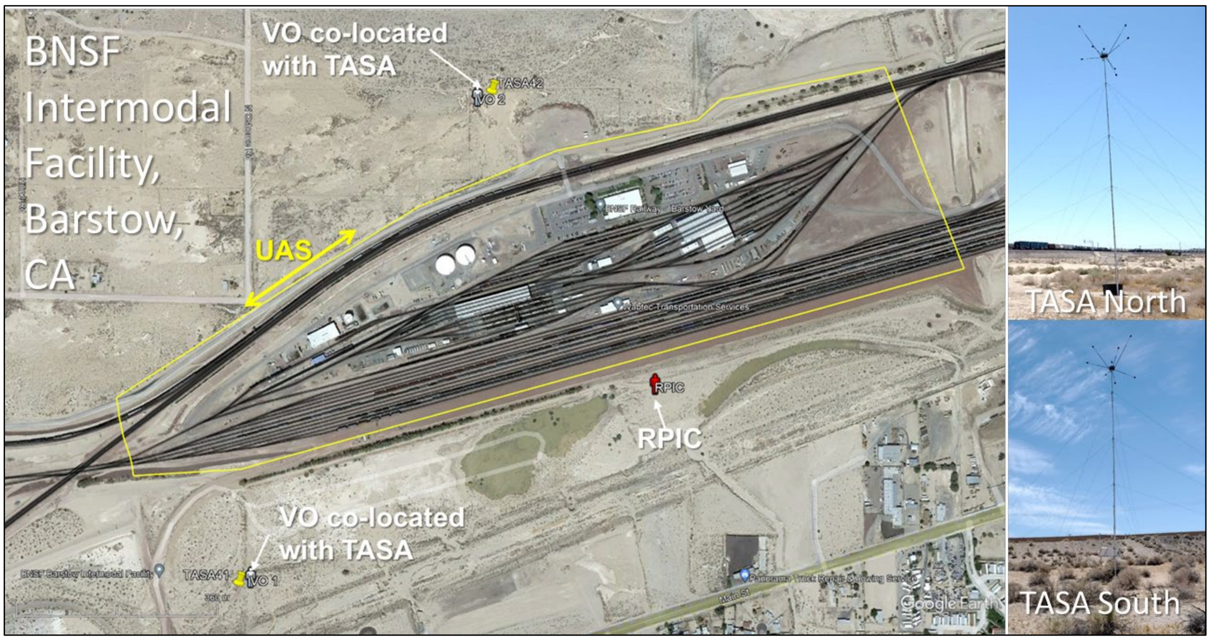

Fig. 3 Barstow Test Location

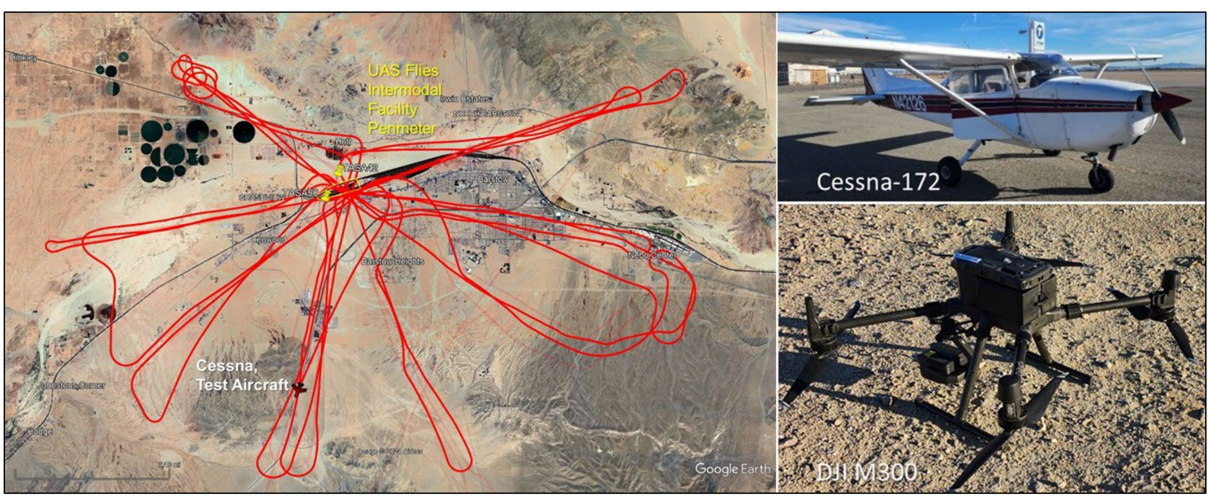

Fig. 4 (left) Aircraft tracks, (top right) Intruder Aircraft, (bottom right) test UAS

NPUASTS rented a Cessna 172, tail number N42126, for use as the intruder crewed aircraft. The Cessna began each test run at a waypoint specified by the Test Conductor. These waypoints were between 6km and 10km from the intermodal facility, bounded by terrain and restricted airspace to the North. From this starting waypoint, the Cessna approached the intermodal facility flying straight and level at 1,000 feet above ground level. This altitude was chosen for test safety, always ensuring at least 600 feet altitude separation (often more) between the Cessna and UAS..Fig. 4 shows the Cessna 172 and UAS (DJI Matrice 300) used during the test, both in January and May.

2.1.2. Simi Valley

VO testing in Simi Valley mirrored Barstow in many ways. The VOs were given the same instructions, they were looking for the exact same Cessna (N42126), and the Cessna was flying almost the same pattern. Simi Valley is part of the Greater Los Angeles Area, with the Santa Susanna Mountains running East to West along the North side of the valley. Testing was conducted on a private test range in the foothills, which made approaches from the North impractical for the Cessna. The test range is approximately 30km from the coast, which generated morning fog and clouds that typically burn off in the afternoon. Fig. 5 shows a satellite image of Simi Valley with the Cessna flight tracks overlaid in red. Simi Valley testing featured the AeroVironment Puma UAS, not the DJI M300. The Puma began each test run orbiting either waypoint A or B at 100 ft AGL. The Cessna would approach at 1000 ft AGL, and when the VO sighted the Cessna, he would radio the RPIC to maneuver the Puma laterally to the other waypoint. The Simi Valley test location had no true shielded area within which to operate, but this had no impact on the test execution.

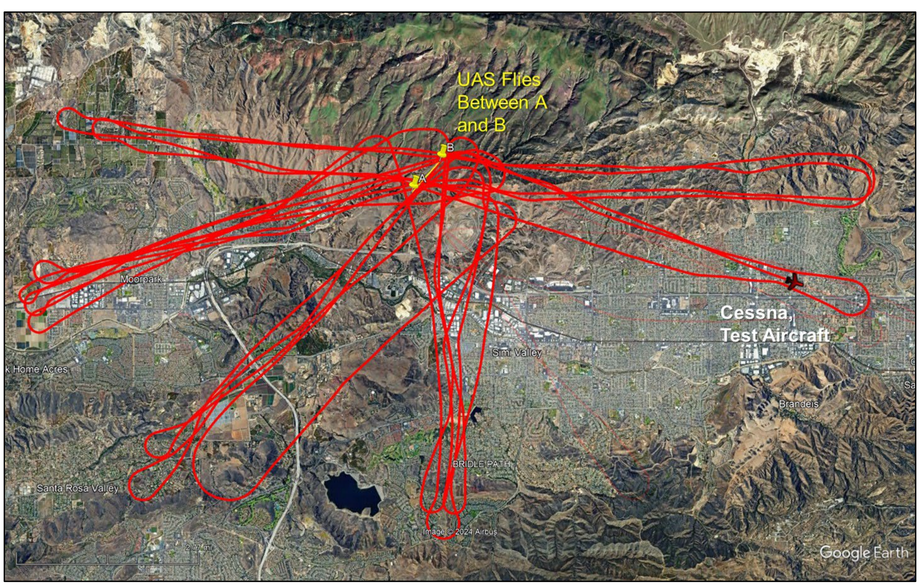

Fig. 5 Simi Valley test location and Cessna flight tracks

Visual Observers, PANCAS on the Puma UAS, and TASA were all evaluated in Simi Valley. These systems are shown in Fig. 6.

Fig. 6 PANCAS, TASA and VO in Simi Valley

Three visual observers were positioned throughout the test range, as shown in Fig. 7. VO1 was positioned on a fire road 700m North of the RPIC. Because the mountains rise to the North, VO1 had an excellent view of the test area and all Cessna approach directions. VO2 was co-located with a TASA node and positioned 60m from the RPIC. This position was roughly in the center of the small valley which made up the UAS operating area and provided clear views in all directions. VO3 was located approximately 750m southwest of the RPIC, near the southern extent of the Puma UAS flight path. The Puma flight path is shown in blue in Fig. 7. Nearby hills to the south reduced VO3's view of the horizon somewhat but the team considered it the best location in the general area. Since UAS operate in many different environments and VOs may be positioned in less than desirable viewsheds, VO3's position and viewshed is a relevant data point.

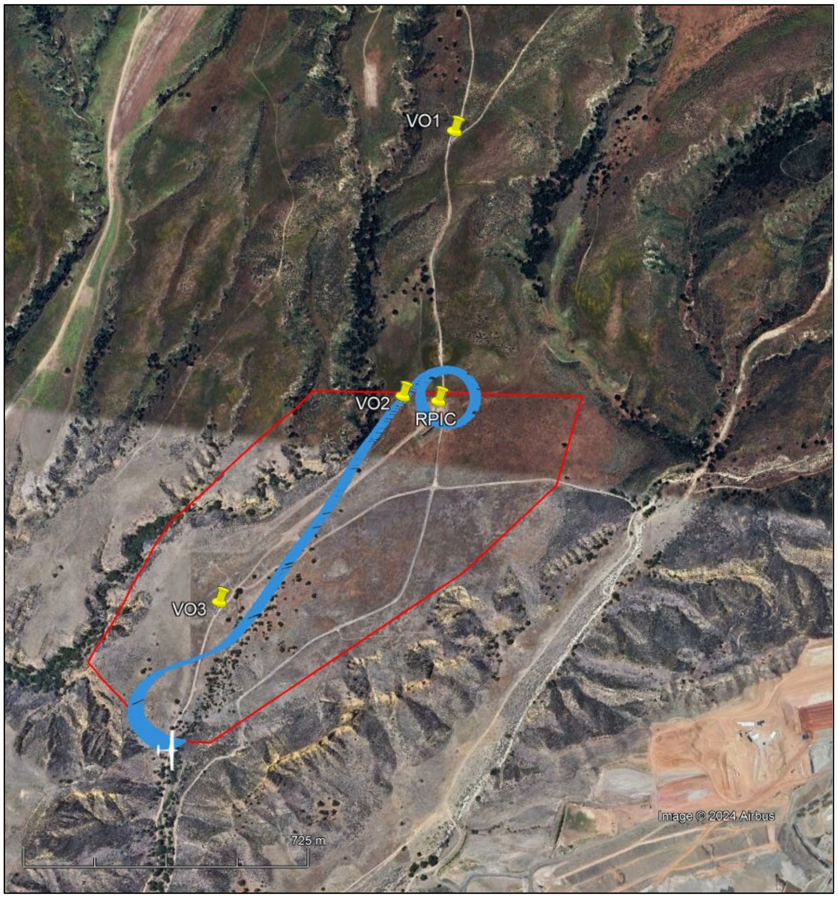

Fig. 7 VO Positions in Simi Valley

In January, at both Barstow and Simi Valley, VO radio communications were recorded by a handheld audio recorder, synchronized to UTC time. UAS and Cessna tracks were recorded with onboard GPS data loggers. Post-test, these data products were combined to analyze VO performance metrics, such as detection range and time required to communicate with the RPIC. The May tests did not use VOs operationally, but VOs were still placed at the same locations and their detections were logged for post-test analysis.

2.2. TASA Testing

TASA nodes were operating and logging data during all four tests. Only in Barstow in May were the TASA nodes used to initiate avoidance maneuvers. At that test, a TASA operator viewed the TASA terminal display (Fig. 8) which simultaneously displayed detections and alert guidance from two TASA nodes. Once either TASA node detected the inbound Cessna and issued an alert for the UAS to avoid, the TASA operator would verbally relay this command to the RPIC, who was co-located.

While TASA information was available on the user display in Simi Valley, as shown in Fig. 8, it was not used to inform avoidance maneuvers, since TASA would be tested in Barstow. PANCAS was the priority in Simi Valley, but weather conditions limited the number of test runs. In Fig. 8, PANCAS and TASA are each represented by a green circle. Serial numbers displayed inside each circle identify the specific TASA node or PANCAS system. Red beams point to acoustic targets which have been tracked and determined to be a collision hazard. Purple chevrons indicate the position, tail number, and altitude of ADS-B equipped traffic in the area. An alert symbol pops up in the lower left corner, as well as an audio alert, when the RPIC should initiate a maneuver to shielded airspace. System health and status, user account management, and application settings are available in menus along the top right side of the screen.

Fig. 8 Combined PANCAS and TASA User Display

2.3. PANCAS Testing

The SARA PANCAS system was installed on an AeroVironment Puma UAS, as shown in Fig. 1, and flown in Simi Valley in both January and May. In January, VOs would radio the RPIC when the inbound test aircraft was spotted and the RPIC would command the Puma to maneuver laterally to a simulated shielded area. PANCAS logged detections and alerting guidance during this test solely for post-test analysis. In May, PANCAS detections and alerting guidance were viewed by a PANCAS operator, co-located with the RPIC. When PANCAS detected the inbound test aircraft and recommended the Puma avoid, the PANCAS operator verbally relayed this command to the RPIC, who maneuvered the Puma accordingly. This would be described as a pilot-in-the-loop approach. In other cases, PANCAS has directly commanded the autopilot in a pilot-on-the-loop approach.

2.4. Machine Learning Classifier

The BNSF Intermodal Facility in Barstow is a particularly difficult acoustic environment, with constant noise from trains, semi-trucks, and other heavy machinery. This impacted VOs and TASA in similar ways, reducing detection range and generating false alarms. To combat this, SARA has been developing machine learning (ML) classifier models to distinguish aircraft and non-aircraft sounds. The prototype model has been trained on supervised data, validated against additional datasets in both simulation and real-world use, and may be deployed as a static model. SARA provided a prototype ML classifier system for the May tests in Simi Valley and Barstow, which logged results for post-test analysis.

2.5. Risk Ratio Simulation

To evaluate the Risk Ratio performance of UAS operations using PANCAS or TASA, SARA developed a simple test-anchored simulation and ran a statistically significant number of encounter scenarios. Selecting a pre-determined collision avoidance maneuver, either a descent or lateral maneuver to the nearest shielded area, simplifies the simulation effort significantly. Because the intruder aircraft's position and heading do not influence the avoidance maneuver, there is less need to include turns, climbs, and descents in the intruder aircraft's track. This is fortunate, as there are very few real-world datasets that capture the flight paths of low-altitude non-transponding aircraft, and thus it is difficult to create a model. For the shielded area simulation, SARA modeled the intruder aircraft as having linear trajectories at constant velocity, with no climbs, descents or turns. The velocity, starting position, and heading were randomized. Additional information about this model can be found in the PANCAS and TASA Standard Safety Package, in Appendix A

3. Results and Discussion

In this section, SARA provides VO test results, PANCAS test results, TASA test results, TASA ML Classifier test results, and Risk Ratio simulation test results, in that order.

3.1. VO Test Results

Over the course of the project, SARA and NPUASTS conducted a total of 128 scripted encounters between a Cessna-172 and a UAS. A total of 211 VO initial aircraft detections were recorded. All Cessna approaches were on trajectories to overfly the UAS operating area at approximately 1,000 ft AGL. Test runs were randomized within reason, being conducted over 9 different days, two different seasons, two different environments, various illumination angles and lighting conditions, and approaching from 14 different directions. Table 3 details the number of test runs and VO sightings recorded on a test-by-test basis. In the January Barstow and Simi Valley tests, the test conductor ensured that the Cessna approach time and direction were not revealed to the VOs. This was an attempt to replicate a real-world encounter, where the intruder aircraft would be unexpected and surprise the VO. Unfortunately, test constraints made these attempts ineffective. Due to limited windows of good weather and the desire to collect a statistically significant number of test runs, the approach time of the Cessna could only be varied by approximately 5 minutes and the approach direction had a maximum variance of approximately 30 degrees. VOs were quick to catch on and easily anticipated the Cessna's approach time and general direction. We suspect this resulted in detection ranges significantly better than should be expected from a VO during typical operations. In the May tests, no effort was made to hide the Cessna's approach time or direction from the VOs, due to constraints on approach time and direction. The reader may note in Table 3 that not all VO sightings were recorded in January. This was due to the VO instructions not being fully understood. The intent was for each VO to report when they first sighted the aircraft, but in some cases, the second VO would not call out because the first VO had already reported the aircraft, and it seemed redundant. Thus, the number of Logged VO calls is less than or equal to the product of the number of VOs and the number of test runs. Once this misunderstanding was identified, it was easily corrected.

Table 3 VO test run totals

Test No.	Dates	Location	VO Used?	Test Runs	No. of VOs	Logged VO Calls
1	1/9/2024 1/11/2024 1/12/2024	Barstow, CA	Actively	33	2	52
2	1/30/2024 1/31/2024	Simi Valley, CA	Actively	28	3	67
3	5/14/2024 5/16/2024	Simi Valley, CA	Passively	25	2	50
4	5/19/2024 5/22/2024	Barstow, CA	Passively	42	2	83
TOTAL				128		252

Each VO call was UTC time tagged, as was the Cessna GPS position. Lateral separation between the VO and the Cessna, a.k.a. detection range, was calculated at the beginning of each call. This data is presented in Fig. 9. The left figure shows the average detection range for each VO and each test. The right figure is a combined histogram of all 252 VO detection range results. The average of all measurements is 2.88 km. Because the VOs knew the time and direction the aircraft would be approaching from, VO detection range in a typical operating environment would be significantly lower than this.

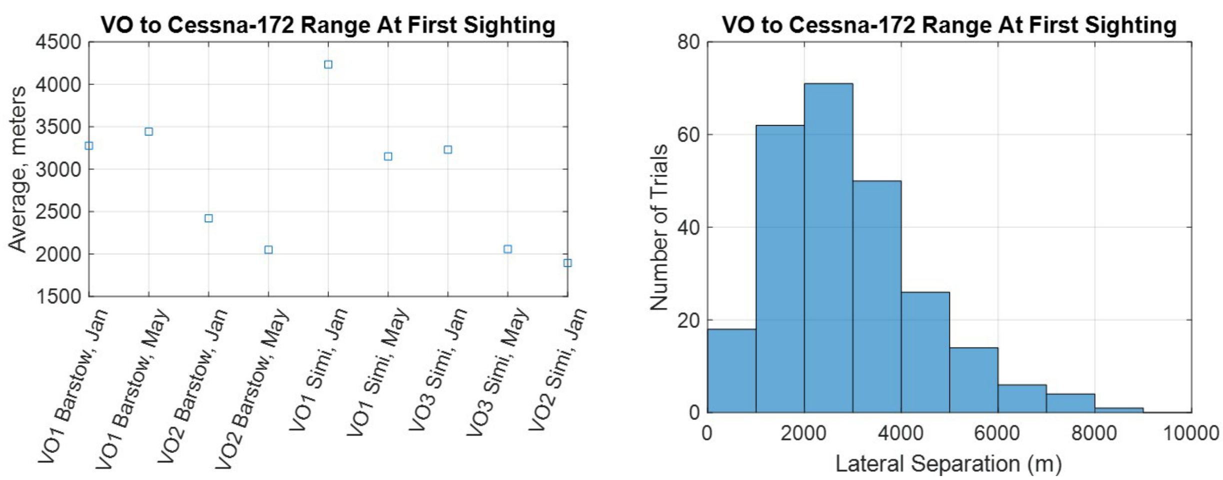

Fig. 9 VO Detection Range Results

3.2. TASA Test Results

Over the course of four tests, 151 measurements were taken where a VO and TASA node were co-located. This data provides the fairest comparison between VO and TASA detection range. Average detection range is presented on a test-by-test basis in Fig. 10. In Simi Valley, TASA significantly outperformed a VO. This was a relatively quiet test environment, like many rural locations across the country where TASA has been operated extensively.

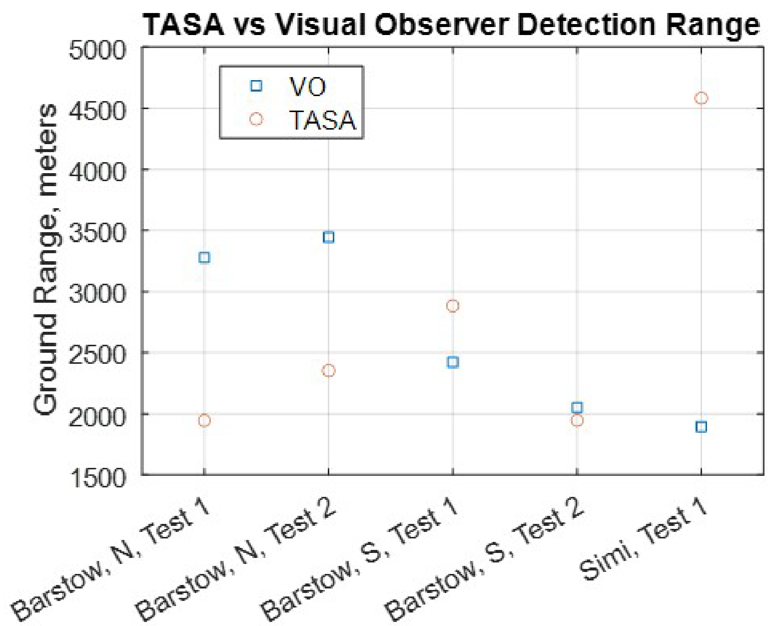

Fig. 10 Comparison of TASA and VO detection range

The BNSF Intermodal Facility in Barstow is a much noisier acoustic environment, with trains, semi tractor trailers, and various other heavy equipment generating noise interference. TASA detection range was reduced in this environment but still provided a useful capability. For instance, the south TASA location in Barstow outperformed the co-located visual observer. Only in the north TASA location in Barstow did a VO outperform TASA. Note that TASA performance is similar between the north and south locations in Barstow, while the VO results vary significantly. This demonstrates that any means of airspace surveillance, be it TASA or a VO or other DAA system, should be installed with attention to the local environment to ensure optimal performance.

3.3. PANCAS Test Results

PANCAS was tested in Simi Valley onboard the AeroVironment Puma UAS in January and May 2024. A total of 52 test runs were conducted. PANCAS range at first detection is shown in Fig. 11, right. The left figure displays the same data, but in terms of time between PANCAS detection and the point of closest approach. Average detection range was 3.16km. Like TASA, this is the detection range that PANCAS can detect aircraft approaching from any direction, providing a 360° bubble of surveillance.

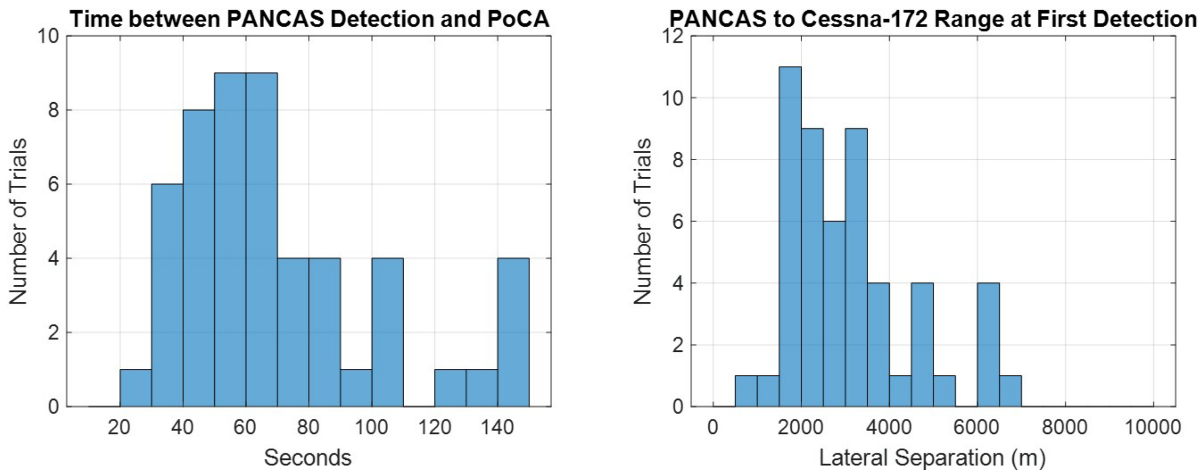

Fig. 11 PANCAS Detection Range Results

During the January test, the avoidance maneuver was determined by the VOs and the RPIC on a run-by-run basis. The choice was either to remain at the current waypoint or transition to the alternate waypoint, such as in Fig. 7. Due to the large time delay associated with this relatively complex decision process, the team modified the procedure for the May test. In May, the avoidance maneuver was pre-determined, such that the RPIC would always redirect the Puma to the alternate waypoint. For example, if the Puma was orbiting around waypoint A when PANCAS detected the Cessna, the RPIC would send the Puma to waypoint B, and vice-versa. This is more representative of shielded area operations, where the RPIC would be trained to always move to the closest shielded area (pre-determined direction) if PANCAS alerted. The May procedure was more effective than the January test, as the maneuver most often led to an increased separation between the aircraft. In post-test analysis, the team evaluated the Closest Point of Approach for each test run, up to the time when the Puma reached the imagined shielded area (the other waypoint). These results are shown in Fig. 12. There is significant spread in the results, with some avoidance maneuvers producing a large increase in separation while other avoidance maneuvers producing no increase in separation. The primary cause was the small test range size, which caused the team to fly the Puma in an orbit rather than a linear trajectory. The orbit and the randomized timing of the turn command produced turn command angles spanning 0° to 180° relative to the current heading. With the Puma constrained to a maximum turn rate of 15°/second, an 180° turn adds 12 seconds to the avoidance timeline and produces lower performance test runs.

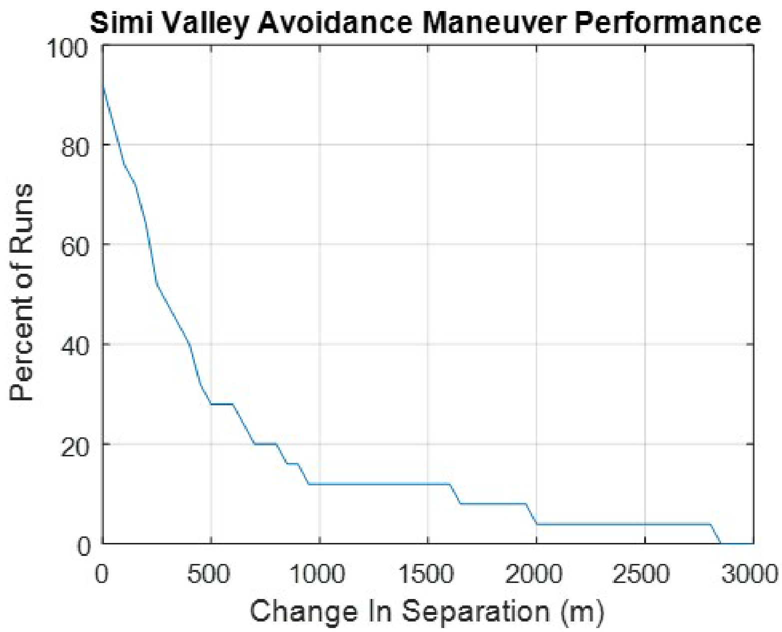

Fig. 12 Puma Lateral Avoidance Maneuver Performance

3.4. Risk Ratio Simulation Test Results

To assess the operational utility of the measured detection ranges, SARA performed four parametric risk ratio analyses:

- TASA analysis using a lateral maneuver to a shielded area
- TASA analysis using a vertical maneuver to a shielded area
- PANCAS analysis using a lateral maneuver to a shielded area
- PANCAS analysis using a descent maneuver to a shielded area

The results of these analyses are summarized here, and additional details are provided in the PANCAS and TASA Standard Safety Package, in Appendix A.

3.4.1. TASA analysis using a lateral maneuver to a shielded area

. TASA networks offer a variety of flexible installation options. A single TASA node provides a bubble of situational awareness large enough for localized UAS operations, while multiple TASA nodes can form a perimeter around an operating area. SARA provides installation support to customers, helping them identify suitable locations for TASA nodes and network laydowns that provide the required surveillance coverage.

For TASA installations supporting UAS operations in and around shielded areas, we locate an alert boundary and specify a required probability of TASA alerting on any low-flying aircraft that cross that boundary. In this way, TASA installation is divided into two steps. The first step is to define the alert boundary based on the operating area and the UAS maneuverability. The second step is to emplace TASA nodes which can enforce that boundary. TASA detection range varies based on its environment, as with any DAA system or VO, so its performance must be verified once installed. Operators can send TASA logs to SARA for analysis, or operators can conduct their own flight testing, similar to the testing SARA and NPUASTS performed in Barstow. The first step, defining the Alert Boundary, is generically analyzed below, while the second step is site-specific and cannot be generalized in this document.

The Alert Boundary simulation geometry is depicted in Fig. 13. The Alert Boundary must encompass the entire operating area, which leads to any section of the boundary only being responsible for alerting on low-flying aircraft crossing into the monitored area. Aircraft remaining outside the boundary need not be reported, and aircraft operating inside the boundary would have been alerted on when it crossed into the bounded area.

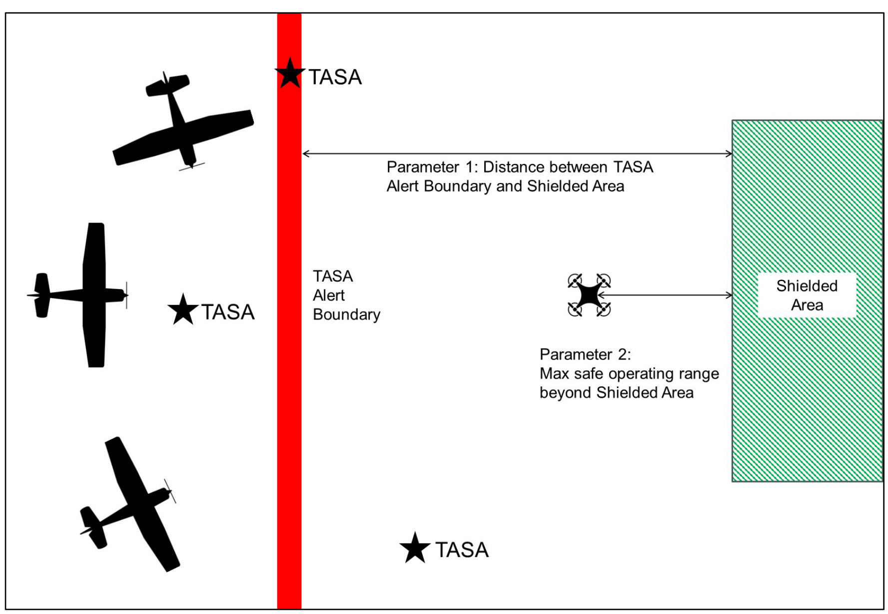

Fig. 13 TASA Simulation for Lateral Maneuvers to Shielded Area

In Fig. 13, aircraft approaching from the top, bottom, or right would be detected by corresponding portions of the Alert Boundary which, for simplicity, have not been drawn. The simulation takes the same approach, analyzing a segment of the Alert Boundary and extending the derived requirements to the entire boundary. Note that the TASA nodes do not need to be placed exactly on the alert boundary, though they can be. Within the limit of TASA detection ranges shown in Fig. 10, TASA nodes can be placed outside the boundary, inside the boundary, or even inside the shielded area in some circumstances.

The simulation environment is first set up with a defined distance between the TASA alert boundary and the Shielded Area. The UAS is initially stationary, at a fixed distance away from the Shielded Area. The intruder aircraft is then assigned a random initial position outside the Alert Boundary from a uniform distribution, and a random heading from a uniform distribution that will lead to a boundary crossing. The intruder is assigned a speed between 45 knots and 170 knots and proceeds to fly straight and level until the Alert Boundary is crossed. The alert boundary is assigned a probability of Alert, and each boundary crossing has a corresponding chance of generating an alert. If an alert is generated, the UAS will maneuver to the Shielded Area. A five-second latency is simulated to account for system latencies, such as time to relay the alert to the UAS and time for the UAS to accelerate toward the shielded area. After two seconds have elapsed, the UAS continues laterally at constant velocity to the Shielded Area, with the goal of reaching the Shielded Area before an NMAC or LoWC occurs. Fig. 14 assumes a 100% probability of alert when the TASA boundary is crossed. Three lines are plotted, corresponding to UAS lateral speeds of 10, 20 and 30 m/s. The figure enables a UAS operator to look up their UAS speed and TASA alert boundary spacing beyond the Shielded Area and identify the maximum distance beyond the Shielded Area their UAS can safely operate. As one would expect, a faster UAS can operate further from the Shielded Area, as it can reach a Shielded Area in less time. Also as expected, the further the TASA alert boundary can be placed beyond the shielded area, the more advance warning is achieved, and the further beyond the Shielded Area the UAS can operate.

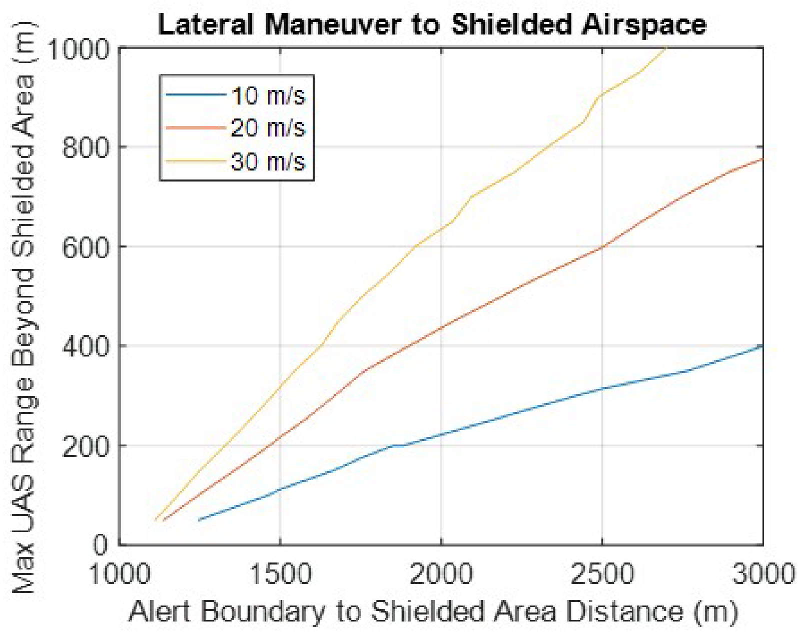

Fig. 14 UAS lateral limits vs TASA boundary placement

Fig. 15 presents a parametric analysis of the TASA boundary placement when the probability of alerting at the boundary is less than 100%. This example assumes a UAS speed of 10 m/s laterally. TASA installations are often constrained by property ownership/access, local terrain, and placement of large structures. If TASA nodes were installed in suboptimal locations due to such constraints, the probability of alerting could be determined by SARA and the UAS operational limits could be found in Fig. 15.

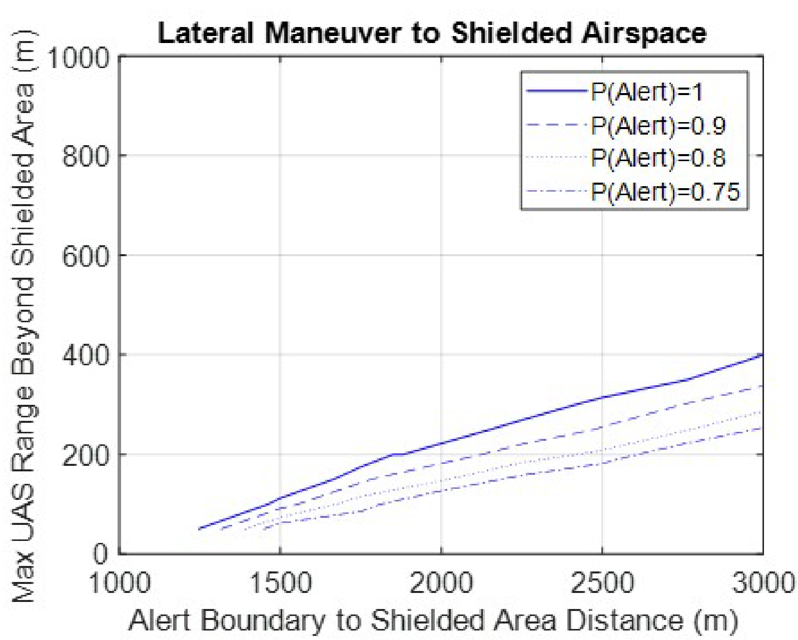

Fig. 15 UAS lateral limits vs TASA Boundary probability of alert

3.4.2. TASA analysis using a vertical maneuver to a shielded area

SARA performed a variant of the above TASA analysis where the UAS operates above a Shielded Area and descends to the shielded area if TASA alerts. All other simulation parameters were unchanged. Fig. 16 shows a parametric evaluation of UAS descent speed, ranging from 3 m/s, typical for most quadcopters, to 7 m/s, typical for the Puma. As one would expect, UAS that can descend faster can operate at higher altitudes, all else being equal. The lateral separation between the TASA alert boundary and the shielded area lateral boundary is plotted on the x-axis. The left y-axis shows the maximum allowed UAS height, in meters, above the Shielded Area such that the ASTM risk ratios for NMAC and Loss of Well Clear are met. The right y-axis is the same metric but displayed in feet. The study stops at 300 feet above the shielded area, assuming a typical shielded area will extend up to 100 feet AGL, making 300 feet on the plot correspond to 400 feet AGL, which is the maximum UAS altitude allowed under Part 107. The plot assumes a 100% probability of TASA alerting when an aircraft crosses the alert boundary.

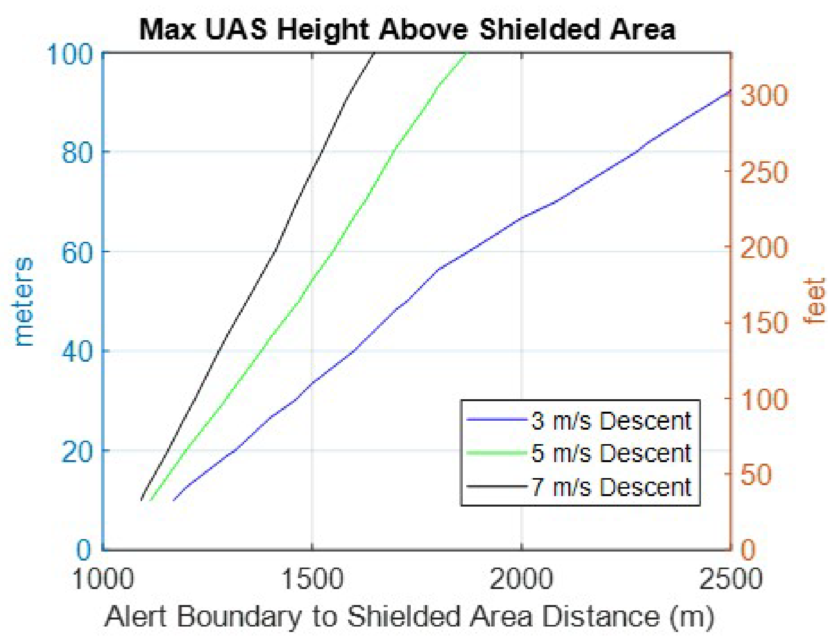

Fig. 16 UAS vertical limits vs TASA boundary placement

Fig. 17 presents a parametric analysis of the TASA boundary placement when the probability of alerting at the boundary is less than 100%. This example assumes a UAS descent speed of 3 m/s. TASA installations are often constrained by property ownership/access, local terrain, and placement of large structures. If TASA nodes were installed in suboptimal locations due to such constraints, the probability of alerting could be determined by SARA and the UAS altitude limits could be found in Fig. 17.

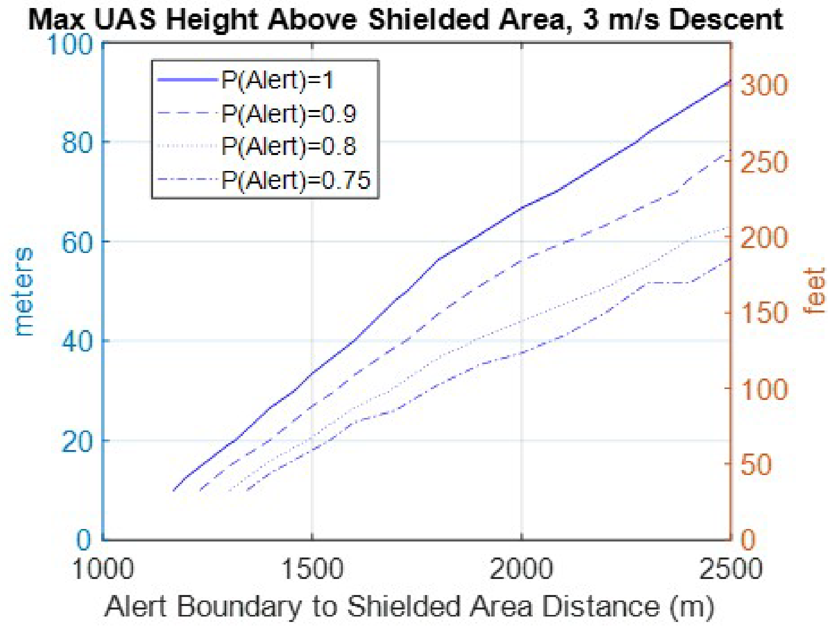

Fig. 17 UAS vertical limits vs TASA probability of alert

3.4.3. PANCAS analysis using a lateral maneuver to a shielded area

In this simulation, a UAS equipped with PANCAS detects an approaching aircraft, turns, and moves to the closest shielded area. The range at which PANCAS detects the aircraft is randomly sampled from a distribution fit to the Simi Valley flight test results shown in Fig. 11. In most applications, PANCAS sends maneuver commands directly to the UAS autopilot, which was simulated as occurring instantaneously. In this example, simulation included a 6-second latency for the UAS to turn and achieve the desired heading. This is based on the Puma's 15°/sec turn rate. The scenario envisions the Puma flying along a long shielded area, such as a utility line or pipeline. If the Puma had to maneuver to the shielded area, it would nominally require a 90° turn, which could be completed in 6 seconds at 15°/sec. Fig. 18 shows a parametric sweep of the initial lateral separation between the PANCAS-equipped UAS and the nearest shielded area, labeled the starting range. . The simulation begins each time with the UAS at the specified starting range. This is a worst-case assumption, as one could reasonably assume the UAS would only spend part of its flight at this range. For each starting range SARA simulates10,000,000 randomized encounters with PANCAS and the same 10,000,000 encounters without PANCAS. Each intruder aircraft is simulated with its starting position sampled from a uniform distribution, placing it within ±20km cross range and ±20km down range from the UAS starting position.

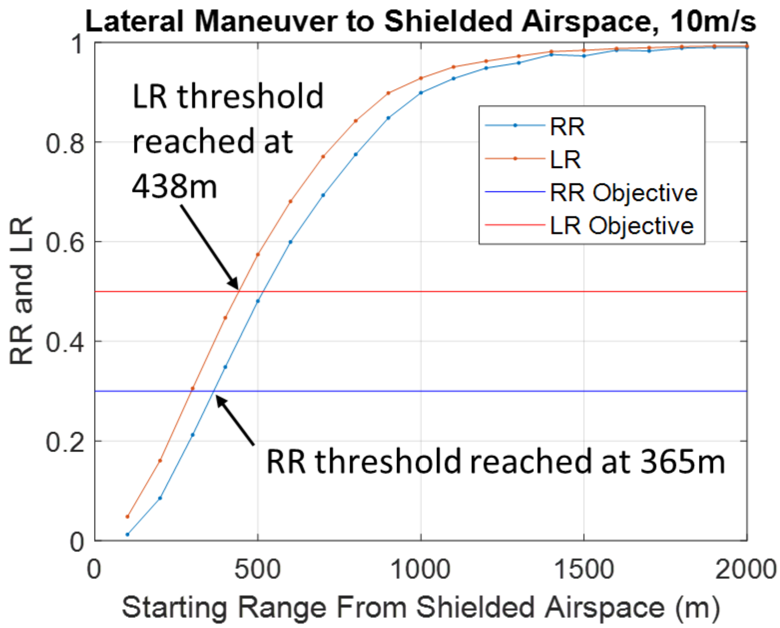

Fig. 18 PANCAS-equipped UAS lateral operating range limit for 10 m/s UAS

The intruder heading is sampled from a uniform random distribution between -180° and 180°, and its speed is sampled from a uniform random distribution between 21 m/s and 87.5 m/s. The minimum speed is an estimated stall speed for a single-engine fixed-wing general aviation aircraft and the maximum speed (170 knots) is a standard assumption used in several standards, including DO-365. After running the simulations, the two sets of results are compared to calculate RR and LR. We sweep through 20 different starting ranges to identify the maximum starting range which does not exceed ASTM F3442 performance requirements of RR≤0.3 and LR≤0.5. Thus, Fig. 18 represents a total of 400,000,000 simulated encounters. For this example, the PANCAS-equipped UAS could safely operate as much as 365m laterally beyond the closest shielded area. Note that this example assumes a UAS lateral speed of 10 m/s. Many UAS can travel significantly faster than this.

SARA repeated the analysis described above to a total of five UAS lateral speeds. These results are shown in Fig. 19. Note that the max allowable UAS speed under Part 107 is 44.7 m/s (100 mph). PANCAS has been tested and shown to function reliably up to 41 m/s.

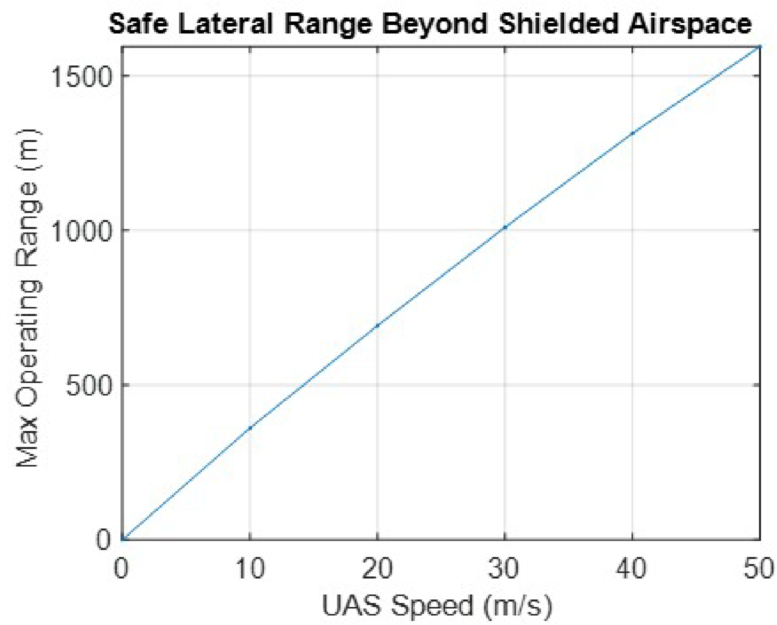

Fig. 19 PANCAS-equipped UAS lateral operating range limit vs UAS speed

Finally, SARA considered scenarios with degraded PANCAS performance in simulation to illustrate the systems margin for performance. To address this, SARA performed another parametric sweep of this simulation, now varying PANCAS alert range. During testing in Simi Valley, the average range was 3.16km. The simulation applies a log-normal fit to the flight test results and measures a standard deviation of the distribution. For each simulated alert range, the same standard deviation is retained while the average value is adjusted.

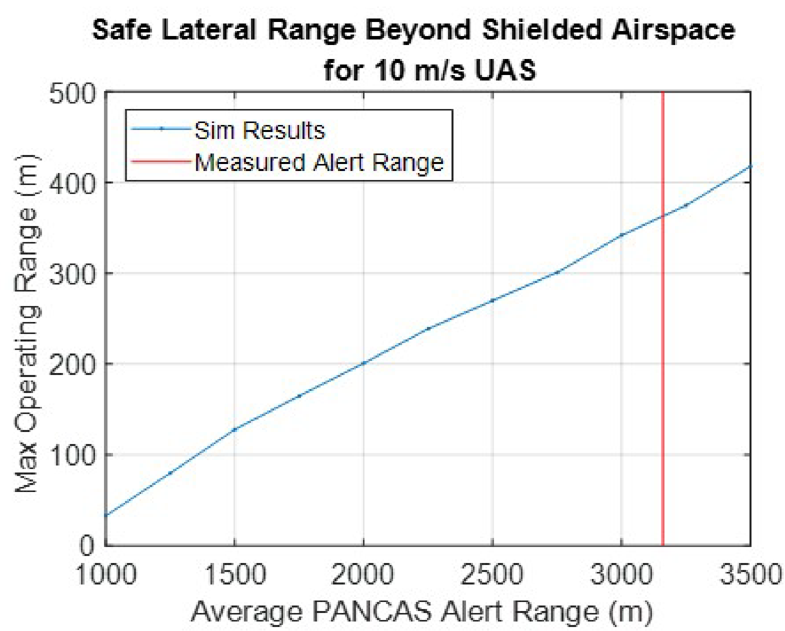

Fig. 20 UAS lateral operating range limit vs PANCAS performance

3.4.4. PANCAS analysis using a descent maneuver to a shielded area

SARA created a second statistical encounter simulation for use cases where the UAS is operating above a shielded area and will descend if PANCAS detects an intruder aircraft. The same simulation parameters for the intruder aircraft as in the lateral maneuver model were used. A parametric analysis was again performed, this time simulating a UAS with 10 m/s lateral speed and 3 m/s descent speed. The PANCAS average alert range varied between 1km and 3.5km. For reference, the flight test results showed PANCAS on Puma performance to be 3.16km, indicated by a vertical red line on the plot. Fig. 21 shows the result of the parametric analysis as a blue line. Assuming the shielded area extends 100 feet above the ground, the UAS could only climb an additional 300 feet before reaching the 400-foot AGL limit for Part 107 operations. Accordingly, a black horizontal line has been plotted at 300 feet. UAS operations could be safely conducted at 400 feet even with a suboptimal PANCAS integration providing a 2.5km alert range. The standard 3.16km alert range measured during testing thus provides a significant margin and would easily enable UAS operation up to 400 feet AGL above shielded areas. The simulated descent speed of 3 m/s is easily achievable by most UAS. The DJI Matrice 300 we tested in Barstow descended at a steady 3.75 m/s. The Puma can reliably descend at 7.5 m/s.

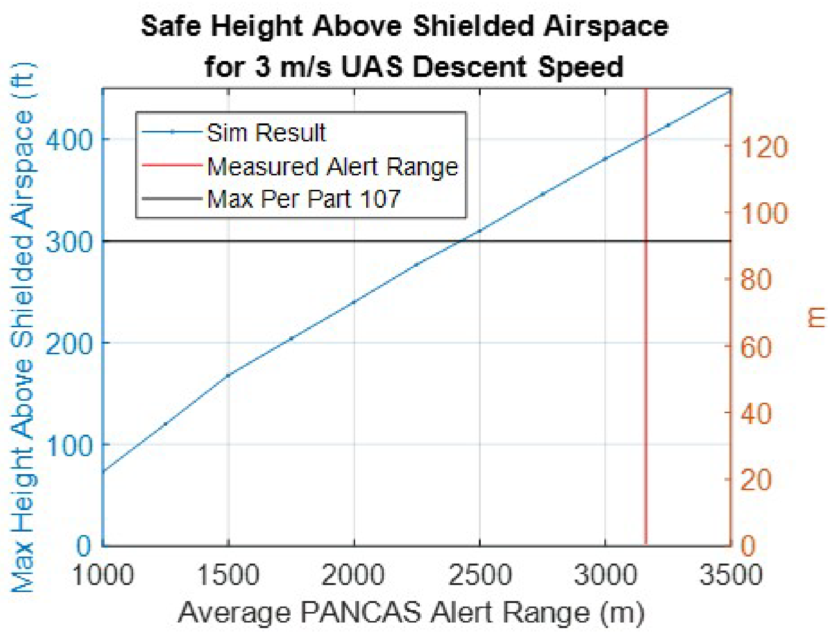

Fig. 21 UAS Altitude Limit vs PANCAS performance

3.5. TASA Machine Learning Classifier Test Results

In many acoustic environments, the standard PANCAS and TASA alerting algorithms are appropriate and sufficient. These are the results reported in Sections 3.2 and 3.3. In some busier environments, acoustic clutter can cause false alarms. SARA typically bolsters TASA performance in these environments by decreasing the spacing between TASA nodes, such that they have overlapping coverage. The TASA nodes can then combine their data, triangulating targets and effectively rejecting many false alarm sources. BNSF's Intermodal Facility in Barstow is a particularly challenging environment for TASA due to the constant, loud, low frequency sounds of trains, semi-trucks and heavy machinery. This environment results in shorter than normal detection ranges, as shown in Fig. 10, as well as high false alarm rates. To reduce TASA's false alarm rate in acoustically challenging environments, SARA has been evaluating the use of a machine learning (ML) classifier. The standard PANCAS and TASA software does not use ML, which can be advantageous for future certification efforts. The ML classifier is a Random Forest which takes in audio data and outputs a confidence level of that audio data containing an aircraft signature. This is a modular approach, which allows the ML classifier to run on a separate processor, which is a desirable feature for future certification efforts. The ML classifier is a learned AI implementation, opposed to learning AI implementation, meaning the ML classifier has been developed through offline training and is static in the runtime environment. The ML classifier was tested in Barstow, where it reduced false alarms by more than 90%. The same ML classifier performed well in different locations about the Barstow railyard and should work well in other railyards. Implementing the ML classifier in acoustic environments substantially different than a railyard will require retraining the model, which is easily done. As TASA nodes are deployed in more acoustic environments, the ML model with become generalized and will no longer require re-training. More detailed results may be found in the proprietary version of this document.

3.6. Human Machine Interface

SARA's combined display for PANCAS and TASA, see Fig. 8, reliably provided unambiguous, timely, and actionable information to the PANCAS/TASA operator. SARA recommends that, whenever possible, UAS operators integrate PANCAS and/or TASA directly into the UAS control software, such that an avoidance maneuver is automatically triggered as soon as PANCAS/TASA issue a command to avoid. The avoidance maneuver itself should be pre-planned and deterministic, consisting of a lateral maneuver or descent to the closest shielded area. The UAS should also perform this maneuver if PANCAS/TASA report a critical error or if their heartbeat messages are not received in time. In such applications, the PANCAS/TASA display would be primarily informational and wouldn't require constant human monitoring during operations. This level of automation requires integration that could not be accomplished under this project, so the tests in Barstow and Simi Valley relied on a PANCAS/TASA operator monitoring the display and verbally relaying commands to the co-located RPIC. We believe that this human-in-the-loop approach is sufficient for safety, but not preferred due to the potential for human delays and errors.

The PANCAS/TASA terminal operator monitored DAA system health on the display via two indicators. First, the small circular icon overlaid on the satellite image, indicating TASA/PANCAS position, reported sensor health via color coding. The sensor itself was continuously running system checks twice a second to verify that all microphones were functional, software processes were executed on time, and network connections had acceptable latencies between the sensor and the terminal. Any safety critical issue at the node (there were none) would have caused the icon to change from green to yellow or red, depending on severity. Second, a Wi-Fi symbol icon on the lower right of the display indicates the data latency between the terminal and the TASA server. If latencies were high, this would have helped identify if the issue was on the sensor side or on the terminal side of the network.

TASA/PANCAS acoustic tracks were displayed on top of the satellite image. This information provided general awareness to the operator and primed them for an upcoming alert. However, this level of information is likely too detailed if the RPIC were monitoring the display directly, rather than relying on a TASA/PANCAS operator. SARA trains RPICs to focus on their primary flight display and simply listen for the audible alerts generated by the TASA/PANCAS terminal, accompanied by a flashing alert symbol. When the RPIC hears the alert, they should initiate the avoidance maneuver.

For several reasons, audible alerts were silenced during testing in Simi Valley and Barstow. First, audible alerts are generated from TASA, PANCAS, and ADS-B sensors. Since our intruder aircraft was equipped with ADS-B out, ADS-B alerts were often generated before the aircraft was detected by PANCAS or TASA. Since only TASA and PANCAS were being evaluated, the team wanted to avoid interference from audible ADS-B alerts. Second, in Simi Valley, TASA and PANCAS data were streaming to the same terminal, but the goal was to avoid based on PANCAS alerts. Silencing the audible alerts allowed the PANCAS operator to suppress TASA alerts. Finally, in Barstow, the terminal was reporting alerts using SARA's standard TASA software, opposed to the better performing ML software which was being evaluated offline. The railyard environment caused false alarms which were silenced so they would not interfere with the test. For both the Simi Valley and Barstow tests, the TASA/PANCAS terminal operator visually observed an alert on the screen generated by the system under test (TASA or PANCAS) and then verbally communicated to the co-located RPIC to begin the avoidance maneuver.

It is assumed the time for the RPIC to react to a human voice versus an alarm sound is the same. The test team recorded when the TASA/PANCAS terminal operator called for an avoidance maneuver and compared this to when the UAS began the avoidance maneuver. This includes the time for the RPIC to recognize the verbal command, react by manipulating the UAS controls, the data transmission time to the UAS, and the time for the UAS to process the command and activate the appropriate control surfaces / motors. Given the line-of-sight operations, the RPIC response time is expected to comprise most of this timeline. Due to limitations of the UAS telemetry logs, timing was only resolvable to the nearest second. A histogram of the timing results of the May test in Barstow is shown in Fig. 22. Most often, the time between alert and avoid was one second.

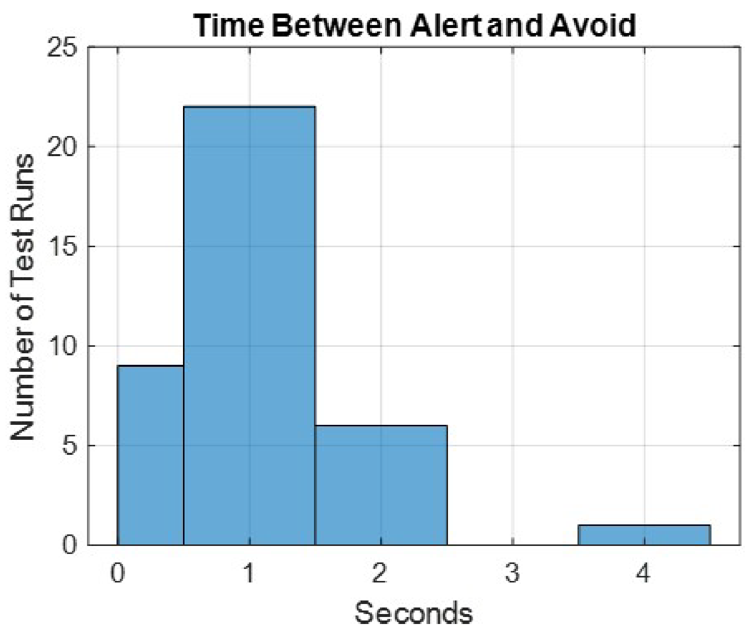

Fig. 22 Time between alert and avoid

These results are in line with the available literature (Kosinski, 2013) which report reaction times less than half a second. The RPIC had to press a few buttons on the controller, first pausing the flight, then commanding the maneuver. This could easily increase the time to the observed 1-2 seconds.

4. Conclusions and Future Work

SARA and NPUSTS have completed a series of tests to evaluate the performance of visual observers, PANCAS, and TASA in the context of small UAS operations in and around shielded areas. SARA used those test results to perform a series of test-anchored simulations which evaluated the safety of the UAS operations against the ASTM F3442 Risk Ratios for noncooperative aircraft. SARA concludes that small UAS BVLOS operations above or alongside shielded areas can be safely conducted when supported by PANCAS and/or TASA. The operational limits of those operations, such as altitude, lateral range beyond a shielded area, UAS speed, and system latencies have been defined for many use cases. In general, these DAA systems enable UAS to operate hundreds of meters laterally beyond shielded areas, and up to 400 ft AGL above shielded areas. It is presumed that this level of flexibility is more than enough to support UAS operations directly related to the critical infrastructure near which they are flying. It is SARA's hope that the provided analyses will be broadly applicable and can help streamline the evaluation and approval of relevant BVLOS waiver requests.

The concept of maneuvering a UAS to a shielded area to avoid a crewed aircraft appears to be viable from the tests and simulations performed. However, several encounter geometries were observed both during flight test and in simulation where, by moving toward the shielded area, the UAS was moving closer to the crewed aircraft. The farther the UAS operates beyond shielded areas, the more often these scenarios occur. For UAS operations unrelated to shielded areas around critical infrastructure, future research should focus on developing and testing avoidance maneuvers which allow the UAS and crewed aircraft to remain well clear of each other and remain in navigable airspace. An example of such software would be the FAA's ACAS sXu. Significant work remains to successfully integrate passive sensors such as PANCAS and TASA with sXu and to create a standard set of minimum operational performance standards.

Appendix A PANCAS AND TASA DAA SYSTEM BVLOS DATA PACKAGE

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TECHNICAL DOCUMENTATION

PANCAS and TASA DAA System BVLOS Data Package

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
This technical document describes SARA's Passive Acoustic Noncooperative Collision Avoidance System (PANCAS) and Terrestrial Acoustic Sensor Array (TASA). It includes technical specifications, instructions for installation, operation, and maintenance. The document is intended to assist users of PANCAS and/or TASA in requesting authorization from the FAA or other certifying authority to operate their uncrewed aircraft beyond visual line of sight.

15. SUBJECT TERMS
BVLOS, DAA, Acoustic, UAS

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List of Acronyms

Acronym	Definition
ASTM	American Society for Testing and Materials
BVLOS	Beyond Visual Line of Sight
CPA	Closest Point of Approach
DAA	Detect and Avoid
dB	decibels
FAA	Federal Aviation Administration
JARUS	Joint Authorities for Rulemaking on Unmanned Systems
LR	LoWC Ratio
LoWC	Loss of Well Clear
ms	milliseconds
NMAC	Near Midair Collision
PANCAS	Passive Acoustic Noncooperative Collision Avoidance System
RR	NMAC Risk Ratio
RPIC	Remote Pilot in Command
VLOS	Visual Line of Sight
TASA	Terrestrial Acoustic Sensor Array
UAS	Uncrewed Aircraft System
VO	Visual Observer

1. How to Use This Data Package

SARA has prepared this data package to support Uncrewed Aircraft Systems (UAS) operators using SARA's Passive Acoustic Noncooperative Collision Avoidance System (PANCAS) or Terrestrial Acoustic Sensor Array (TASA) Detect and Avoid (DAA) systems. The provided information is particularly relevant to UAS operators who wish to fly their UAS beyond visual line of sight (BVLOS) and are therefore applying to the Federal Aviation Administration for a waiver to 14 CFR §107.31.

BVLOS waiver applicants shall follow the guidance in this document whenever applicable to ensure that TASA and PANCAS products are being used as intended. Violating the assumptions of use may result in TASA and PANCAS products not providing the expected level of safety. SARA offers support for the entire mission lifecycle, including application of waivers to 14 CFR §107.31.

Aspects of this data package may also inform the thought process of operators using other DAA technologies, as well as operators seeking BVLOS authorization from certifying authorities other than the FAA. Operators should take care to balance their operational objectives against the capabilities and limitations of their UAS and the DAA system. Consulting subject matter experts like SARA can streamline the planning and approval process.

1.1. Shielded Areas

This data package considers maneuvering UAS to shielded areas to remain safely separated from crewed aircraft. Applicants shall work with the aviation authority responsible for the airspace in which the UAS operations will occur to define the extent and boundaries of all shielded areas.

2. Referenced Documents

- TAS-D0007_TASA Installation Manual V02, SARA document.
- TAS-D0030_TASA User Terminal Manual_V02, SARA document.
- ASTM F3442/F3442M-20 Standard Specification for Detect and Avoid Systems Performance Requirements.
- JARUS Specific Operations Risk Assessment (SORA) (package) V2.0, 30 January, 2019.

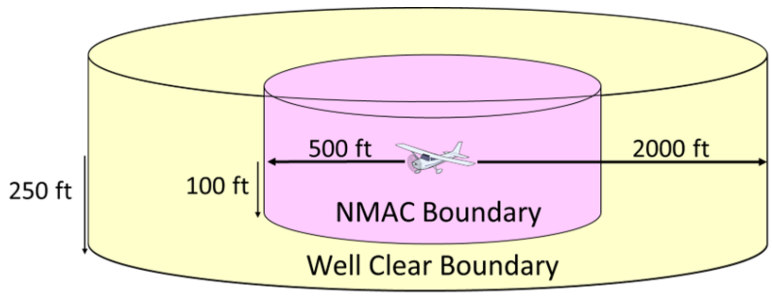
3. SCOPE

PANCAS and TASA are used in several applications but most commonly for airspace surveillance in support of UAS operations. They detect and track crewed aircraft, issue traffic alerts, and provide resolution advisories for the UAS to follow and remain well clear of crewed aircraft. There are many types of UAS with many unique use cases. UAS may operate anywhere from the surface up to above 60,000 ft, within all airspace categories. Their size, flight characteristics, and equipage vary significantly as well.

SARA has attempted to align the scope of this document with the scope of the ASTM F3442/F3442M-20 Standard Specification for Detect and Avoid Systems Performance Requirements. Specifically, this document applies to uncrewed aircraft with a maximum dimension ≤ 25 ft, operating at airspeeds below 100 knots, and of any configuration or category. It is intended to be applied to UAS operations near shielded areas, with the UAS avoidance maneuver being a return to the closest shielded area. As crewed aircraft are already in the habit of avoiding shielded areas, the airspace in the vicinity of shielded areas is “lower risk” [low- and medium-risk airspace as described by Joint Authorities for Rulemaking on Unmanned Systems (JARUS)]. The area where the UAS will operate BVLOS should be well defined, bounded, and well characterized in terms of airspace, geography, obstructions, command and control link reliability and latency, etc.

4. Requirements

In this document, it is presumed the UAS operator is developing a BVLOS capability in compliance with the ASTM F3442/F3442M-20 Standard Specification for Detect and Avoid Systems Performance Requirements. This document will focus on the set of logic Risk Ratio requirements put forth in the standard, specifying the performance of a DAA system against cooperative and non-cooperative aircraft in terms of preventing a Loss of Well Clear (LoWC) and avoiding a Near Midair Collision (NMAC). Figure 1 depicts the Well Clear and NMAC boundaries, the equation for RR, the NMAC Risk Ratio, and the equation for LR, the LoWC Risk Ratio. The table defines the four Risk Ratio requirements.



	NMAC Risk Ratio (RR)	LoWC Risk Ratio (LR)
Cooperative	≤0.18	≤0.40
Noncooperative	≤0.30	≤0.50

$$RR = \frac{Prob\ of\ NMAC\ with\ DAA}{Prob\ of\ NMAC\ without\ DAA}$$

$$LR = \frac{Prob\ of\ LoWC\ with\ DAA}{Prob\ of\ LoWC\ without\ DAA}$$

Figure 1: Risk Ratio Requirements and Definitions

5. TASA

SARA's Terrestrial Acoustic Sensor Array (TASA) is a ground-based detect and avoid (DAA) system. It uses passive acoustics to detect and track aircraft without the need for transponders or any RF emissions from the aircraft. A TASA node is shown in Figure 2. An array of acoustic probes connects to an edge processor, which computes aircraft tracks. While airspace may be monitored with a single node, it is more common for multiple TASA nodes to be deployed over an area. The TASA nodes transmit tracks via LTE cellular, LAN, or WLAN to a central server. The central server combines all TASA tracks and provides a consolidated airspace picture to the operator. UAS operators can use this airspace picture as part of their safety measures, replacing visual observers, as a key component of safe UAS operations beyond visual line of sight (BVLOS).

Figure 2: A TASA node, with acoustic array and edge processor

An example UAS operation supported by TASA is depicted in Figure 3. The image depicts a small UAS flying BVLOS, inspecting critical infrastructure. To remain safely above terrain and to optimize sensor payload performance, the UAS is operating at 400 ft AGL. TASA nodes are stationed along the flight route, providing airspace surveillance. During the operation, a low-flying crewed aircraft approaches, unaware of the UAS operation, on a collision course. This is depicted as the intersection of the orange and red arrows, circled in yellow. TASA detects the sounds emitted by the crewed aircraft (drawn as red waves), computes a track and identifies the collision hazard. TASA automatically alerts the UAS (the magenta radio wave), which quickly descends to the shielded area above the critical infrastructure, indicated by the green line. Once the crewed aircraft has departed, TASA gives the all-clear for the UAS to climb back up to its mission altitude and resume its inspection flight.

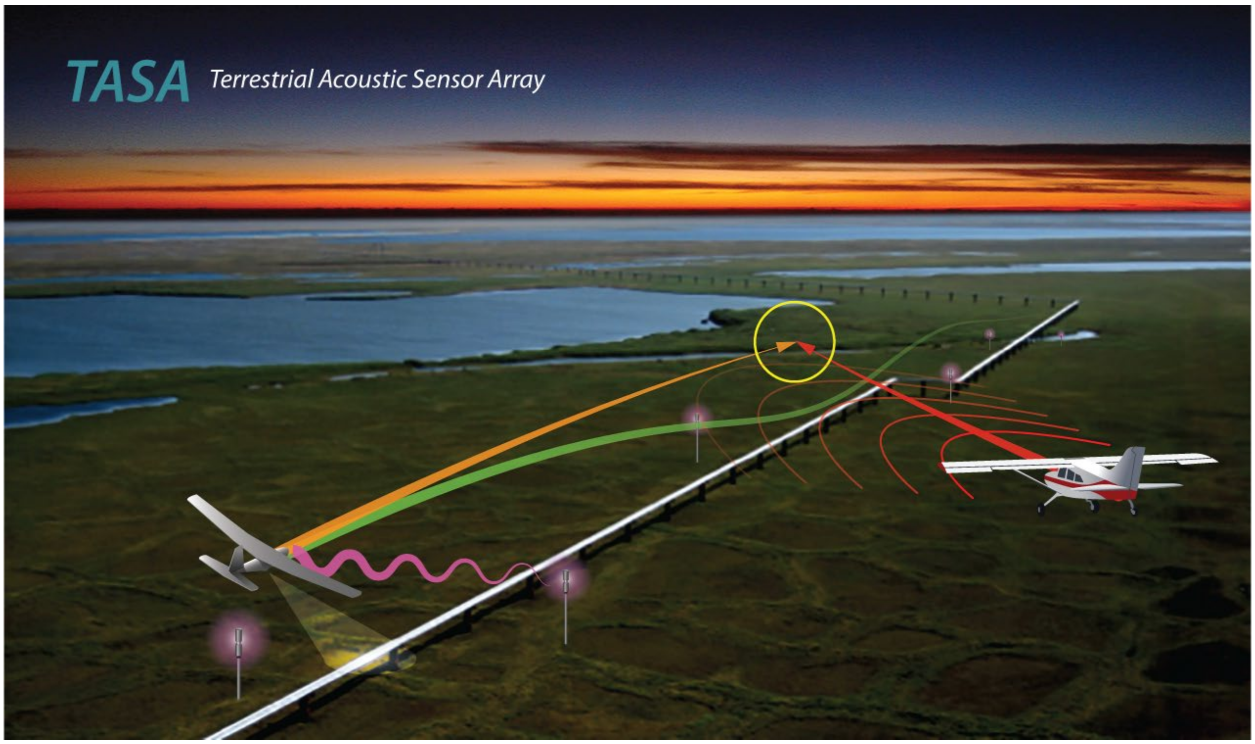


Figure 3: BVLOS UAS operation using TASA for DAA

5.1. TASA Node Specifications

TASA Node Specifications are provided in Table 1. TASA nodes have been tested extensively in real-world environments, including extended operations in extreme temperatures, winds, and precipitation. TASA nodes have proven to be highly reliable and low maintenance.

Table 1: TASA Node Specifications

TASA Node Specifications	
Model Number	TA-100000
Acoustic Probes	8
Performance (nominal conditions)	
Field of Regard	Azimuth: 360°, Elevation: surface to zenith
Detection Range	4.2 km (Cessna 172) radial
Bearing Resolution at Range	3.6° (Cessna 172)
Communication	
Wireless Network	3G, 4G LTE
Networks Supported	Verizon/ATT
Local Area Network	Ethernet
Flight Data Recorder	Integrated
Positioning	Integrated GPS
Environmental	
Temperature Rating	-40° C – 71° C
Windspeed Rating (Destructive)	100 mph *Optional upgrade to 150 mph*
Windspeed Rating (Operational)	35 mph
Ingress Protection (IP)	68
Electrical	
Input Voltage	12-30 VDC
Power (Steady)	15 W
Power (Peak)	25 W
Grounding	NFPA 70, National Electric Code
Mechanical	
Weight	17 lbs.
Enclosure Dimensions	17.4” x 16.5” x 8.7”
Deployed Dimensions	11 ft Diameter Sphere
Mounting Height (AGL)	20-50 ft
Mast Mount Interface	1-1/2” Pipe Fitting

5.2. Environmental Testing

TASA has been evaluated and operated across the United States in extreme environments, including:

- Extended cold below -20° F

- Extended heat above 100° F
- Snow
- Icing
- Driving rain
- Salt fog
- High wind

SARA supplemented this real-world environmental testing with laboratory testing for factors such as water submersion, hurricane-force winds, and vibration. Some samples of TASA environmental testing are shown in Figure 4.

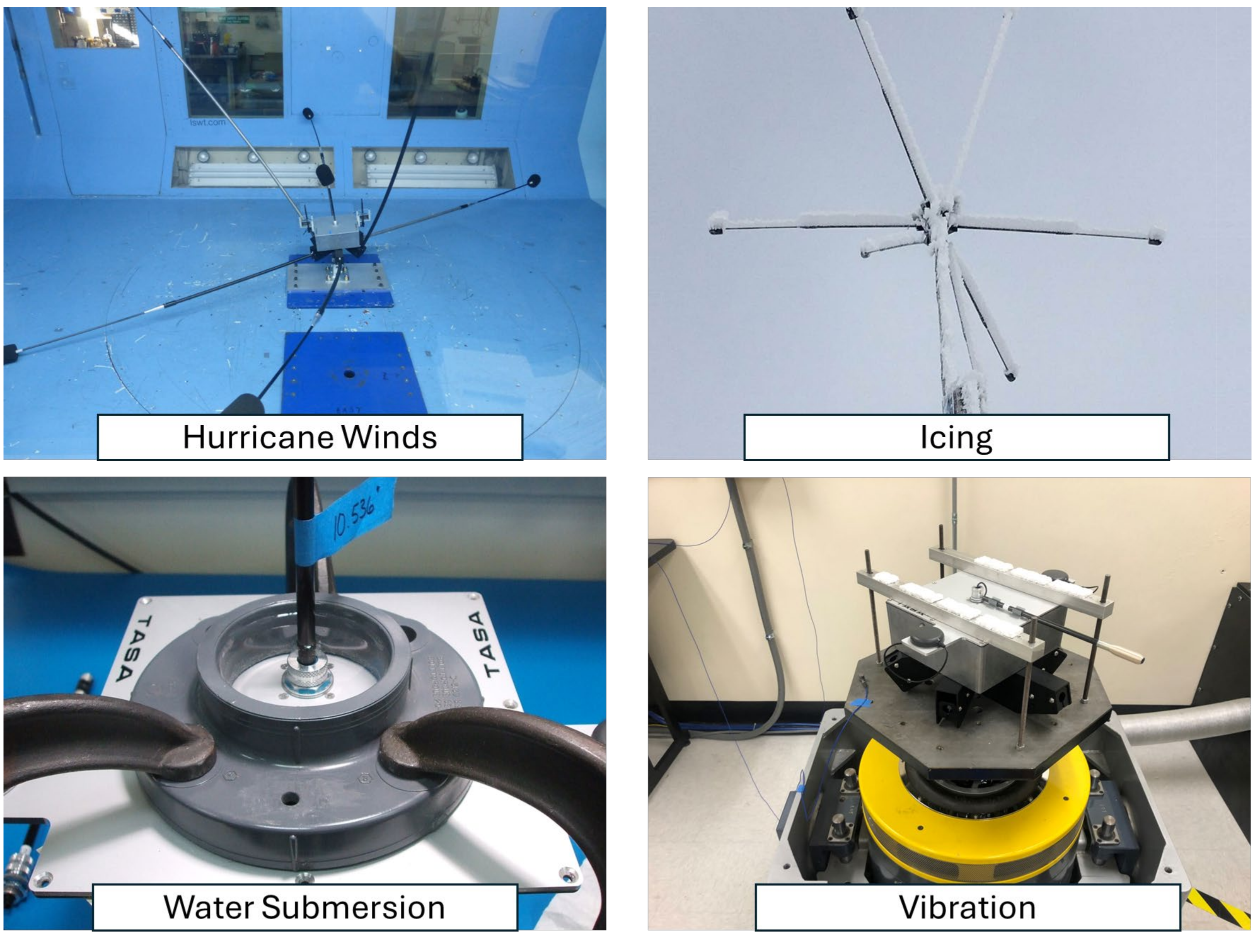


Figure 4: Sample Environmental Tests Performed

5.3. Health Monitoring

TASA software processes run on timed loops. Each loop is monitored, and a warning is issued if any process exceeds its time budget or does not complete. Health and status messages are transmitted twice a second. These messages also serve as a heartbeat, which external systems such as the TASA Terminal display or a UAS ground control station can use to verify TASA nodes are fully functional. Health and status messages include checks for:

- Microphone functionality / connectivity
- Configuration file present and successfully read
- FPGA initialization
- Algorithm execution time
- Algorithm throughput
- Network connectivity
- RTOS monitoring
- CPU monopolization
- File hash consistency checks
- Data recorder connectivity
- GPS connectivity
- LED indicator light functionality
- Ambient noise levels

5.4. Communications Latency Testing

The time required to transmit data from a TASA node to the remote pilot must be quantified as part of the timing analysis required in the ASTM Detect and Avoid Performance Standard. We have separated this analysis into two segments, the time to transmit data from the TASA node over the LTE cellular network to the TASA cloud server (upload time), and the time to transmit data from the cloud server to the TASA Operator Display (download time).

Over 30 days of continuously operating a 5-node TASA network, SARA measured the time for a TASA node to send a message over the LTE cellular network to a TASA cloud server. Out of 5.5 million messages sent, the average upload time was 254 milliseconds. Of the millions of messages, 107 messages were corrupted or not received by the cloud server, totaling 0.00195% of all messages. The transmission time includes several stages of handshaking between TASA and the cloud server, which highlights the possibility of reducing the transmission time in the future if desired. However, the current performance is sufficient for almost all applications. A histogram of upload time results is provided in Figure 5.

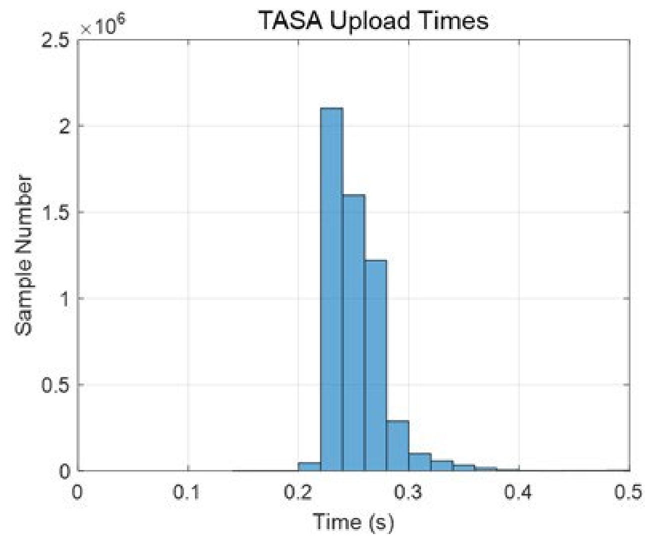


Figure 5: TASA message upload time

SARA measured the download time between the TASA cloud server and the TASA operator display. Out of 102 million samples, the average download time was 15 milliseconds. Of those samples, 919,000 download attempts failed, representing a 0.9% failure rate. Even though this is a small percentage, the real-world impact is even smaller. If a download attempt fails, the TASA terminal will retry within 100 milliseconds, and it is extremely unlikely that two consecutive download attempts.

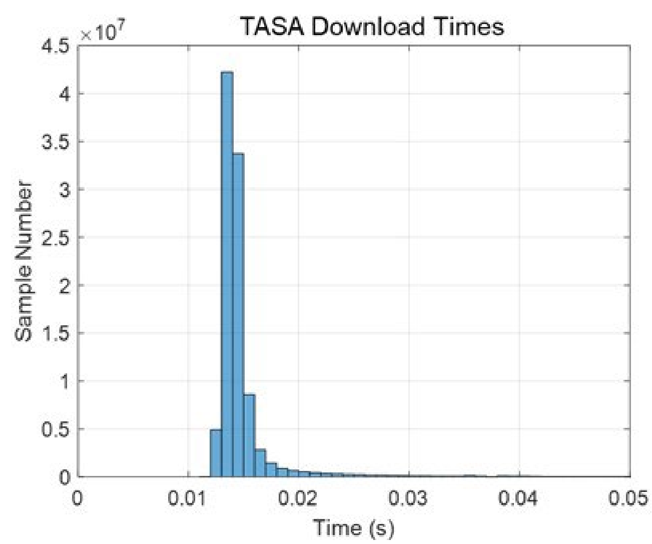


Figure 6: TASA message download time

5.5. TASA Operator Display

SARA provides a TASA software application that can be used as an operator display. The application also outputs alerts as a message stream which can be sent directly to a UAS to initiate automatic maneuvers to shielded areas. Figure 7 shows the display. TASA node locations are indicated by a green circular icon, with the TASA node ID in the center of the circle. PANCAS system locations are also viewable on this display. In this example, the left green circle represents a TASA node, and the right green circle represents a PANCAS system. Both systems are shown detecting a nearby crewed aircraft. Red beams indicate the direction of the acoustic detections, and the crewed aircraft position is at the intersection of the beams. The TASA operator display includes an ADS-B overlay for detecting and avoiding cooperative traffic. The crewed aircraft's ADS-B reported position and heading is indicated with a purple arrow with its tail number and altitude displayed in an adjacent black box. An alert symbol in the lower left corner appears and flashes when a collision hazard is identified. This is accompanied by an audible alarm. These indicators persist until the operator acknowledges and dismisses them.

Figure 7: TASA Operator Display

For most use cases, TASA nodes are installed around a UAS operations area to form a perimeter. An example of this is shown in Figure 8. The black dashed line drawn between five TASA nodes bounds a UAS operating area. The white dashed line beyond this is the TASA alert boundary. When two TASA nodes triangulate an aircraft position within this boundary, TASA will issue an alert and the UAS must begin maneuvering to the closest shielded area.

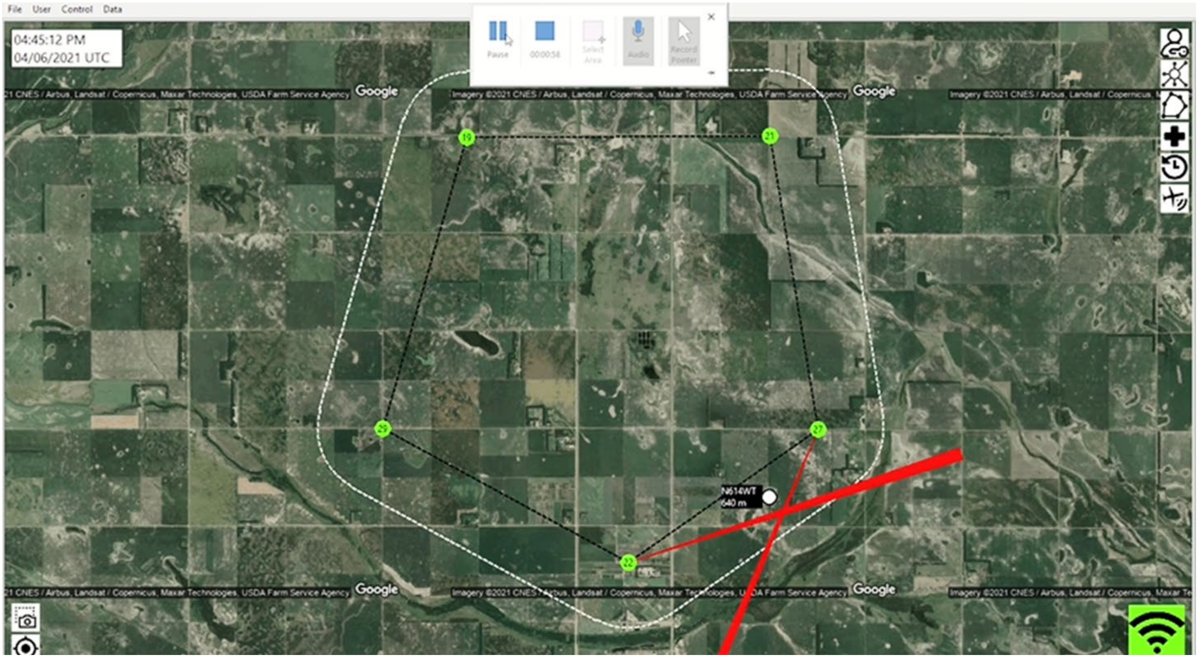


Figure 8: Five TASA nodes forming a perimeter

5.6. TASA Integration

TASA integration is accomplished in three phases: planning, installation, and verification. With careful and detailed planning, the installation and verification phases can be completed very quickly. While detailed planning is required, most of the planning questions should be easy for UAS operators to answer.

5.6.1. Planning

The planning phase focuses on identifying requirements and capabilities of the proposed BVLOS system. Common requirements are listed below:

- Mission Requirements
  - UAS operating boundary (latitude, longitude, altitude)
  - Maximum desired distance beyond closest shielded area
  - Identify phases of flight that cannot easily be interrupted, such as transitioning from VTOL to forward flight, or lowering a package
  - Airspace class, nearby airports, types of aircraft that could be reasonably expected
- UAS Maneuverability Requirements
  - Turn rate
  - Lateral speed
  - Descent speed

- TASA Boundary Placement Requirements
    - Distance between TASA Alert Boundary and UAS operating boundary
    - Property access in the surrounding area
- Communications Requirements
    - UAS command and control link reliability and latency
    - Cellular availability for TASA networking, or is LAN / WLAN required?
- Emergency Procedure Requirements
    - Lost link procedures
    - Lost DAA procedures

Other requirements may be discovered during the BVLOS application process. Generally, these requirements must be balanced against each other until an achievable set of requirements is identified. For example, if the TASA boundary requirements for a pilot-in-the-loop maneuver are not implementable due to land access issues, an automatic maneuver capability may need to be implemented.

The planning phase should include an air collision avoidance timing analysis, in accordance with ASTM F3442 §6. The timing components for TASA to detect and alert are provided in Table 2. Timing parameters of the avoidance maneuver must be defined by the UAS operator based on the performance characteristics of the UAS. The maneuver parameter represents the time budget for the UAS to reach the closest shielded area. This parameter should be determined through simulation study results, as described in Section 5.6.1.2. The simulation balances many design considerations, including desired operational capability, UAS performance, and TASA installation location requirements.

Table 2: TASA Timing Analysis Parameter List

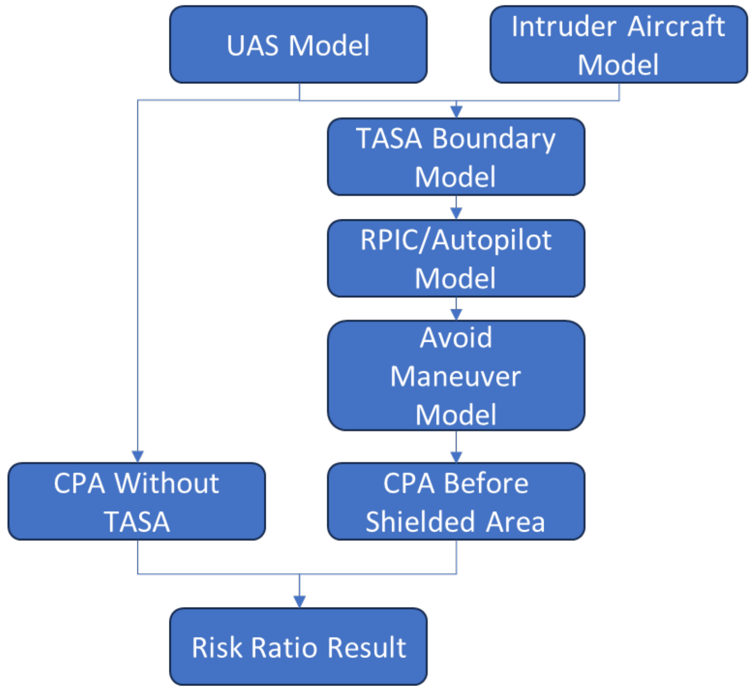
Timing Parameter	Value for TASA Network
t_Scan	1000 ms
t_Relay	269 ms
t_Filter	249 ms
t_Publish	1 ms
t_Classify	250 ms
t_Notify	Defined by UAS Operator
t_Plot	

t_Vector	
t_Translate	
t_Command	
t_Control	
t_Maneuver	Defined through simulation
t_Fix	Defined by UAS Operator
t_Telemetry	

5.6.1.1. Risk Ratio Simulation Setup

To aid BVLOS waiver applicants, SARA has performed Risk Ratio simulations for many common use cases. In this section, we describe the simulation setup and inputs. In Section 5.6.1.2, we provide simulation results for a variety of input parameters.

The Risk Ratio simulation approach is depicted as a flow diagram in Figure 9. The simulation uses a Monte Carlo approach which models a single UAS and a single crewed intruder aircraft. Millions of one-vs-one encounters are simulated, with each specific encounter simulated twice, one without a DAA system and one with TASA. Without TASA, the closest point of approach (CPA) is calculated as the minimum lateral separation between the UAS and crewed aircraft over all time. This can be computed analytically because they both fly constant speed, linear trajectories. With TASA, the CPA is calculated as the minimum lateral separation between the UAS and crewed aircraft over all time until the UAS reaches a shielded area.



CPA = Closest Point of Approach

Figure 9: Flow Diagram of Risk Ratio Simulation

The UAS model requires the following input parameters:

- Lateral speed
- Descent speed
- Reaction Time: Time to receive TASA Alert, compute the avoidance maneuver to the nearest shielded area, send the command to the UAS, plus time for the UAS to establish the new trajectory.

Given those inputs, the UAS Model simulates the UAS on a constant-speed constant-course trajectory.

The Intruder Aircraft Model samples lateral speed from a uniform random distribution between 40 knots and 170 knots, where 40 knots is a typical stall speed for fixed wing aircraft and 170 knots is a max airspeed used in several relevant standards, including ASTM F3442 and DO-365C. The intruder aircraft starting position relative to the UAS is sampled from a uniform random distribution between -10.8 NM and 10.8 NM cross range and down range. The intruder aircraft flies a constant-velocity constant-course track, where the course is sampled from a uniform random distribution between -180° and 180°.

Figure 10 shows a sampling of simulated intruder geometries. For reference, a 500 ft radius (152 m) red circle is drawn about the origin depicting the NMAC Boundary, and a larger 2,000 ft radius (610 m) red circle depicts the LoWC Boundary. Intruder tracks cross the plot randomly, with only some entering the LoWC or NMAC boundaries.

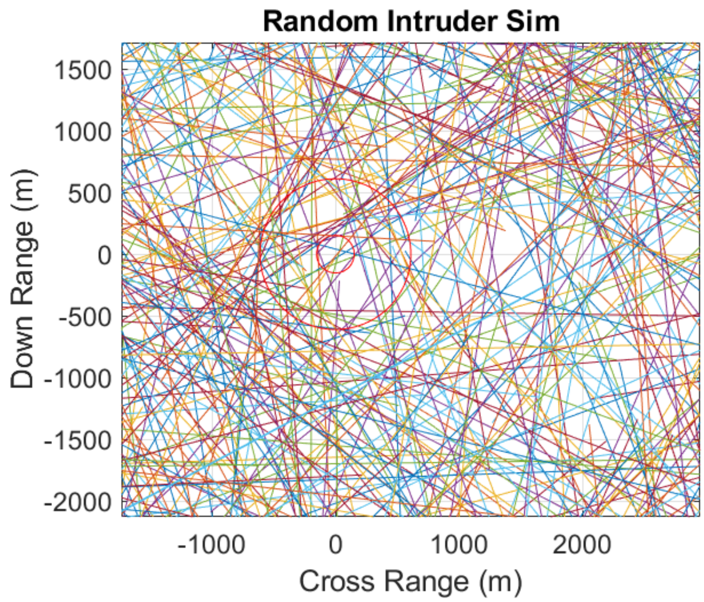


Figure 10: Sample Intruder Tracks from Risk Ratio Simulation

Simulating each shielded area geometry and every possible set of TASA positions quickly becomes an intractable problem. SARA has found it instructive to break the problem into two parts. First, SARA uses a risk ratio simulation to define the required location of a TASA Alert Boundary, which will be a fixed distance beyond the shielded area boundary. The simulation helps operators understand the trade between TASA Alert Boundary placement and the maximum safe operating range for the UAS beyond the shielded area. Second, outside the simulation, operators can locate TASA nodes along the TASA Alert Boundary according to the detection range performance SARA measured during flight testing under the FAA BAA Call 004 contract. Because each TASA node has a 360° field of regard, they do not need to be placed precisely along the TASA Alert Boundary, but rather can be placed, on, outside, or inside the boundary. This is an important capability, as land access constraints often play a large role in TASA node placement decisions. Figure 11 illustrates the concept of a TASA Alert Boundary enforced by a network of TASA nodes. Two of the most relevant parameters are called out, (1) the distance between the TASA Alert Boundary and the Shielded Area, and (2) the maximum safe operating range beyond the Shielded Area. These two parameters trend with each other. Note that this is a simplified illustration, and in practice the TASA Alert Boundary must completely surround the shielded area.

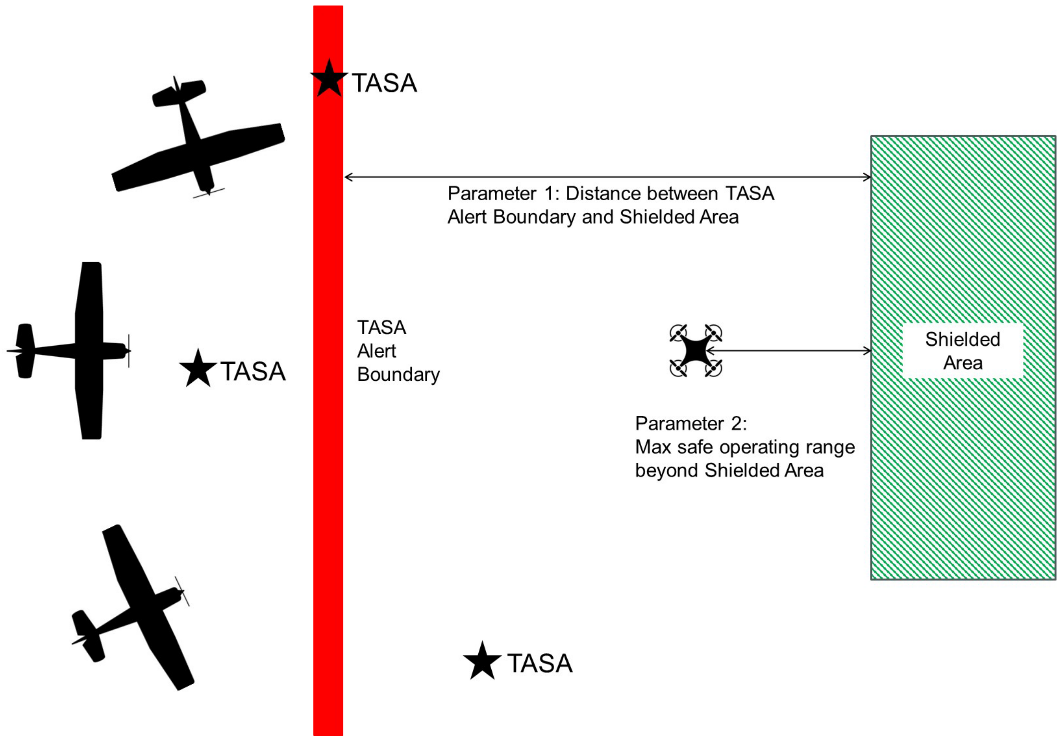


Figure 11: Depiction of TASA Alert Boundary

Given the intruder aircraft flight path, the TASA Boundary Model calculates the time at which the TASA Alert Boundary would have been crossed, prompting the UAS to maneuver to the shielded area. To simplify the simulation, the TASA Alert Boundary is conceptually placed a uniform distance beyond the shielded area. This results in the Risk Ratio results being impacted by the size and shape of the shielded area. An example of this is shown in Figure 12. Large, shielded areas result in a large TASA Alert Boundary, and intruder aircraft approaching from the far side of the shielded area will be alerted on very early. The blue line labeled R1 indicates the range between the UAS and an intruder aircraft crossing the TASA Alert Boundary from the left. The UAS has much less time to avoid compared to a different scenario where an intruder aircraft crosses the TASA Alert Boundary from the right. The R2 line is large because the Shielded Area is large. The most challenging case is very small, point-like shielded areas.

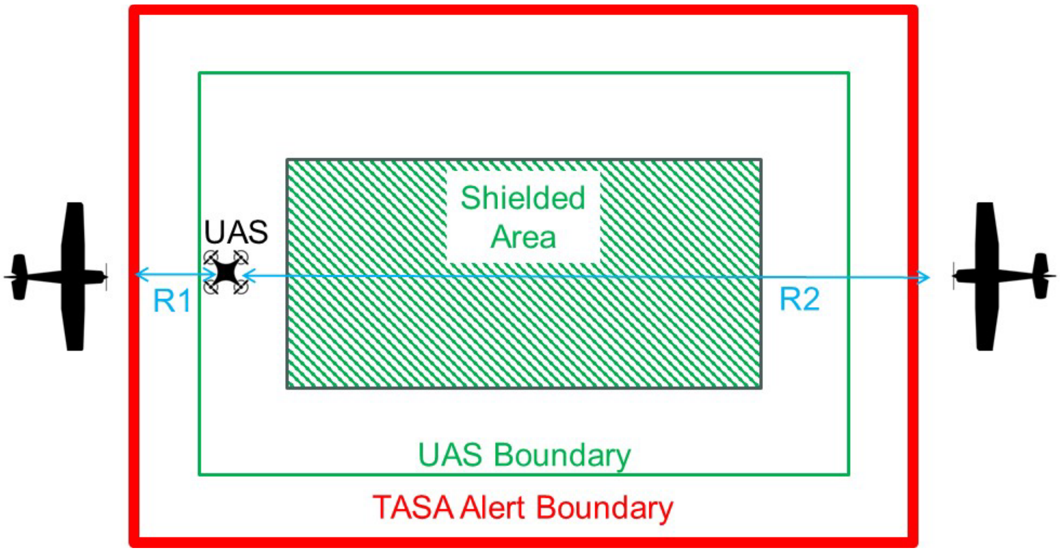


Figure 12: Time for UAS to avoid depends on intruder approach direction

Simulating every Shielded Area shape would be too large an undertaking for this project, so SARA has made a conservative simplifying assumption. The smaller the shielded area, the higher the resulting Risk Ratio. Conservatively, SARA simulated an infinitesimal shielded area placed at the origin, with a circular TASA Alert Boundary placed around it. This is depicted in Figure 13.

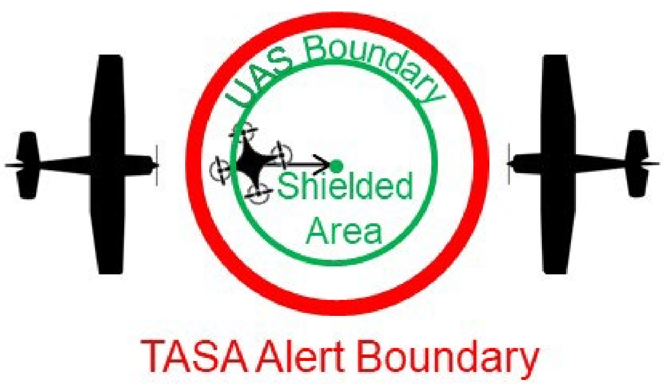


Figure 13: TASA Simulation Geometry

The RPIC/Autopilot Model is simply a time delay, meant to capture the delay between the alert being issued and the time at which the UAS achieves the commanded avoidance maneuver parameters. These parameters are defined in the Avoid Maneuver Model. The benefit of this approach is that it is very easy to measure this time delay in the field by recording TASA alerts and comparing them against the UAS telemetry logs. For the following TASA simulation studies, SARA selected a five second time delay, based on analysis of Barstow test results. The model name indicates that the timing model can accommodate automatic avoidance maneuvers as well as pilot-in-the-loop maneuvers. Pilot-in-the-loop can have a significant negative impact on the risk ratio results due to the increase in response time.

The Avoid Maneuver Model stops the UAS flight after TASA issues an alert and the RPIC/Autopilot time delay has expired. In a piecewise-linear fashion, the UAS then flies at a constant-speed constant-course route to the closest shielded area. The model is configurable to either simulate a lateral maneuver or a descent. Once the UAS reaches the shielded area, the test run ends and the CPA is calculated.

The Risk Ratio results for NMAC (RR) and LoWC (LR) are calculated according to the equations in Figure 1. SARA ensures that a statistically relevant number of test runs are simulated by observing the convergence of the RR and LR values. An example of this is shown in Figure 14. With a small number of trials, the RR and LR results are not repeatable. As the number of trials increases, the results converge and become repeatable. For this simulation, convergence occurs at 100,000 trials or more.

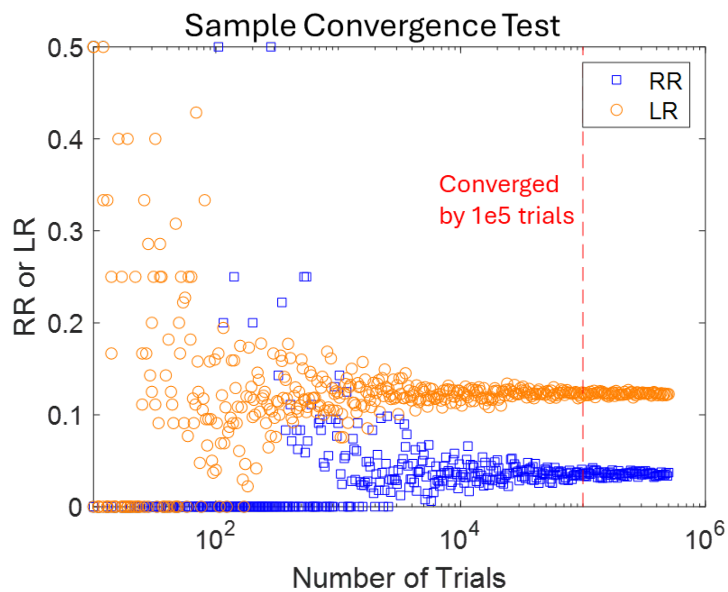


Figure 14: Simulation Convergence Test

SARA has swept through a series of input parameters and plotted the corresponding Risk Ratios to help validate the behavior of the model. One of the most important parameters to study is the initial separation between the UAS and the shielded area. When the UAS is very close to the shielded area, RR and LR values should be close to zero, indicating a very large safety improvement from the DAA system, because the time to reach safety is significantly shorter than the reaction time afforded by the DAA system. When the UAS is very far from the shielded area, RR and LR should be close to 1, indicating that the DAA system has no safety effect. This is because the UAS never reaches the shielded area before CPA. Figure 15 confirms that the simulation produces the expected trends. This test run featured a TASA Alert Boundary 1,000 meters beyond the shielded area and a UAS speed of 20 m/s.

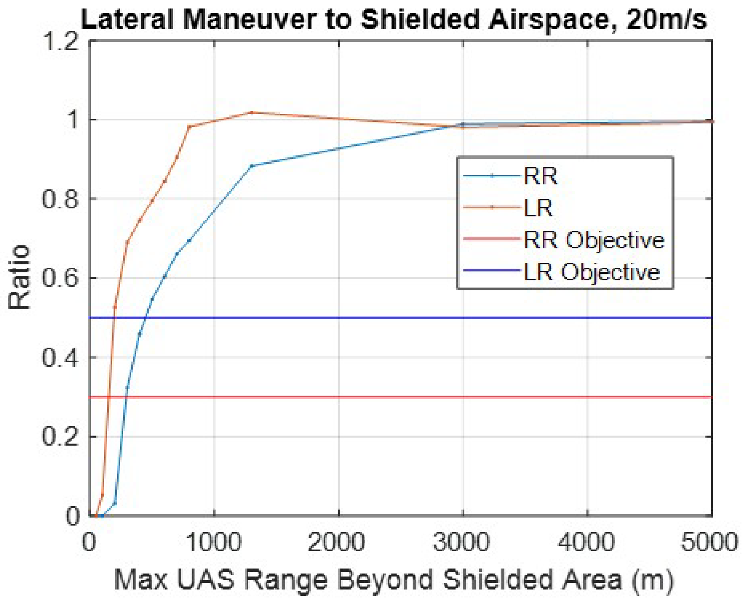


Figure 15: RR and LR Trends Are as Expected

5.6.1.2. Risk Ratio Simulation Results

UAS operators wishing to integrate TASA into their operations should consult this section to help define their system timing requirements and operational limitations. Many common parameter combinations have been evaluated, though every combination has not been exhausted.

An example parametric analysis is shown in Figure 16. The left plot shows a parametric analysis of the NMAC Risk Ratio results as two key parameters are varied, with TASA Alert Boundary placement being varied on the x-axis and UAS range beyond the shielded area varied on the y-axis. The RR result is indicated by the color at each grid intersection. The center figure is a simplified plot, where yellow indicates results that fail the risk ratio requirement (RR required to be less than 0.3) and blue indicates the results pass. Note that some interpolation is required between grid points to produce this image, resulting in the dividing line between yellow and blue not being perfectly smooth. That dividing line between yellow and blue indicates the operational limitations, from an RR requirement perspective. That line, along with the corresponding LR line, are extracted and plotted on the right figure. A UAS operator could reference the plot on the right, look up their desired operational range beyond a shielded area on the y-axis, trace over to the most conservative line, and trace down to the x-axis to find the required TASA Alert Boundary placement.

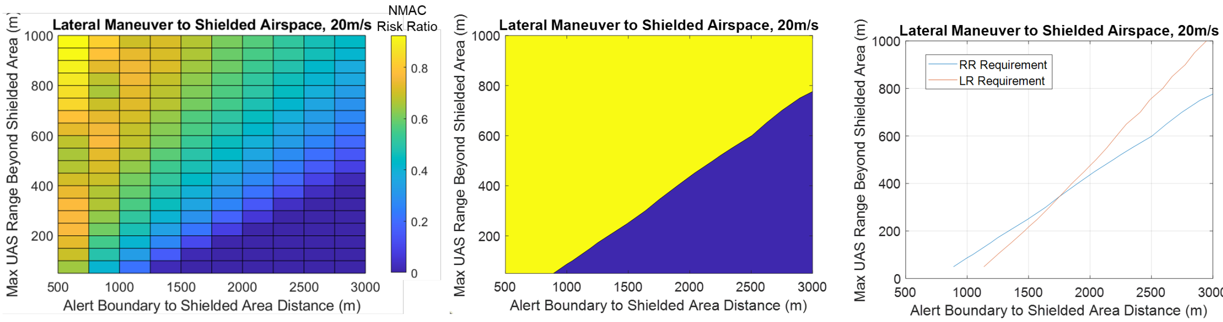


Figure 16: Parametric Sweep of RR (left), Intermediate Result (center) and Simplified Result (right)

SARA took the most conservative requirement between RR and LR and produced a pareto front dividing unsafe and safe operation. SARA then repeated this analysis for common UAS speeds of 10 m/s, 20 m/s, and 30 m/s. These results are shown in Figure 17. This figure defines the relationship between TASA Alert Boundary placement and UAS operational boundaries where the UAS collision avoidance maneuver is to turn and fly straight to the closest shielded area. It assumes a five-second latency between the TASA Alert being issued and the UAS achieving the indicated lateral speed in the direction of the shielded area.

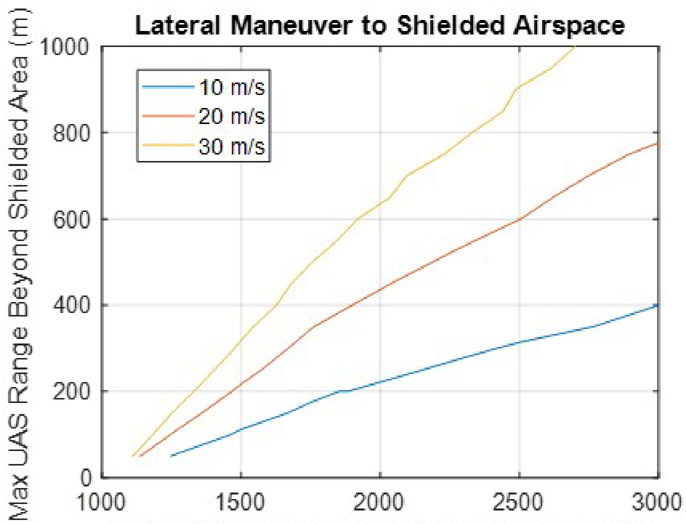


Figure 17: UAS lateral limits vs TASA boundary placement

The TASA Alert Boundary must be more than 1km beyond the shielded area before any UAS operations beyond the shielded area can achieve the Risk Ratio performance requirements. With each TASA node having an average detection range around 4km, there is a significant amount of flexibility in the physical placement of each TASA node. It is also interesting, though not surprising, to observe the importance of UAS speed. By comparing the 10 m/s and 20 m/s, it is found that doubling the UAS speed during the avoidance maneuver roughly doubles the range that the UAS can operate beyond the shielded area. Figure 17 assumes the TASA network will alert on 100% of aircraft crossing the TASA Alert Boundary at collision hazard altitudes. This level of performance is common and expected for most TASA networks. However, it is certainly possible that some TASA network installations may be suboptimal in the future. UAS operators are expected to install TASA network according to SARA guidelines and perform post-installation verification to measure the probability of alert, P(Alert), at the TASA Alert Boundary. If P(Alert) is less than 100%, Figure 18 below can provide operators guidance on how to reduce UAS operational ranges to maintain the required level of safety. If the UAS range reductions are not acceptable, UAS operators will have to adjust the TASA node placements to increase P(Alert).

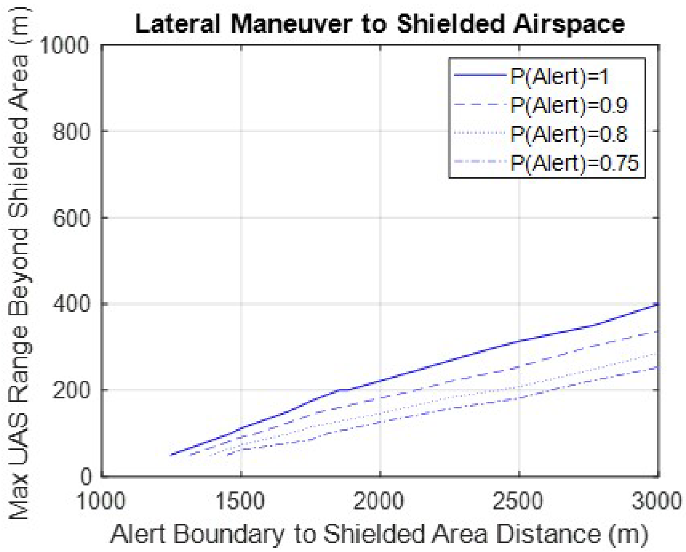


Figure 18: UAS lateral limits vs TASA Boundary Probability of Alert

SARA performed a variant of the above TASA analysis where the UAS operates above a Shielded Area and descends to the shielded area if TASA alerts. All other simulation parameters were unchanged. Figure 19 shows a parametric evaluation of UAS descent speed, ranging from 3 m/s, typical for most quadcopters, to 7 m/s, typical for the Puma. As one would expect, UAS that can descend faster can operate at higher altitudes, all else being equal. The lateral separation between the TASA alert boundary and the shielded area lateral boundary is plotted on the x-axis. The left y-axis shows the maximum allowed UAS height, in meters, above the Shielded Area such that the ASTM risk ratios for NMAC and Loss of Well Clear are met. The right y-axis is the same metric but displayed in feet. The study stops at 300 feet above the shielded area, assuming that a typical shielded area will extend up to 100 feet AGL, making 300 feet on the plot correspond to 400 feet AGL, which is the maximum UAS altitude allowed under Part 107. The plot assumes a 100% probability of TASA alerting when an aircraft crosses the alert boundary.

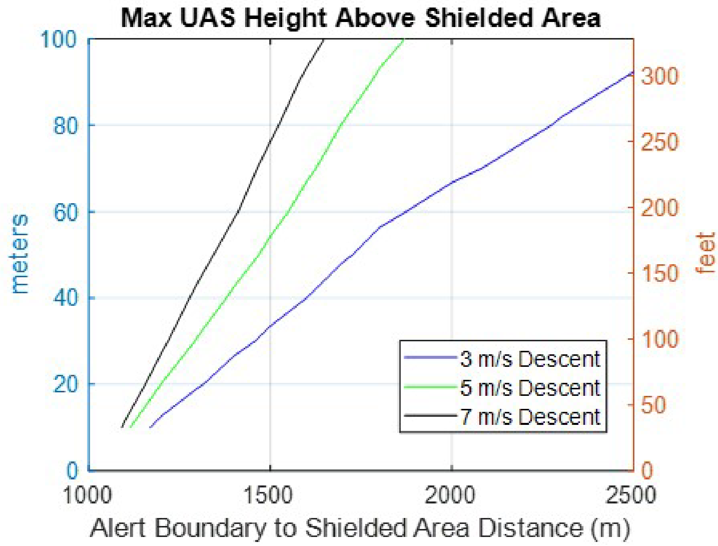


Figure 19: UAS vertical limits vs TASA Alert Boundary placement

Figure 20 presents a parametric analysis of the TASA boundary placement when the probability of alerting at the boundary is less than 100%. This example assumes a UAS descent speed of 3 m/s. TASA installations are often constrained by property ownership/access, local terrain, and placement of large structures. If TASA nodes were installed in suboptimal locations due to such constraints, the probability of alerting could be determined by SARA and the UAS altitude limits could be found in Figure 20.

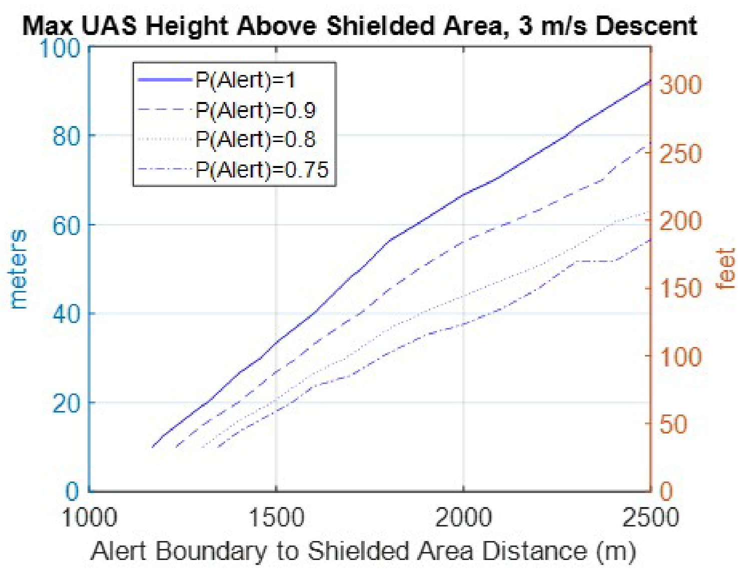


Figure 20: UAS vertical limits vs TASA Probability of Alert

5.6.2. Installation

During the installation phase, TASA locations are identified which are expected to meet the identified requirements and enable the placement of the TASA Alert Boundary. TASA nodes are installed according to SARA-provided procedures and their orientations are calibrated. SARA offers telescoping masts for semi-permanent installations and solar power kits for locations where line power is not available. See TAS-D0007_TASA Installation Manual V02.pdf for detailed instructions.

5.6.3. Verification

Once the TASA network is installed, UAS operators must verify that it is achieving the intended performance before UAS operations can commence. The most economical approach is often to let the TASA network run while monitoring the TASA terminal. Aircraft targets of opportunity with functional ADS-B will be displayed via TASA's integrated ADS-B receiver, in addition to their acoustic detections being displayed. Operators should verify that each TASA node in the network is acoustically tracking aircraft within the required range and altitude bounds and that the TASA Terminal is issuing Alerts when the TASA Alert Boundary is crossed. At least 20 TASA Alert Boundary crossings with aircraft below 2,000 ft AGL must produce Alerts before UAS operations begin. Once UAS operations commence, operators shall continually log boundary crossings and adjust UAS range limitations if P(Alert) degrades. A mismatch between acoustic tracks and ADS-B tracks may often be traced back to a TASA node which has exceeded its alignment tolerance. Alignment corrections can be made remotely or on-site.

The time required to initially verify the TASA network functionality will depend on the air traffic density and common flight patterns in the area. In some rural areas, it may be necessary to hire an aircraft, such as a Cessna-172, to fly across the TASA Alert Boundary to expedite the verification process. 20 perimeter crossings may often be completed in a single flight.

5.7. TASA Operating Procedures

The TASA network must be active before UAS operations requiring TASA may begin. Each TASA node must not be reporting any critical errors, and any automated processes, such as UAS avoidance maneuvers triggered directly by TASA, must be checked.

UAS avoidance maneuvers must be pre-defined for each point along the UAS flight path. SARA strongly recommends automating the avoidance maneuver. The highest level of automation features TASA triggering an avoidance maneuver, the UAS looking up the appropriate pre-planned maneuver, and the UAS automatically executing the avoidance maneuver. Specific operating procedures will depend on the level of automation.

During operations, the UAS and remote pilot in command must be ready to commence the pre-defined avoidance maneuver if the TASA Alert Boundary is crossed, or if TASA becomes non-functional. The TASA health and status messages will catch most errors, and a complete loss of connection with TASA for more than five seconds should also trigger the avoidance maneuver.

Un-annunciated failures shall be mitigated through continuous verification of acoustic detections against ADS-B tracks within the acoustic tracking volume, as described in 5.6.3.

5.8. TASA Maintenance

TASA nodes are designed to be low maintenance. All components are outdoor rated and ruggedized for a wide range of environmental effects. TASA nodes should be visually inspected from ground level after any severe storms. Regular maintenance consists of replacing the eight foam windscreens on each TASA node every 18 months, and checking all bolts, screws and connectors for tightness at the same time. If TASA nodes are being temporarily operated on a SARA-provided telescoping mast, the mast guy wires should be checked for tension every three months.

6. PANCAS

The Passive Acoustic Noncooperative Collision Avoidance System (PANCAS) is a novel DAA system developed by SARA. By using passive acoustic sensing, PANCAS detects collision threat aircraft with no cooperation or communication with the threat aircraft and no reliance on data links outside the UAS platform. An example integration of PANCAS on an AeroVironment RQ-20 Puma UAS is shown in Figure 21. A PANCAS system consists of an onboard, real-time processor, an array of acoustic probes and a harness connecting the probes to the processor. The number and location of microphones can be varied as needed and a flexible software architecture allows for alert range to be tuned to the user's needs. A simple operator display is provided which allows for fully automatic avoidance or human-in-the-loop operation.

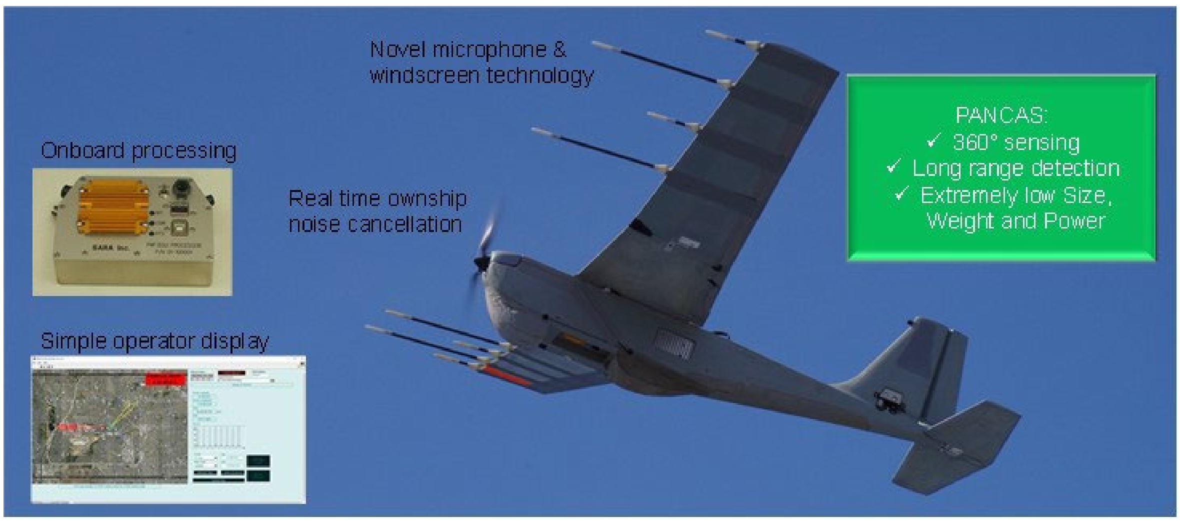


Figure 21: PANCAS DAA System flown on Puma UAS

6.1. PANCAS Specifications

PANCAS system specifications are provided in Table 3.

Table 3: PANCAS Specifications

PANCAS Specifications	
Model Number	PA-400000
Acoustic Probes	8
Performance (nominal conditions)	
Field of Regard	4π steradians (all azimuths and elevations)
Detection Range	3.2 km (Cessna 172) radial
Bearing Resolution at Range	5^{o} (Cessna 172)

Communication	
Connection to Ground Terminal	Uses UAS platform's C2 link
Connections to autopilot	Ethernet, Serial
Flight Data Recorder	Integrated
Positioning	Dedicated GPS/INS or uses platform's
Environmental	
Temperature Rating	-40° C – 71° C
Ingress Protection (IP)	68
Electrical	
Input Voltage	12-30 VDC
Power (Steady)	8 W
Mechanical	
Processor Weight	410 grams
Processor Dimensions	3.2" x 5.4" x 1.9"
Acoustic Array Dimensions	8 ft

6.2. Environmental Testing

PANCAS has been operated in a wide variety of conditions, including:

- Flown on UAS ranging in size from 6 ft wingspan to 36 ft wingspan.
- Flight altitudes from sea level to 10,000 ft MSL
- Airspeeds up to 80 knots
- Daytime and nighttime flights
- Operated in below-freezing temperatures and above 100°F external temperatures.
- Ruggedized and tested for takeoff, flight, and both soft and hard landings (hard terrain, soft terrain, water)
- Acoustic probes and harnesses specially designed to break away on hard landings
- Fresh water submersion
- Saltwater submersion

PANCAS has been tested at airspeeds up to 92 mph, and we expect PANCAS to perform well on faster UAS. Operators wishing to install PANCAS on UAS that fly faster than 92 mph can verify PANCAS performance quickly using SARA's temporary installation PANCAS kit. Note that 14 CFR Part 107 restricts small UAS speeds to 100 mph or less. UAS in other categories will fly faster.

Figure 22 shows an example of a stressing environment where PANCAS performed well. PANCAS was flown on an AeroVironment Puma LE 60 miles off the coast of Florida in the Pacific Ocean.

The Puma is waterproof and designed to land in the water. PANCAS survived multiple hard landings and submersion, with no repairs necessary between flights.

Figure 22: PANCAS water landing testing

6.3. Health Monitoring

PANCAS software processes run on timed loops. Each loop is monitored and a warning is issued if any process exceeds its time budget or does not complete. Health and status messages are transmitted twice a second. These messages also serve as a heartbeat, which external systems such as the PANCAS Terminal display or a UAS ground control station can use to verify PANCAS is fully functional. Health and status messages include checks for:

- Microphone functionality / connectivity
- Configuration file present and successfully read
- FPGA initialization
- Algorithm execution time
- Algorithm throughput
- Network connectivity
- RTOS monitoring
- CPU monopolization
- File hash consistency checks
- Data recorder connectivity
- GPS connectivity
- LED indicator light functionality

• Ambient noise levels

6.4. Communications Latency Testing

PANCAS can send commands directly to the UAS autopilot over Ethernet or serial protocols, which produces very small latencies, on the order of milliseconds. The robustness and low latency of automatically triggering a pre-determined maneuver to a shielded area makes this a very attractive approach. However, PANCAS does also support pilot-in-the-loop response. PANCAS transmits system health, status, and resolution advisories via the UAS command and control link to the UAS ground control station and to a PANCAS operator display. UAS operators wishing to use PANCAS with a pilot in the loop should ensure they will have acceptable levels of latency, bandwidth, and connectivity during all segments of the planned flight. Some forms of C2 link, particularly satellite links, are known to have latencies up to tens of seconds.

6.5. PANCAS Operator Display

PANCAS and TASA use the same operator display. This display is described in Section 5.5 and shown in Figure 7. This figure is repeated below as Figure 23 for the reader's convenience. PANCAS position is indicated as a green circle with the PANCAS serial number inside. Acoustic detections are displayed as red beams. When the UAS should begin the pre-determined avoidance maneuver, an alert symbol flashes on the lower left side of the screen and an audible alarm is activated. These alerts will persist until the operator dismisses them.

Figure 23: PANCAS Operator Display

6.6. PANCAS Integration

PANCAS integration can be divided into three phases: planning, installation, and verification. Detailed planning ensures that the desired UAS operations will be enabled if PANCAS is installed.

Installation normally requires collaboration between SARA and the UAS manufacturer to permanently modify the UAS airframe to accept PANCAS. However, test kits are available which allow temporary operation of PANCAS without permanent modifications to the UAS. Verification consists of flight testing to verify and document end-to-end DAA performance. SARA provides PANCAS integration support throughout the planning, installation and verification phases. We find this necessary, as most UAS operators and manufacturers are not familiar with acoustic sensors and require technical support to achieve optimal PANCAS performance.

6.6.1. Planning

The planning phase focuses on identifying requirements. Common requirements are listed below:

- Mission Requirements
  - UAS operating boundary (latitude, longitude, altitude)
  - Maximum desired distance beyond closest shielded area
  - Identify phases of flight that cannot easily be interrupted, such as transitioning from VTOL to forward flight, or lowering a package
  - Airspace class, nearby airports, and types of aircraft that could be reasonably expected
- UAS Maneuverability Requirements
  - Turn rate
  - Lateral speed
  - Descent speed
- PANCAS Installation Requirements
  - UAS size, weight and power budgets
  - Physical placement and mounting concept
- Communications Requirements
  - UAS command and control link reliability and latency
  - Ethernet or serial connection to autopilot and comms link
- Emergency Procedure Requirements
  - Lost link procedures
  - Lost DAA procedures

Other requirements may be discovered during the BVLOS application process. Generally, these requirements must be balanced against each other until an achievable set of requirements is identified. It is most efficient and cost effective to balance these requirements as early as possible.

The outcome of the planning phase should include an air collision avoidance timing analysis, in accordance with ASTM F3442 §6. The timing components for PANCAS to detect and alert are provided in Table 2. Timing parameters of the avoidance maneuver must be defined by the UAS operator based on the performance characteristics of the UAS. The t_Maneuver parameter represents the time budget for the UAS to reach the closest shielded area. This parameter should be found through simulation study results, as described in Section 5.6.1.2. The simulation balances many design considerations, including desired operational capability, UAS performance, and PANCAS performance. When evaluating Table 4, it is important to note that SARA reports PANCAS alert ranges corresponding to the output of the t_Classify function.

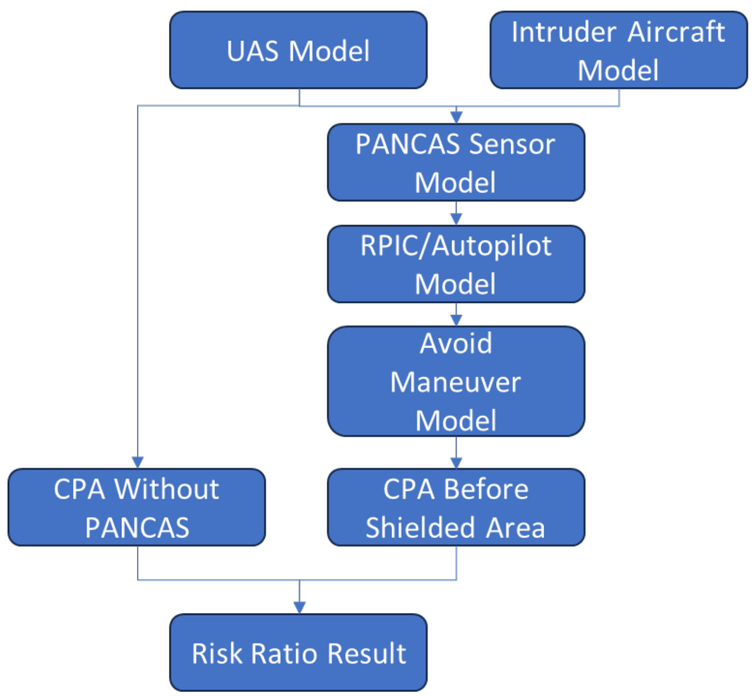
Table 4: PANCAS Timing Analysis Parameter List

<table>
<tr><th>Timing Parameter</th><th>PANCAS Value</th></tr>
<tr><td>t_Scan</td><td>0.49 ms</td></tr>
<tr><td>t_Relay</td><td>0.0033 ms</td></tr>
<tr><td>t_Filter</td><td>49 ms</td></tr>
<tr><td>t_Publish</td><td>0.49 ms</td></tr>
<tr><td>t_Classify</td><td>500 ms</td></tr>
<tr><td>t_Notify</td><td>500 ms</td></tr>
<tr><td>t_Plot</td><td rowspan="5">Defined by UAS Operator</td></tr>
<tr><td>t_Vector</td></tr>
<tr><td>t_Translate</td></tr>
<tr><td>t_Command</td></tr>
<tr><td>t_Control</td></tr>
<tr><td>t_Maneuver</td><td>Defined through simulation</td></tr>
<tr><td>t_Fix</td><td rowspan="2">Defined by UAS Operator</td></tr>
<tr><td>t_Telemetry</td></tr>
</table>

6.6.1.1. Risk Ratio Simulation Setup

To aid BVLOS waiver applicants, SARA has performed Risk Ratio simulations for many common use cases. In this section, we describe the simulation setup and inputs. In Section 6.6.1.2, we provide simulation results for a variety of input parameters.

The Risk Ratio simulation approach is depicted as a flow diagram in Figure 24. The simulation uses a Monte Carlo approach which models a single UAS and a single crewed intruder aircraft. Millions of one-vs-one encounters are simulated, with each specific encounter simulated twice, one without a DAA system and one with PANCAS. Without DAA, the closest point of approach (CPA) is calculated as the minimum lateral separation between the UAS and crewed aircraft over all time. This can be computed analytically because they both fly constant speed, linear trajectories. With DAA, the CPA is calculated as the minimum lateral separation between the UAS and crewed aircraft over all time until the UAS reaches a shielded area.



CPA = Closest Point of Approach

Figure 24: Flow Diagram of Risk Ratio Simulation

The UAS model requires the following input parameters:

- Lateral speed
- Descent speed

- Reaction Time: Time to receive PANCAS Alert, compute the avoidance maneuver to the nearest shielded area, send the command to the UAS, as well as time for the UAS to establish the new trajectory.

Given those inputs, the UAS Model simulates the UAS on a constant-speed constant-course trajectory.

The Intruder Aircraft Model samples lateral speed from a uniform random distribution between 40 knots and 170 knots, where 40 knots is a typical stall speed for fixed wing aircraft and 170 knots is a max airspeed used in several relevant standards, including ASTM F3442 and DO-365C. The intruder aircraft starting position relative to the UAS is sampled from a uniform random distribution between -10.8 NM and 10.8 NM cross range and down range. The intruder aircraft flies a constant-velocity constant-course track, where the course is sampled from a uniform random distribution between -180° and 180°. This is the same Intruder Aircraft Model used for TASA simulations, as described in 5.6.1.1.

Figure 10 shows a sampling of simulated intruder geometries. For the reader's convenience, this is repeated below as Figure 25. For reference, a 500 ft radius (152 m) red circle is drawn about the origin depicting the NMAC Boundary, and a larger 2,000 ft radius (610 m) red circle depicts the LoWC Boundary. One can see that intruder tracks cross the plot randomly, with only some entering the LoWC or NMAC boundaries.

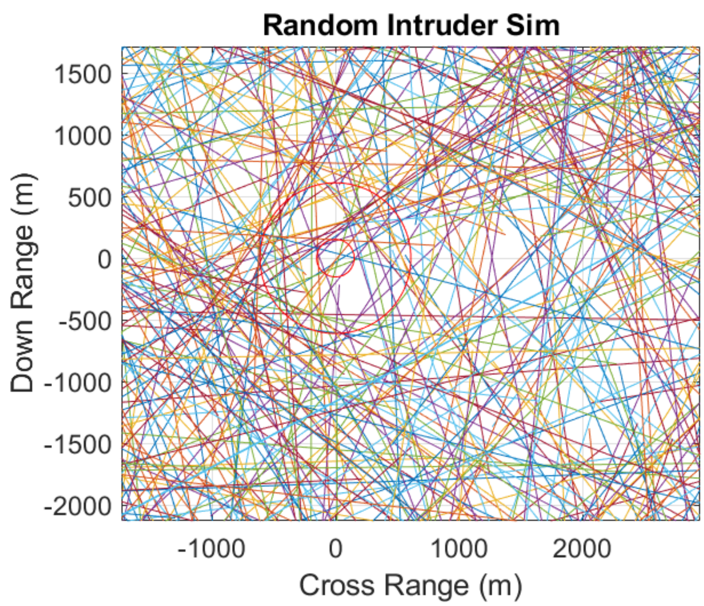


Figure 25: Sample Intruder Tracks from Risk Ratio Simulation

The PANCAS Sensor Model samples alert ranges from a log-normal fit to flight test results conducted under FAA BAA Call 004 contract number 697DCK-23-C-00288. The log-normal probability density function is shown in Figure 26. Any point on this line represents the probability that the corresponding x-axis alert range will be measured in a given trial. The sum of the area under the curve is 1.

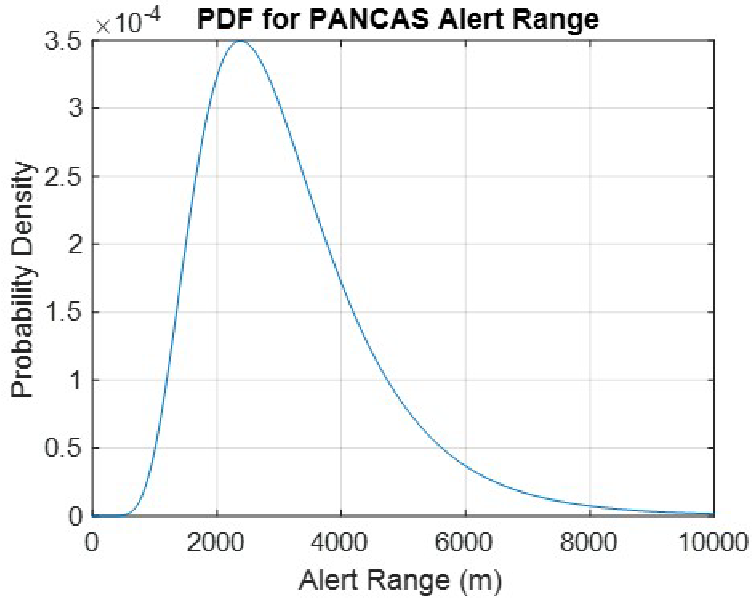


Figure 26: PANCAS Alert Range Model

The RPIC/Autopilot Model is simply a time delay, meant to capture the delay between the alert being issued and the time at which the UAS achieves the commanded avoidance maneuver parameters. These parameters are defined in the Avoid Maneuver Model. The benefit of this approach is that it is very easy to measure this time delay in the field by recording PANCAS alerts and comparing them against the UAS telemetry logs. The model's name indicates that the timing model can accommodate automatic avoidance maneuvers as well as pilot-in-the-loop maneuvers. Pilot-in-the-loop response times can have a significant negative impact on the risk ratio results.

The Avoid Maneuver Model stops the UAS flight after PANCAS issues an alert and the RPIC/Autopilot time delay has expired. In a piecewise-linear fashion, the UAS then flies at a constant-speed constant-course route to the closest shielded area. The model is configurable to either simulate a lateral maneuver or a descent. Once the UAS reaches the shielded area, the test run ends and the CPA is calculated.

The Risk Ratio results for NMAC (RR) and LoWC (LR) are calculated according to the equations in Figure 1. SARA ensures that a statistically relevant number of test runs are simulated by observing the convergence of the RR and LR values. This was described in 5.6.1.1 and an example of this is shown in Figure 14. For the reader's convenience, this is repeated below as Figure 28. With a small number of trials, the RR and LR results are not repeatable. As the number of trials increases, the results converge and become repeatable. This occurs at 100,000 trials or more.

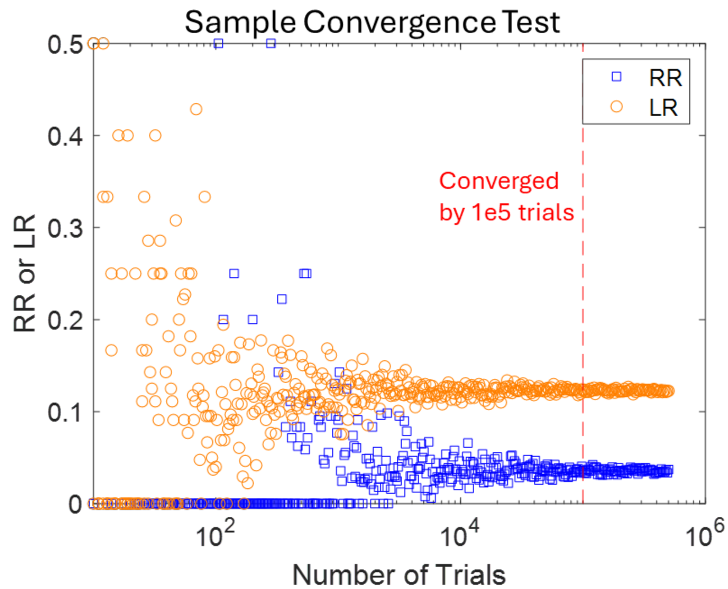


Figure 27: Simulation Convergence Test

SARA has swept through a series of input parameters and plotted the corresponding Risk Ratios to help validate the behavior of the model. One of the most important parameters to study is the initial separation between the UAS and the shielded area. When the UAS is very close to the shielded area, we expect RR and LR values close to zero, indicating a very large safety improvement from the DAA system, as the time to reach safety is significantly shorter than the reaction time afforded by the DAA system. When the UAS is very far from the shielded area, we expect RR and LR to be close to 1, indicating that the DAA system has no safety effect. This is because the UAS never reaches the shielded area before CPA. Figure 28 confirms that the simulation produces the expected trends.

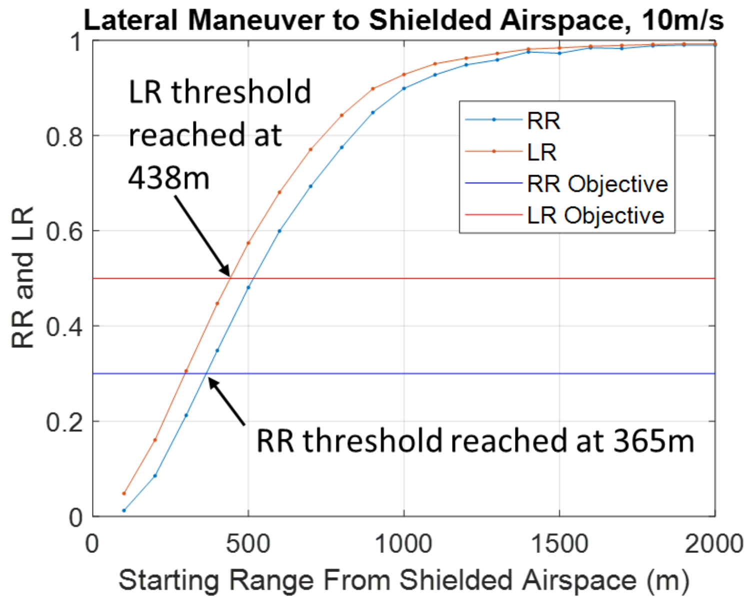


Figure 28: RR and LR trends are as expected

6.6.1.2. PANCAS Risk Ratio Results

UAS operators wishing to integrate PANCAS into their operations should consult this section to help define their system timing requirements and operational limitations. Many common parameter combinations have been evaluated, though every combination has not been exhausted.

PANCAS simulation parameters are:

- UAS lateral speed
- UAS descent speed
- PANCAS alert range
- Reaction Time: Time to receive PANCAS/TASA Alert, compute the avoidance maneuver to the nearest shielded area, send the command to the UAS, as well as time for the UAS to establish the new trajectory.
- Maximum range from or height above shielded area

Figure 29 shows how a faster UAS can safely operate farther beyond a shielded area. Note that the max allowable UAS speed under Part 107 is 44.7 m/s (100 mph). Because of this, the simulated range of UAS speeds is fairly comprehensive. Note that PANCAS has only been tested at speeds up to 41 m/s. Acoustic detection performance at greater speeds would need to be verified through flight testing.

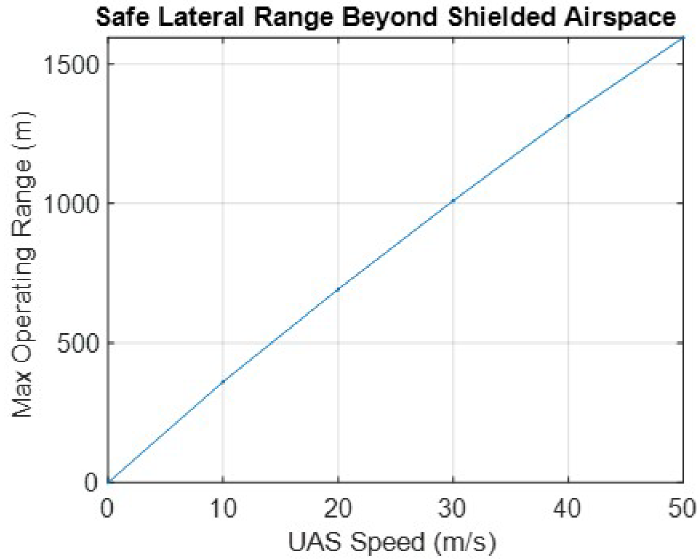


Figure 29: PANCAS-equipped UAS lateral operating range limit vs UAS speed

Figure 29 assumes a reaction time of six seconds. Since PANCAS is onboard the UAS and typically sends commands directly to the autopilot or onboard mission computer, the time to receive the PANCAS alert, compute a maneuver, and issue a maneuver command totals a fraction of a second, and the reaction time primarily consists of the time for the UAS to maneuver. For an operation where the UAS is flying along the shielded area boundary, the appropriate lateral maneuver for collision avoidance would be a 90-degree turn in 6 seconds, requiring a 15°/sec turn rate. Achievable turn rates are a function of UAS design, UAS speed and density altitude.

Figure 29 also assumes PANCAS on the UAS platform achieves the same alert range performance as tested on the AeroVironment Puma. While this will often be the case, PANCAS alert range will ultimately be measured on each new platform, as described in 6.6.3, and results may vary. SARA explored the sensitivity of the simulation to PANCAS alert range, and those results are presented in Figure 30.

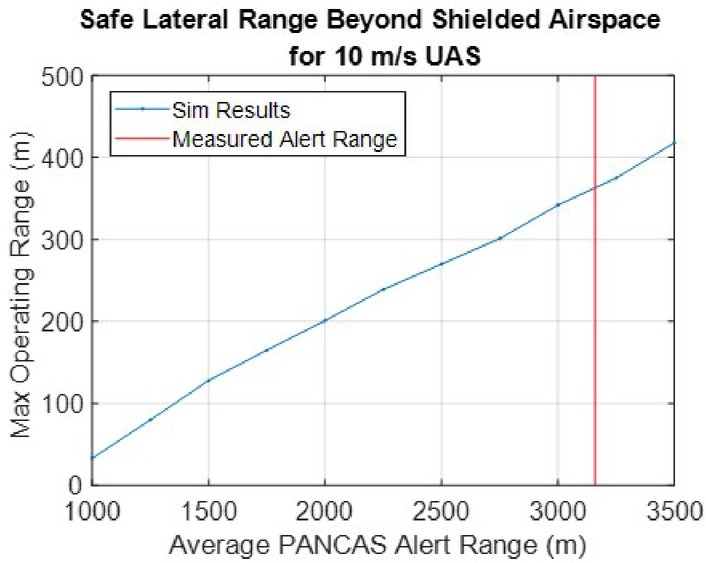


Figure 30: UAS lateral operating range vs PANCAS performance

SARA created a second statistical encounter simulation for use cases where the UAS is operating above a shielded area and will descend if PANCAS detects an intruder aircraft. We used the same simulation parameters for the intruder aircraft as in the lateral maneuver model. A parametric analysis was performed again, this time simulating a UAS with 10 m/s lateral speed and 3 m/s descent speed. The study varied PANCAS average alert range between 1km and 3.5km. For reference, flight test results showed PANCAS on Puma performance to be 3.16km, indicated by a vertical red line on the plot. Figure 31 shows the result of the parametric analysis as a blue line. Assuming the shielded area extends 100 feet above the ground, the UAS could only climb an additional 300 feet before reaching the 400-foot AGL limit for Part 107 operations. Accordingly, a black horizontal line has been plotted at 300 feet. UAS operations could be safely conducted at 400 feet even with a suboptimal PANCAS integration providing a 2.5km alert range. The standard 3.16km alert range measured during testing thus provides significant margin and would easily enable UAS operation up to 400 feet AGL above shielded areas. The simulated descent speed of 3 m/s is easily achievable by most UAS. The DJI Matrice 300 we tested in Barstow descended at a steady 3.75 m/s. The Puma can reliably descend at 7.5 m/s.

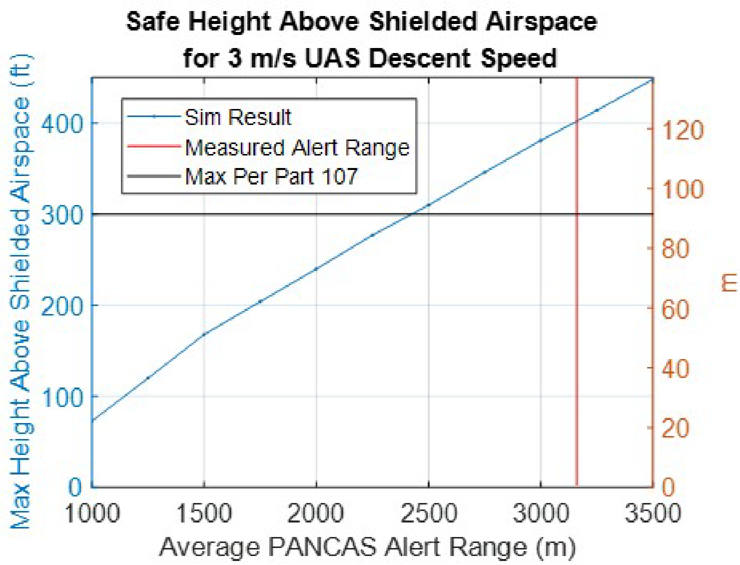


Figure 31: UAS altitude limit vs PANCAS performance

6.6.2. Installation

PANCAS is designed for integration on fixed-wing UAS. Standard placement of acoustic probes is along the leading edge of the wing. This is an acoustically favorable location because the probes are in the free stream airflow. It is also convenient because almost no other sensors use that location. Since PANCAS is a core piece of avionics equipment used for every flight, it is desirable for it to not be contending for space used by various mission payloads, which may be reconfigured before each flight.

Once PANCAS acoustic probes are integrated onto the UAS wing, a wire harness must be installed to connect the probes to the onboard PANCAS processor. The processor is typically mounted inside an avionics bay. The PANCAS processor is then connected to platform power and the autopilot.

SARA typically provides a temporary installation kit for an initial flight. This allows system performance to be verified before permanent modifications begin. Then, once fully integrated, a series of test flights verify surveillance performance and reliability of the avoidance maneuver.

6.6.3. Verification

Once PANCAS is integrated into a UAS, DAA performance must be verified. Key metrics are the same as the PANCAS simulation inputs:

- UAS lateral speed
- UAS descent speed
- PANCAS alert range

- Reaction Time: Time to receive PANCAS/TASA Alert, compute the avoidance maneuver to the nearest shielded area, send the command to the UAS, plus time for the UAS to establish the new trajectory.

UAS lateral speed and descent speed can be measured before PANCAS is integrated, as the installation of PANCAS will not impact UAS flight dynamics. The other metrics are tested after PANCAS is integrated. SARA recommends an initial Functional Check Flight to verify all systems are operational, followed by measurements of avoidance maneuvers induced by a simulated encounter aircraft. This establishes a level of trust with the automatic avoidance maneuver in a benign environment. The final verification flight of PANCAS on a new UAS platform should include tests against a single-engine fixed-wing crewed aircraft to verify PANCAS alert range. Altitude separation may be used as a safety measure. PANCAS alert range is larger against rotorcraft and multi-engine fixed wing aircraft, so the single-engine fixed-wing results can be viewed as the worst-case performance. SARA has conducted dozens of PANCAS test flights against crewed aircraft and can support testing of PANCAS on new UAS platforms. Verification is required after integration on a new UAS model, not on a unit-by-unit basis.

6.7. PANCAS Operating Procedures

Before each flight, PANCAS acoustic probes must be visually inspected for damage and then inserted into their receptacles on the UAS wing. PANCAS should be powered on as well as the PANCAS Operator Display. The PANCAS Operator must:

- Verify PANCAS data is being received
- Each acoustic probe is registering sound levels within acceptable bounds
- PANCAS is receiving GPS and INS data
- PANCAS can communicate with the UAS autopilot
- PANCAS is not issuing any critical errors
- PANCAS automatic maneuvers are disengaged

With PANCAS automatic maneuvers disengaged, PANCAS will display air traffic to the operator, but will not issue any commands to the autopilot. Once the UAS is launched, it should climb up to a safe altitude. Then, the PANCAS operator should engage automatic maneuvering. Once automatic maneuvering is engaged, PANCAS will send avoidance maneuver commands to the UAS autopilot whenever an air collision hazard is identified.

PANCAS will continuously transmit system health, status, and air traffic information, to the PANCAS Operator Display. If PANCAS reports an error, the remote pilot should immediately return the UAS to the closest shielded area. Some limited troubleshooting of PANCAS is possible while in flight, but such actions must be approved by the FAA as part of the BVLOS waiver. If the PANCAS error cannot be corrected in flight, the UAS will have to land for further troubleshooting and potential repair.

UAS operators should test their flight routes before requesting a waiver to fly those routes BVLOS. Through this process, they should ensure they will have reliable command and control of the UAS through all stages of flight. However, in a lost-comms event, PANCAS will still be capable of commanding automatic collision avoidance maneuvers. While this is an attractive safety feature, it must be harmonized with the UAS lost-comms procedure. Operators should be trained to know what the UAS and PANCAS will do during a lost comms event.

At the end of the flight, the UAS should return to the remote pilot or visual observer to land. Once within visual line of sight, PANCAS automatic maneuvers should be disengaged. This will prevent disruption of low-altitude maneuvers and the landing sequence, even if nearby air traffic is detected.

If any aircraft transmitting ADS-B enter the PANCAS detection volume, the operator should observe if ADS-B tracks and acoustic tracks are both present and aligned. PANCAS uses the UAS platform's INS, so any misalignment or malfunction of the INS should be identified as part of the standard preflight check. The comparison of tracks is simply a convenient end-to-end check of PANCAS when targets of opportunity present themselves.

6.8. Maintenance

UAS have a variety of launch and recovery methods, including catapult launch, net recovery, and belly skid landings. PANCAS acoustic probes may be damaged after repeated impact, so visual inspections are required before each flight. If the microphone within the acoustic probe is damaged, it will register an unusually high or low sound level, which can be easily identified on the PANCAS Operator Display.

SARA offers a handheld acoustic probe calibrator, which can be used in the field to more accurately check acoustic probes which an operator suspects may be damaged. The calibrator produces a tone of known frequency and amplitude. The measured amplitude, shown on the PANCAS Operator Display, can be compared to the expected amplitude. Acoustic probes more than 3dB out of tolerance should not be used.

PANCAS acoustic probes are tipped with a hard plastic windscreen. These windscreens must be attached for every flight and inspected for damage whenever the acoustic probe is inspected. If windscreens are cracked or broken, they should be replaced.

One notable cause of damage to PANCAS acoustic probes is due to test personnel accidentally kicking or leaning on acoustic probes as they stage the UAS for launch. SARA recommends acoustic probes be installed near the end of the standard pre-flight checks to minimize this risk, as well as training launch crews to be aware of the probes as they walk around the UAS.

7. Conclusion

This data package has been provided as a resource for UAS operators to understand DAA requirements, the performance of PANCAS and TASA systems, and the process required to integrate PANCAS or TASA into their UAS operations. Processes for planning, installation, operation and maintenance have all been provided. While the document emphasizes UAS operations near shielded areas, many of the themes and considerations are applicable to any BVLOS operation. It is SARA's hope that this document will help operators establish safe BVLOS operations and streamline their BVLOS waiver request process. The ability to operate UAS BVLOS provides tremendous value to UAS operators and their prospective customers. SARA's DAA solutions can make BVLOS operations a reality.