Evaluation of Avoidance Maneuvers Using SARA PANCAS DAA System

Final Report

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2. EXECUTIVE SUMMARY

Billions of dollars have been invested in developing Unmanned Aerial System (UAS) technology for commercial applications in the U.S. National Airspace System (NAS) including specialized aircraft, takeoff and landing systems, communications systems, sensors, data managing and data processing systems, an FAA operational UAS Unmanned Traffic Management (UTM) System and USS (UAS Service Suppliers) along with methods to carry and deliver packages. However, the return on most all of these investments and the benefits of this technology is yet to be realized. This is largely because affordable, satisfactory Detect And Avoid (DAA) solutions to replace a man in the cockpit to ensure safe separation of UAS from manned aircraft has yet to be delivered.

DAA is a particularly challenging problem. In the future UAS economy, the vast majority of UAS are expected to be much smaller and much slower than a manned aircraft. Due to their small size, manned aircraft cannot reasonably be expected to see and avoid UAS. Instead, the UAS must detect and avoid the manned aircraft. Their small size constrains DAA technologies to be extremely small, lightweight, and low power, low SWaP. The slow speeds small UAS operate at allow manned aircraft to unknowingly approach them in overtaking, head-on, or crossing geometries. Furthermore, these slow speeds result in the small UAS taking a long time to avoid a manned aircraft. This requires DAA systems to have a 360° field of view and long-range detection, while maintaining low SWaP. Cooperative systems like ADS-B are able to meet these constraints by requiring the manned aircraft to carry a transponder and report its position at all times. ADS-B equipage continues to climb, and UAS should certainly use ADS-B IN as part of their DAA solution. However, not all aircraft are required to have ADS-B OUT and installed systems may be nonfunctional or disabled. Non-transponding, also called noncooperative, aircraft must be detected another way.

SARA's Passive Acoustic Noncooperative Collision Avoidance System, or PANCAS, detects manned aircraft by detecting the sounds naturally emitted by aircraft components, such as propellers, engines, turbines and jets. By using passive acoustics, PANCAS achieves a very low SWaP, allowing it to be installed on small UAS. As the UAS flies, PANCAS tracks aircraft sounds and determines if the UAS should maneuver to remain well clear of the manned aircraft. Because manned aircraft are naturally loud, PANCAS achieves long detection ranges. Just like a human ear, PANCAS microphones provide a 360° field of regard.

PANCAS and competing DAA systems are just becoming available to commercial customers and will meet their pent-up demand, so long as they are used appropriately. Understanding new DAA technology, integrating it into a rapidly changing fleet of UAS, and applying it to novel use cases is the next challenge the industry will face. Under FAA contract 697DCK-21-C-00174, SARA demonstrated a process for balancing UAS performance characteristics, mission constraints and DAA sensor performance to arrive at a valid system design. This exemplifies the approach that industry must take to ensure safe UAS integration into the NAS. SARA used PANCAS as the DAA system, installing it on an AeroVironment Puma UAS, and applying it to use cases defined by US Coast Guard and US Border Patrol.

Through flight testing and test-anchored simulation, SARA verified that PANCAS, installed on the puma, conducting USCG and USBP missions, meets the ASTM Detect and Avoid Performance Standard Requirements.

3. PANCAS SYSTEM OVERVIEW

This project used SARA's onboard DAA system called PANCAS, the Passive Acoustic Noncooperative Collision Avoidance System. SARA offers a Government variant of PANCAS called PANAMA, the Passive Acoustic Noncooperative Aircraft Motion Analyzer. The hardware for PANCAS and PANAMA is the same, though we expect the designs to diverge with future iterations. The core software is also the same, though additional features exist for Government use. For simplicity, the term PANCAS will be used in this report unless a PANAMA-specific feature is being discussed.

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 1.

FIGURE 1: PANCAS DAA SYSTEM INSTALLED ON RQ-20 PUMA UAS

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.

PANCAS has been tested extensively, including evaluations by the Air Force Test Pilot School, Navy 4th Fleet, NAVAIR, NASA, USCG and NOAA.

FIGURE 2: ENCOUNTER AIRCRAFT PANCAS HAS BEEN TESTED AGAINST

4. V-Process Development

Founded in 1989, SARA has primarily developed innovative technologies as a defense contractor, and we still have many Government customers today. Like most companies in the defense industry, SARA follows the V-process for systems engineering. This is a methodical approach that begins with the definition of a concept of operations, or CONOPS. From the CONOPS we derive system and subsystem requirements. We then design subsystems and systems to meet those requirements. We then build components, test them against requirements, assemble components into subassemblies and test again, then finally assemble the system. We test the system in a relevant environment, and we create test-anchored models to simulate performance in scenarios that cannot be tested. With PANCAS and other products, SARA is bringing this same V-process to commercial customers. The commercial UAS industry has a wide variety of participants who have varying levels of systems engineering knowledge and design rigor. Because UAS fly in the National Airspace System and there are tangible air risks and ground risks, we favor working with UAS OEM's who use time-tested development processes. Even so, a challenge emerges when a quality DAA system and a quality UAS have been developed independently. Due to schedule and budget constraints, it is often not feasible to make large changes to either system. The two systems are combined, and the customer, and the FAA, are left wondering if the DAA capability is reliable. A process for DAA validation is required to solve this problem.

5. Requirements

One challenge for the small UAS community is that there are no requirements defined for a DAA system or other equipage that would allow a UAS to operate safely beyond visual line of sight (BVLOS). For FAA approval to fly BVLOS, most applicants apply for a waiver to 14 CFR Part 107. Government agencies may apply to the FAA for a Certificate of Waiver or Authorization (COA). Both the Part 107 waiver and the COA are evaluated on a case-by-case basis.

DAA standards have been developed by industry but have not been endorsed by the FAA. RTCA DO-365 *Minimum Operating Performance Standards (MOPS) for Detect and Avoid (DAA) Systems* was written for UAS greater than 55 pounds and prescribes the use of TCAS II, ADS-B In, and an air-to-air radar (ATAR). By prescribing a RADAR sensor modality for DAA, there is no clear way for an acoustic DAA sensor like PANCAS to meet the MOPS, so DO-365 cannot be followed.

ASTM F3442 *Standard Specification for Detect and Avoid System Performance Requirements* was written for UAS with a maximum dimension less than 25 feet, operating at airspeeds below 100 knots, operating in low or medium risk airspaces. The standard is sensor-agnostic and thus one that PANCAS can be evaluated against. This standard is also particularly relevant to many commercial use cases, where businesses seek to perform inspection or delivery services below 400 feet above ground level. Because of its applicability, and the lack of alternative standards, SARA evaluated PANCAS against the ASTM F3442 Standard.

The ASTM DAA standard defines two boundaries around a UAV. The Near Midair Collision (NMAC) Boundary is a puck shape with 500 ft radius, extending 100 ft above and 100ft below the UAV. The Well Clear Boundary is a larger puck shape, with 2,000 ft radius and extending 250 ft above and below the UAV. These boundaries are depicted in Figure 3.

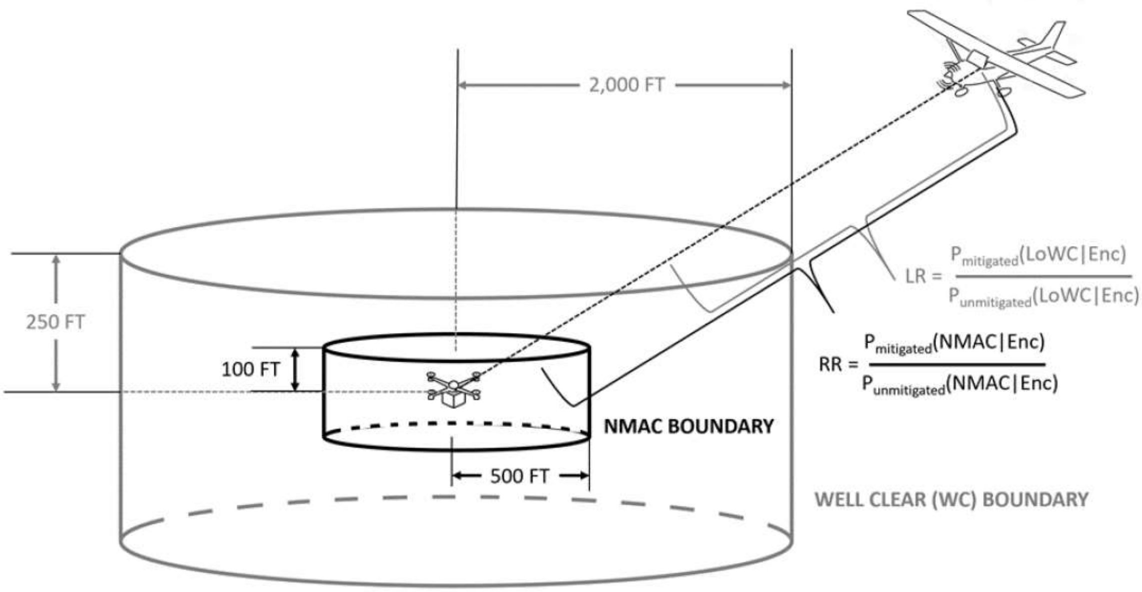

FIGURE 3: ASTM DEPICTION OF NMAC AND WELL CLEAR BOUNDARIES

The primary requirements specified in the ASTM standard are in the form of Risk Ratios. Risk Ratios specify a level of relative decrease in air risk by use of a DAA system. RR is defined as the probability of NMAC boundary violation given an encounter when air risk has been mitigated (for example by using PANCAS), divided by the probability of NMAC had air risk not been mitigated. LR is similarly defined as the same ratio, but for loss of well clear (LoWC) instead of NMAC. The ASTM DAA Standard specifies different RR and LR requirements for cooperative and non-cooperative aircraft. PANCAS uses ADS-B In to aid detection of cooperative aircraft, and industry generally agrees that ADS-B solves the cooperative aircraft sensing challenge, so we focus on evaluating PANCAS against the risk ratios for non-cooperative aircraft.

TABLE 1: ASTM RISK RATIO REQUIREMENTS

Parameter	Description	Requirement vs Noncooperative Aircraft
RR	NMAC Risk Ratio	≤0.3
LR	LoWC Risk Ratio	≤0.5

6. Process for DAA Validation

Under this contract, SARA developed and demonstrated a process for DAA validation supporting any small UAS based on the ASTM DAA Performance Standard. The process is based on the standard test-model-test methodology and is depicted in Figure 4. The process is described in the following sections.

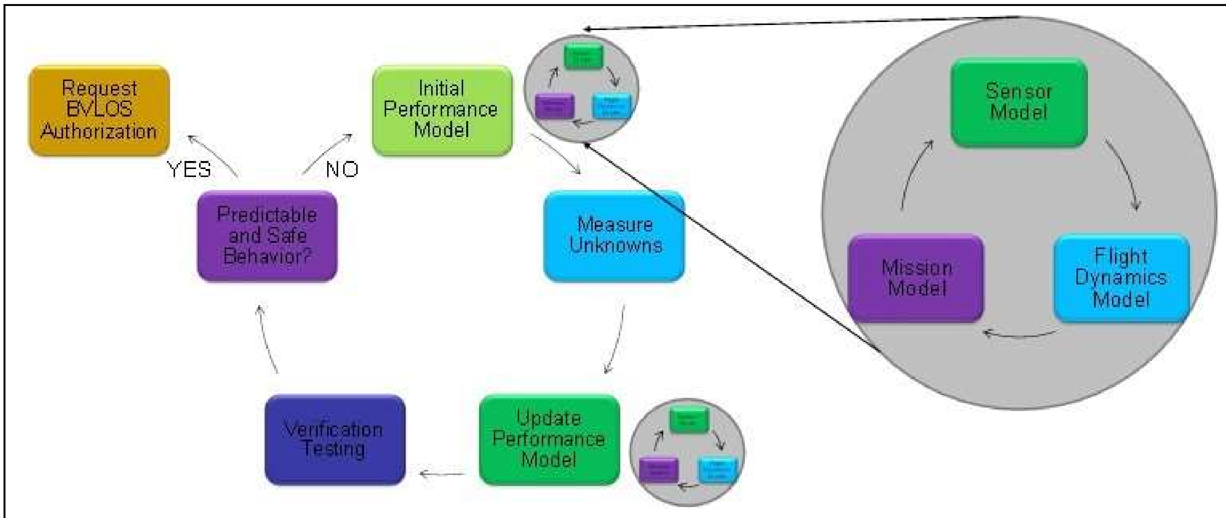

FIGURE 4: DAA VALIDATION PROCESS AS A FLOW DIAGRAM

6.1 Initial Performance Model

The DAA system must balance requirements between the mission, the DAA sensor and the UAS. The particular mission being flown may influence flight speed and altitude, for example if the UAV is running an imaging sensor that requires a specific speed and altitude to resolve targets on the ground. Environmental factors such as darkness, fog, rain, extreme heat or cold, wind, terrain and RF interference may impact the UAV and the DAA system. The mission location will define what the manned aircraft encounter set will be.

The DAA sensor will have performance parameters such as detection range, field of view, and SWaP (size, weight and power). Once an intruder aircraft is detected, a determination must be made if it is a collision hazard or not, and an avoidance maneuver must be calculated. These functions are hosted inside PANCAS, but other DAA products are simple sensors and will require these functions be hosted elsewhere.

The unmanned aircraft is responsible for conducting the avoidance maneuver, so a flight dynamics model is required. With the wide variety of UAS designs, there is a wide range of possible flight speeds, climb/descent rates and turn rates that will all influence what avoidance maneuver is optimal and how long the maneuver takes.

As a first step to DAA integration, an initial performance model should be generated that captures key parameters about the mission, DAA sensor and UAS. Requirements should be balanced between these three components until a valid approach is conceived that is expected to meet DAA safety requirements.

The nature of the model may vary depending on the application. For example, physics-based models may be good for modeling flight trajectories while empirical models may be more appropriate for modeling DAA sensor performance across environmental conditions. The focus should be on using a model that allows requirements to be reallocated and studied. As performance parameters are varied, the results should agree with physics-based intuition and factors of safety should be applied around regions of uncertainty.

6.2 Measure Unknowns

When creating the initial performance model, some models will be low fidelity and there will be unknowns. For example, most UAS will publish their cruise speed but will not report climb rates. To determine if a climbing avoidance maneuver would be practical, climb rate would have to be measured. The temperature and humidity at the mission location may impact climb rate, as will the added weight of a DAA sensor. To capture all these interdependencies, testing will likely be required.

Each unknown should be identified, and its range bounded. The initial performance model can be used to perform a sensitivity analysis, which will indicate to what precision unknowns must be measured. Testing should be documented for traceability.

6.3 Update Performance Model

One all unknowns have been measured, the initial performance model should be updated. Requirements may need to be reallocated between the mission, DAA sensor and UAS. Uncertainties should be reduced and DAA performance can be predicted within bounds, such that verification testing may commence.

6.4 Verification Testing

The decision to begin verification should indicate that the team is confident that test results will fall within identified bounds, and that bounded performance achieves the objective level of safety. Testing should be as representative as possible of the mission, the fielded DAA system and the operational UAS. One or more representative encounter aircraft should be flown in collision hazard scenarios to verify the end-to-end functionality of DAA system, including detection, alerting and avoidance. Flight test safety usually prevents a true collision trajectory from being flown, but minimum safe separation patterns can be flown. Testing should be documented for traceability.

6.5 Predictable and Safe Behavior?

If verification testing does not agree with the updated performance model, the model assumptions should be revised, and retesting is likely required. If verification testing does agree with the updated performance model, and those results achieve the desired level of safety, this is good but incomplete evidence. The challenge with flight testing is the limited number of encounter scenarios that can be tested, given budget, schedule and safety constraints. To comprehensively characterize DAA performance, a test-anchored simulation must be used. In simulation, very large numbers of encounters can be simulated, allowing performance to be reported across the range of relevant conditions. Once armed with experimental test results and a test-anchored simulation that corroborates those results and extends them to untested cases, the DAA system is ready to be considered by the competent authorizing agency for approval to fly beyond visual line of sight.

7. USCG and USBP Missions

United States Coast Guard (USCG) and United States Border Patrol (USBP) both provided descriptions of a typical UAS flight beyond visual line of sight that they wish to conduct with PANCAS. Among other UAS, both organizations own and operate AeroVironment RQ-20 Pumas. Combined with SARA's previous work on that platform, Puma use cases were an obvious choice for this project. As shown in Figure 1, the Puma is a fixed-wing UAS weighing 15 pounds. It can be launched by hand or with optional rail or bungee systems produced by AeroVironment. The Puma typically operates below 500' AGL, using its EO/IR camera for ISR for up to 3 hours flight endurance. The All Environment, or AE, model is waterproof and can be landed in the water next to a vessel, as shown in Figure 5.

USCG operates in a maritime environment, conducting search and rescue operations as well as supporting the Navy in maritime domain awareness missions. USCG seeks to launch the Puma either from shore or from a ship and fly beyond visual line of sight.

USBP operates the Puma primarily over land along the southern border. Their objective is to better monitor illegal crossings in remote areas and scale the reach of their officers on the ground. Due to the nature of their mission, USBP operates both day and night.

Both USCG and USBP missions are great initial use cases for PANCAS because the operations are primarily in remote areas where the air risk and ground risk are low to begin with. With PANCAS driving the air risk even lower, the operations can be conducted with a high level of safety and provide tremendous benefit to Government agencies performing critical missions.

FIGURE 5: (LEFT) USCG STANDARD RECOVERY OF PUMA AFTER FLIGHT. (RIGHT) USBP HAND-LAUNCHING A PUMA.

8. Initial Performance Model

SARA had performed work with PANCAS on the Puma previous to the FAA contract, so we were able to use pre-existing modeling and simulation tools. For initial performance estimation and to allocate requirements, SARA prepared a mission model, a PANCAS sensor model, and a Puma flight dynamics model. The mission model simulates the Puma flying a BVLOS mission and simulates representative encounter aircraft approaching from random directions. As the mission model runs, it makes calls to the PANCAS sensor model, to determine for each timestep if the intruder aircraft causes PANCAS to issue an Alert to avoid. We use an empirical PANCAS sensor model based on flight test results against relevant encounter aircraft in a relevant environment. Once an avoidance maneuver is commanded, the Puma flight dynamics model is called, and the avoidance maneuver is simulated. SARA initially simulated three types of avoidance maneuvers: turning, descending, and an "autoland and recover" maneuver, described in the next paragraph. The intruder aircraft continues to approach as the avoidance maneuver is simulated. The mission simulation tracks the vertical and horizontal separation between the Puma and the manned aircraft and reports the point of closest approach (PoCA) for each encounter.

The Puma has a unique "autoland" feature which is used by all Puma operators. With a couple button presses on the handheld controller, the autoland command causes the Puma to pitch up and cut the motor. The Puma stalls, the nose pitches over, and the Puma rapidly descends. The onboard camera automatically stows at the same time. If no further action is taken, the Puma will descend to the ground and land rather forcefully. The Puma has been designed to land in this manner and withstands the impact by using breakaway connectors so the wing can disconnect and dissipate the energy of the landing. However, the air vehicle operator (AVO) can also recover from an autoland by commanding 100% throttle. This causes the Puma to level out at a lower altitude. The "autoland and recover" is a common method Puma AVO's use to lose altitude quickly.

The mission model and PANCAS sensor model were already defined with sufficient fidelity from previous efforts, but the Puma flight dynamics model was poorly defined. The avoidance maneuvers contained several unknowns:

- Standard descent rate
- "Autoland" descent rate
- Effects of added weight of DAA system
- Command latencies
- Reliability of maneuvers considering winds, operator error, etc.

Unknowns such as these are expected in initial models. Having identified the specific unknowns, the next step was to conduct flight testing to measure those unknowns.

9. Flight Test 1: Measuring Unknowns

SARA conducted our first flight test in January 2022 at the Charles R Johnson Airport, in Port Mansfield, Texas. Lone Star UAS Center of Excellence provided the test range, range safety, and pilot for a rented Cessna 206 single-engine fixed-wing encounter aircraft. NAVAIR provided two RQ-20 Puma UAS and US Border Patrol (USBP) provided a third. USBP provided Puma air vehicle operators (AVOs).

FIGURE 6: FLIGHT TEST 1 SETUP

A combined 15 hours of flight time was logged on the Pumas during the week-long test. Turning, descending and "autoland and recover" maneuvers were tested. Figure 7 (left) shows the descent rates achieved using a standard descent and the "autoland and recover" maneuver. The "autoland and recover" maneuver was 3-4x faster and was a clear favorite during the test. The maneuver was effective, repeatable and was easy for the USBP operators to execute. Due to the puck shape of the LoWC volume, a UAV can remain well clear in the event of a head-on collision either by descending 250 ft (76 m) or by turning and traversing 2000 ft (610 m) laterally. An "autoland and recover" maneuver at 7 m/s can lower the Puma 76 m in about 11 seconds. For a turning maneuver to cover 610 m in 11 seconds, the Puma would have to be able to travel 55 m/s. Figure 7 (right) shows the speeds achieved were significantly lower than this. Turning maneuver efficacy was also highly dependent on wind directions. This solidified our conclusion that "autoland and recover" is the preferred avoidance for the Puma when operating at low altitudes.

See "DAA Encounter Test 1 Report" for additional information about the flight test setup, execution and analysis.

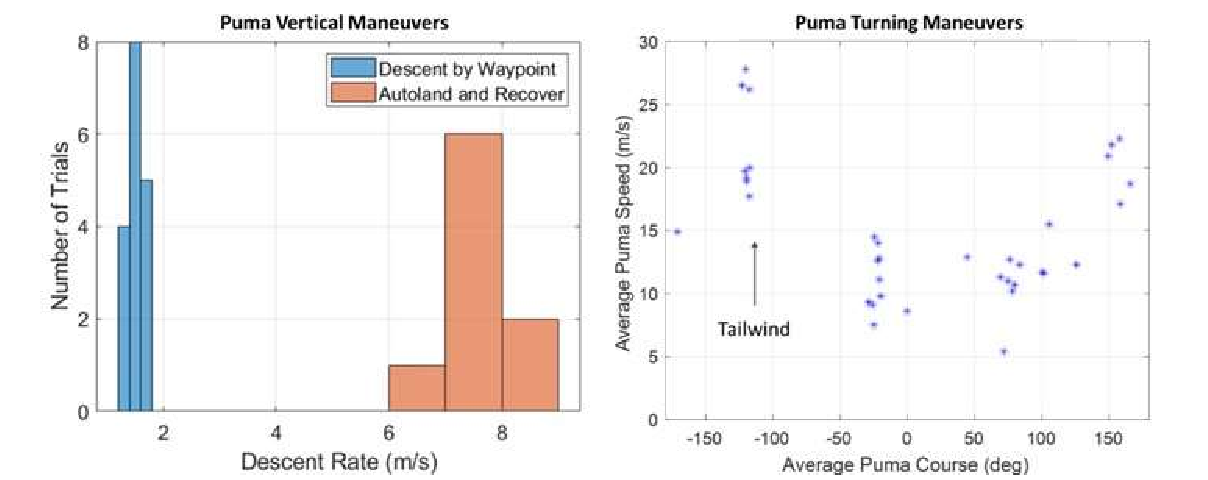

FIGURE 7: PUMA MANEUVER SPEEDS MEASURED DURING FLIGHT TEST 1

10. Updated Performance Model

Now favoring the "autoland and recover" avoidance maneuver, SARA updated our mission model to use that maneuver exclusively. As shown in Figure 8 (left), the model is initialized with randomly selected altitudes for the Puma and an intruder aircraft. When PANCAS commands an avoidance maneuver, the Puma descends at a rate randomly sampled from the descent speed distribution (right) fit to the flight test results.

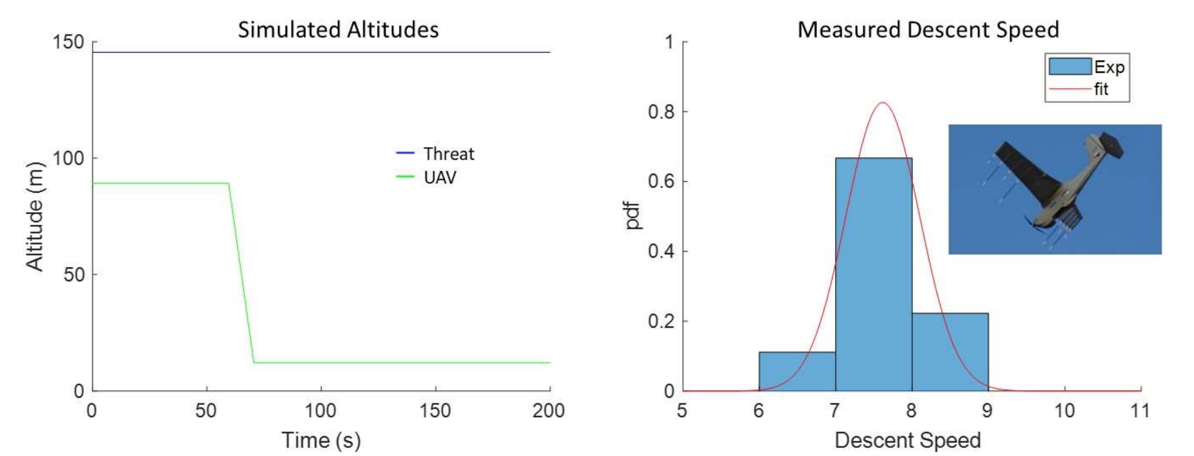

FIGURE 8: UPDATED SIMULATION OF PUMA "AUTOLAND AND RECOVER" MANEUVER

11. Flight Test 2: Verification testing

Having shown that PANCAS meets the ASTM risk ratios using test-anchored simulation, SARA was ready to perform verification testing with the second and final flight test of the project. SARA, Lone Star, and

USBP returned to Port Mansfield in May 2022, joined this time by the FAA and US Coast Gard. The same three Puma UASs were operated as in the first test, two being provided by NAVAIR and one provided by USBP. Lone Star secured the same Cessna-206 that was flown during the first flight test.

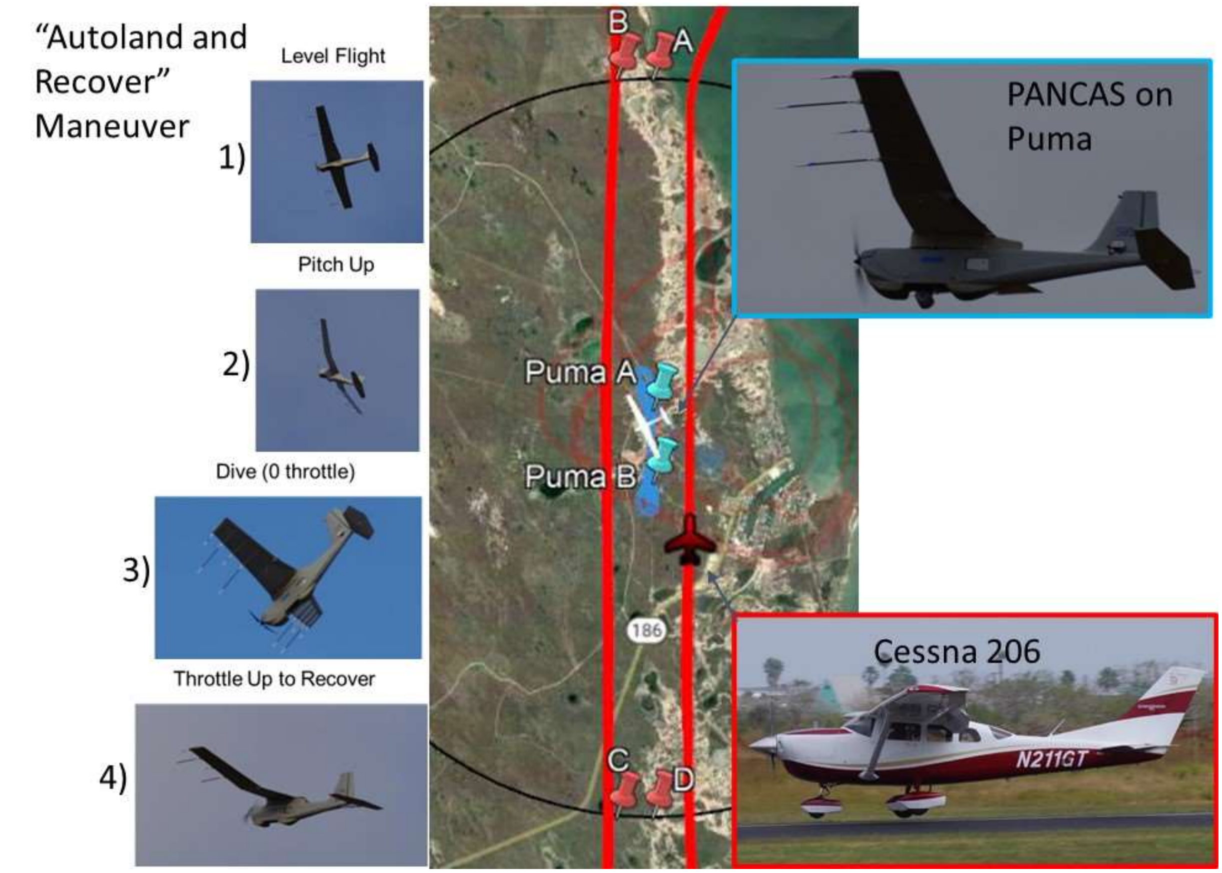

FIGURE 9: VERIFICATION FLIGHT TESTING IN PORT MANSFIELD, TEXAS

The flight pattern is shown in Figure 9. The Cessna flew a North-South racetrack pattern at 900 ft AGL, defined by waypoints A, B, C and D. The Puma flew a smaller racetrack at 400' AGL between waypoints "Puma A" and "Puma B". Altitude separation provided test safety and PANCAS performance would have been the same had the two aircraft been colatitude. As the Cessna approached, PANCAS detected the sound generated by the propeller and engine and reported these detections to the PANCAS operator on the ground display. Detections are visualized as a yellow beam in the direction of the threat. This primes the PANCAS operator, and co-located Puma operator, to be ready to execute an avoidance maneuver. As the Cessna continues to approach, PANCAS escalates the threat to a collision hazard and sends an Alert to the PANCAS operator. Alerts are displayed as a red beam pointing toward the intruder, as well as a red flashing warning symbol with text "ALERT – AVOID NOW". An alarm is also sounded through the PANCAS terminal PC speakers. Once an Alert was received, the Puma AVO executed an "autoland and recover" maneuver. The Puma remained at a same minimum altitude until the intruder passed and PANCAS stopped tracking it, at which point the AVO commanded the Puma back to 400' AGL. It is also possible for PANCAS to automatically command an avoidance maneuver, but this was not tested under this contract.

The flight test was successful, though test issues did arise. Initial operation of PANCAS showed a high false alarm rate. The cause was ultimately traced back to an RPM sensor failure on the Puma. The RPM sensor was replaced with a spare and PANCAS began performing normally. The challenges did not end there, as the Puma next suffered three failed launches. Ultimately, the cause was determined to be debris that restricted the motion of the tail servo. Eventually getting PANCAS and the Puma back to full functionality, the final challenge was the constant, strong wind. The winds were often just below 25 knots, which is the operational limit of the Puma. The winds at 400' ALG were strong enough that the Puma made negative headway when flying upwind on several occasions.

Despite test challenges, PANCAS performed well. 16 encounter scenarios were completed, with PANCAS detecting the Cessna-206 on every approach (16/16 = 100% Probability of Detection). PANCAS issued and Alert on each approach and the Puma AVO conducted the "autoland and recover" maneuver. These maneuvers were completed in time to keep the Puma safely separated from the Cessna at all times.

12. Safety Case Simulation: proving predictable and safe behavior

While the flight test results demonstrated effective DAA performance in a relevant environment, simulation is required to extrapolate performance to thousands of encounter geometries and report statistical results in the form of the ASTM Risk Ratios. To facilitate this, SARA's updated model was used to simulate 100,000 encounters, with the intruder aircraft approaching randomly in head-on, overtaking and crossing geometries, and above, below, or co-altitude with the Puma. A stability analysis of this model showed that results converge by 100,000 trials, as shown in Figure 10.

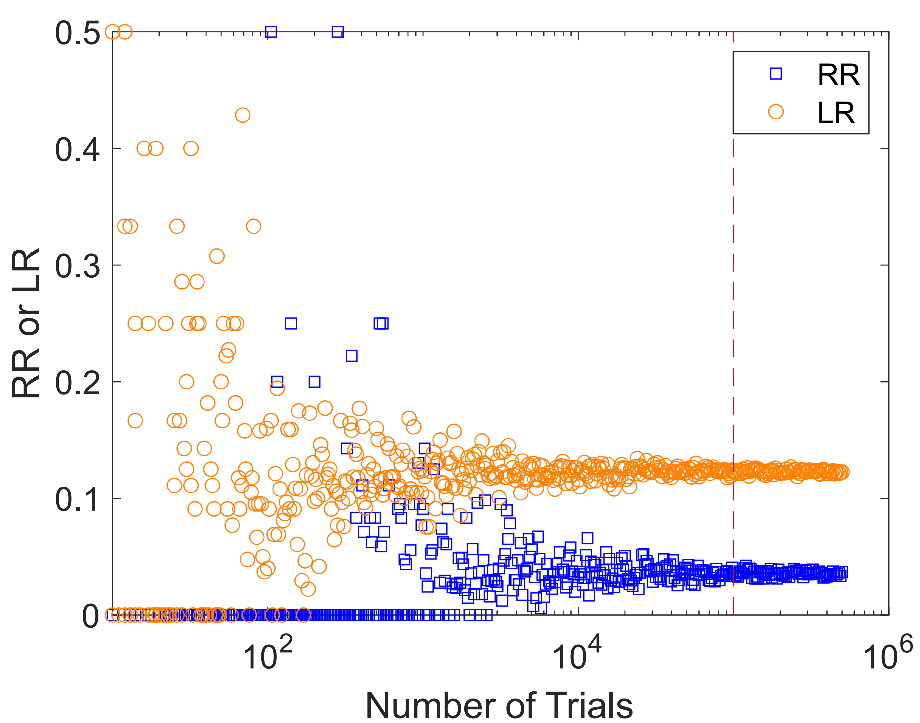

FIGURE 10: SIMULATION WAS RAN UNTIL RESULTS CONVERGED TO STABLE VALUES

The results of the simulation are shown in Table 2. Both the RR and LR risk ratios for noncooperative aircraft were met with significant margin, showing even more safety was achieved than required. The margin gives us confidence that PANCAS would meet the requirements even if our modeling assumptions or approaches were changed.

TABLE 2: PANCAS RISK RATIO RESULTS

Noncooperative Requirement	PANCAS Result	ASTM Requirement
RR	0.03	≤0.3
LR	0.11	≤0.5

By combining flight test results and test-anchored simulation, we have a high level of confidence that PANCAS, integrated on the AeroVironment Puma UAS, conducting USCG and USBP missions, meets the ASTM DAA Performance Standard Risk Ratios and allows for safe operations BVLOS. The "autoland and recover" maneuver has been shown to be effective, repeatable, and easy for Puma operators to execute. By virtue of always conducting the same avoidance maneuver, regardless of the encounter geometry, we have minimized human decision making and reaction time, making human-in-the-loop operations feasible.

13. Conclusions and Recommendations

SARA has defined and demonstrated a process for validating and verifying a DAA system integration on a UAS in support of specific use cases. The process of allocating requirements between the DAA sensor, the UAV and the mission provides the integrator the best chance of identifying a valid DAA approach, while flight testing and test-anchored simulation work together to ensure the integrator can predict how the DAA system will behave and verify that the DAA behavior meets the available safety standards.

Enabling UAS to detect and avoid noncooperative aircraft is a challenging problem, but one that must be solved to ensure the safety of our National Airspace. Equipage of small UAS with DAA systems has progressed slowly, likely due to several reasons. Technology solutions have been slow to come to market, but this project has demonstrated that solutions do exist, and they are available today. Wariness about the regulatory approval process has many companies sitting on the sidelines, waiting for others to forge a path. SARA is up to this challenge. UAS companies have explored a wide variety of business models, and many have proven to not be viable as operating costs become better defined. The industry is learning from these experiences and more valid business models are emerging. Finally, some companies buy a UAS and a DAA sensor, but lack the systems engineering expertise to combine them and prove that they meet a safety standard. We hope that work completed under this contract, along with SARA's continued collaboration with UAS operators, will make DAA integration easier, more affordable, and more successful.

SARA's PANCAS DAA system, integrated on the AeroVironment RQ-20 Puma can safely fly USCG and USBP missions BVLOS while achieving the ASTM DAA Performance Standard Risk Ratio safety requirements. Recommended next steps are to operationalize the capability by having USCG and USBP conduct BVLOS operations in low-risk environments. This will help define site-specific procedures. For example, there is likely no single "safe minimum altitude" for the Puma to descend to. Rather, operators will have to balance the desire to descend as low as possible for safety against the need to maintain radio link with the Puma for reliable command and control. These operations would also expose PANCAS to more acoustic and weather environments and the gathered data would further mature SARA's simulations.

We thank the FAA UAS Integration Office for funding this research. The BAA program has nurtured collaboration between the UAS industry, FAA, and the State UAS Test Sites and we see immense value in the BAA program continuing.