Final Report: Deployment, Demonstration and Validation of the Terrestrial Acoustic Sensor Array (TASA) – Detect and Avoid (DAA) System

Contract 692M15-20-C-00006

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EXECUTIVE SUMMARY

SARA's Terrestrial Acoustic Sensor Array (TASA) is a novel ground based Detect and Avoid (DAA) system. Each TASA node consists of an array of passive acoustic probes and an edge processor. Aircraft detection 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 size 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.

Under this contract, SARA deployed a five-node TASA network near Blacksburg, VA and operated it for eight months. A flight test was conducted to gather high-quality measurements of TASA performance against a Cessna-172 airplane and a Robinson R44 helicopter. Extended operations provided a wealth of clutter data, targets of opportunity, and exposure to a span of environmental conditions.

TASA node data can be combined in several ways. Three "zero conflict airspace" use cases were investigated:

- single TASA node use case
- multi-node TASA perimeter use case
- multi-node TASA triangulation use case

The single node use case can trigger an air collision avoidance maneuver based on measurements from a single TASA node. This approach meets the ASTM Standard Specification for Detect and Avoid System Performance Requirements and works well in rural areas. Further software updates are required for this approach to work well in a more suburban environment, where false positives on ground sources are currently higher than desired.

The multi-node TASA perimeter use case was evaluated extensively and performed very well. This approach requires multiple TASA nodes to detect an aircraft crossing a perimeter before triggering a collision avoidance maneuver. This approach met the ASTM DAA performance requirements and achieved a very low false alert rate in a suburban environment. This approach requires TASA nodes to be placed specifically along a boundary, which may limit its practicality for some use cases.

The multi-node TASA triangulation use case has been recently developed and is currently being evaluated and refined. This approach uses two or more TASA nodes to triangulate the position of an intruder aircraft and command a UAS to execute a collision avoidance maneuver if a zero-conflict airspace is compromised. Available results are very encouraging, with evidence that the ASTM DAA performance requirements can be met. Even though the current contract ends on May 28, 2021, SARA plans on continuing evaluation and refinement of the triangulation approach.

This contract has been a great opportunity for SARA to validate and verify the TASA DAA system with the FAA and with the Mid Atlantic Aviation Partnership. We have tested multi-node use cases that are fully ready to support safe BVLOS operations in the NAS. We have made great progress maturing the multi-node TASA triangulation use case and we believe this will be ready for operations very soon. We hope to find additional opportunities to continue working with the FAA in the future.

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Figure 1 – SARA's Terrestrial Acoustic Sensor Array is a low-altitude surveillance system based on passive acoustic sensing.

1.1   The Need for Noncooperative Detect and Avoid Systems

Guidance from the FAA has been clear that UAS pilots are responsible for detecting and avoiding manned aircraft, just as manned aircraft pilots are required to see and avoid each other. Finding a sensor solution to enable such detect and avoid (DAA) capability has been a key challenge holding back the drone economy. Most manned aircraft are now required to broadcast their position over ADS-B, and it is a relatively easy process for UAS to use this data feed to avoid so-called "cooperative" aircraft. However, not all manned aircraft are equipped with ADS-B transponders, and some that are equipped are non-functional or disabled. These "noncooperative" aircraft still must be detected and avoided. Only a few companies have focused on developing DAA systems that work against noncooperative aircraft. Their approaches can be classified into two categories: ground-based DAA systems and airborne DAA systems, which are installed on the UAS itself.

Most business providing UAS services, such as facility inspection or package delivery, are only profitable when UAS operate over the same route or in the same area repeatedly over months or years. These UAS have very limited size, weight and power (SWaP) available for an onboard DAA system. Additionally, UAS designs are evolving rapidly and most businesses are upgrading equipment multiple times per year. Finally, most UAS still have limited endurance and are looking to operate over relatively short distances. In many cases, these factors lead UAS operators to conclude that a ground-based DAA system is preferable. Ground-based DAA systems do not add any weight to the UAS, allow operators to change UAS with minimal disruption to the DAA system.

1.2   The Terrestrial Acoustic Sensor Array (TASA) System

SARA developed the Terrestrial Acoustic Sensor Array (TASA) system to enable small unmanned aerial systems (sUAS) and manned aircraft to remain safely separated while operating in the same airspace. TASA maintains well clear separation while requiring no cooperation from the manned aircraft and no instrumentation onboard the UAS. Much like a human visual observer, TASA listens for the sounds naturally emitted by manned aircraft. By using a three-dimensional array of acoustic probes mounted on a mast (Figure 1), a single TASA node can detect multiple aircraft simultaneously and track azimuth, elevation, frequency, and amplitude of each signal. By using many TASA nodes, TASA can be scaled to very large areas of operation at a low cost and with low infrastructure burden.

1.3 TASA Node Description

A TASA node, as shown in Figure 2, consists of:

- An edge processor housed in a weatherproof enclosure
- Eight acoustic probes in a three-dimensional array
- An LTE radio
- Optional portable mast
- Optional solar power kit

The acoustic array passively detects low frequency sounds such as those emitted by aircraft. If an aircraft is detected, the edge processor extracts the aircraft sound, determining bearing and rough range, as well as frequency, amplitude and other metrics. These metrics are monitored over time and formed into tracks, which are transmitted over the LTE cellular network to the cloud. Additionally, the TASA node performs self-health diagnostics on hardware and software, reporting results over LTE twice a second. TASA nodes are built with audio components already mass produced for cell phones and consumer electronics, making the systems very low cost to manufacture. A TASA node can be assembled and configured in roughly 30 minutes, while mounting on a portable mast and setting up solar power can be achieved in roughly 1 hour, with no site improvements required. The TASA nodes set up in Virginia were place in locations where trees and buildings obstructed visual observers, but caused no issue for acoustic detection. The ability of a TASA node to operate on a 20' mast below the height of nearby trees translates into a large cost savings when compared to the cost of erecting a 100' mast required to provide a radar an unrestricted field of view.

Figure 2 – TASA Node installed with telescoping mast and solar power kit.

1.4 TASA User Terminal

Each TASA node in the user's network sends data over LTE to the cloud, where it can be accessed by a remote pilot anywhere in the world. SARA provides a user interface application, or terminal, which combines data from each TASA node, corroborating aircraft detections and sifting out false positives, then displaying a picture of the airspace
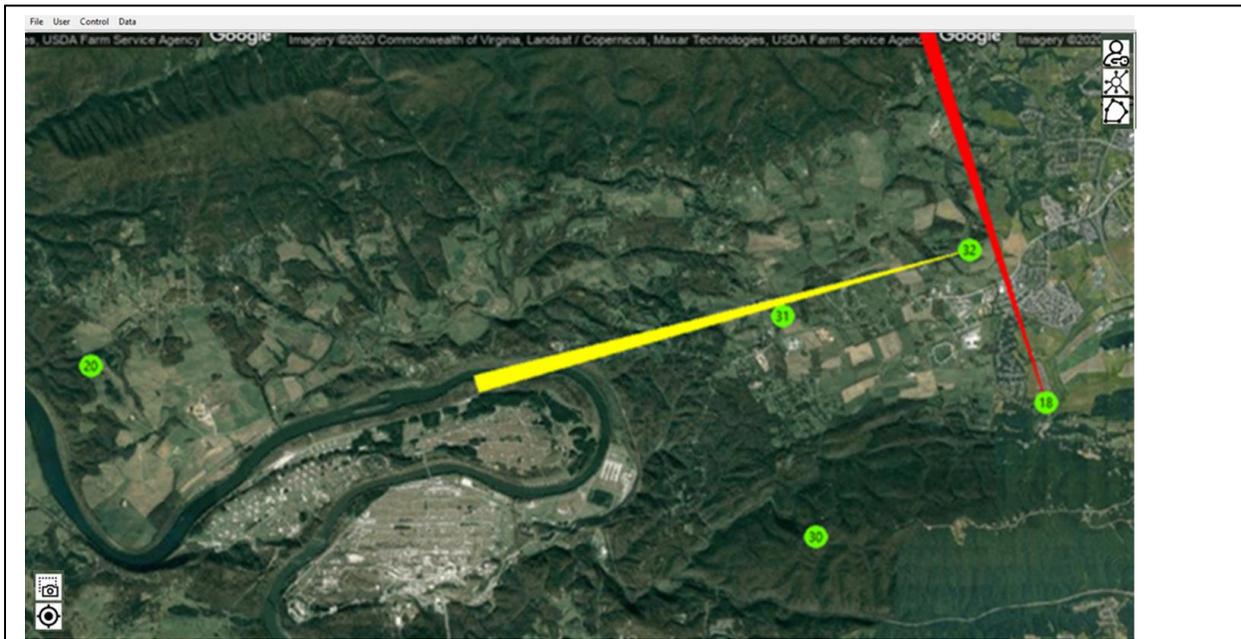

Figure 3 – TASA user terminal display

to the remote pilot. The user terminal primary display is shown in Figure 3. Each TASA node reports its position, which is indicated on the display with a green circle containing the TASA node ID. Twice a second, the TASA node reports its system health and the terminal measures the latency of the node data. If there are no issues, the circle is colored green. If the TASA node has a hardware issue, software issue, or if messages are being delayed, the circle will turn yellow, orange and red, depending on severity of the issue. The operator may click on the icon for a description of the issue.

Yellow beams radiating from the TASA nodes indicate the direction to an aircraft upon initial detection. Red beams indicate the detected aircraft is persistent and is being tracked. Not shown in Figure 3, a boundary can be programmed between neighboring TASA nodes, like the four TASA nodes to the right in the image forming a diamond. Then, if an aircraft is tracked crossing that boundary, a visual and auditory alert will prompt the remote pilot to immediately command their UAS to land or move to a safe space.

1.5   Advantages of Passive Acoustic DAA

The technical challenges of detecting low-altitude aircraft often go unrecognized. Most people have heard the idiom "flying under the radar" and can recall at least one movie where an aircraft flies close to the terrain to avoid radar detection, but they have often not considered how one would detect such an aircraft. Radar companies have been working to produce smaller, lower cost radars as DAA sensors. Clutter and field of view are fundamental challenges these products face. Low altitude environments are filled with objects on the ground that will produce a radar return and generate false tracks. These systems also require line of sight, so 50' to 100' masts are common for elevating the radar above the nearby trees and buildings. Some of the most popular radars have a 90° or 120° field of view, requiring four radars to be used to achieve the required 360° coverage. This then leads to high cost and large power consumption. Some companies are developing optical DAA sensors. The biggest challenge to this approach is achieving a large detection range over a 360° field of view. While optical sensors are passive, the large amount of image processing required to identify aircraft results in high power consumption. As with radar, optical systems battle myriad sources of clutter at low altitudes. The other big challenge for optical systems is the need for good visibility conditions and high contrast.

A passive acoustic system like TASA is able to avoid many of the technical challenges facing radar and optical systems. Key advantages include:
- 360° field of regard
- Long range detection
- Low power operation
- Does not require line of sight

360° Field of Regard: Just like the human ear can hear sounds from all directions simultaneously, each of the eight microphones in a TASA node has a 360° field of regard. By using an array of microphones, a TASA node can point to an aircraft within a few degrees accuracy.

Long Range Detection: By using an array of eight microphones, TASA can hear signals too faint for a human to detect. This translates to long detection ranges. Manned aircraft are one of the loudest objects encountered in daily life. Most low-flying aircraft are propeller driven fixed-wing airplanes or helicopter. These propellers and rotors move at very high speeds and generate very loud, very unique sounds.

Low Power Operation: By virtue of being a passive sensor, acoustic probes require very little power. Unlike optical systems that have to process very large image files, audio files are very compact and can be measured at low sample rates. This results in TASA being a very low power system that can easily operate on a small solar panel. Not having to run line power to a new location results in a large cost savings for operators.

Does Not Require Line of Sight: Unlike radar and optical systems, acoustic sensors like TASA do not require line of sight to detect an aircraft. Sound easily passes through trees and diffracts around buildings. Most people can recall hearing an airplane flying overhead as they sit inside their house. This is a big benefit, as it allows TASA nodes to be mounted on short, inexpensive masts in areas that would not be suitable for a radar or optical system.

2.0   TASA CONCEPT OF OPERATIONS
2.1   Zero Conflict Airspace
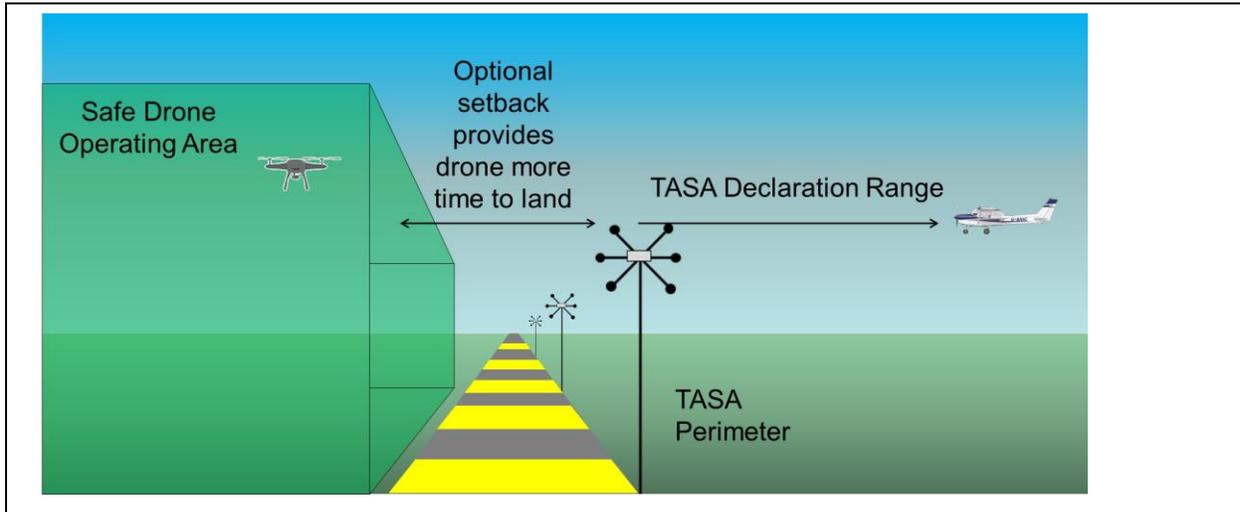
Figure 4 – Zero Conflict Airspace implemented with TASA

SARA is taking a crawl, walk, run approach to integration of UAS into the National Airspace System. We begin with extremely conservative use cases and demonstrate that detection, alert and avoidance all perform as expected, producing a safe, reliable and predictable operation. A zero-conflict airspace (ZCA) is a great approach for this crawl step, which has been used for years by the FAA and DoD as they evaluate DAA systems. For SARA's implementation of a ZCA, one or more TASA nodes are deployed to create a perimeter. Set back within this perimeter, an operating area is defined where a UAS may operate beyond visual line of sight. If a low-flying manned aircraft approaches the TASA perimeter, the TASA network will monitor the aircraft and notify the remote pilot. This notification is only for situational awareness and the UAS may continue operating. If the manned aircraft continues to approach, it will eventually cross the TASA perimeter, triggering the TASA network to send an alert to the remote pilot, and in some cases directly to the UAS. Upon receiving an alert, the UAS must execute a pre-programmed maneuver that quickly moves the UAS to a safe state. Continuing with the "crawl" mentality, we initially favor an avoidance maneuver where the UAS lands at the closest safe landing zone. If the UAS is on the ground, there is no way for it to pose a safety hazard to the manned aircraft. As we mature to a "walk" state, we will seek to add other avoidance maneuver options, such as moving to shielded airspace.

2.2   Single Node Use Case
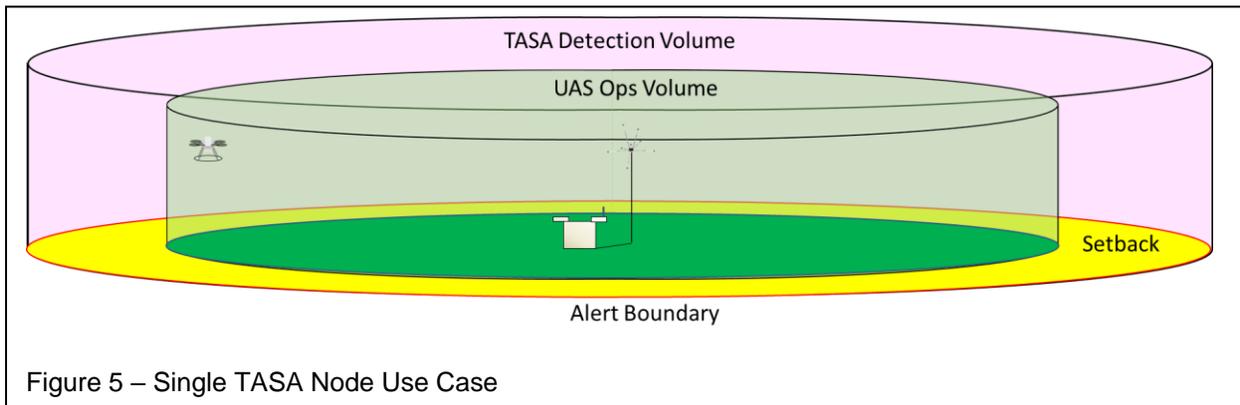
Figure 5 – Single TASA Node Use Case

A single TASA node can enforce a ZCA and enable BVLOS operations at a fixed site. As shown in Figure 5, the TASA node monitors a detection volume and enforces an Alert Boundary. If an aircraft crosses that boundary, TASA commands the U AS to move to a safe state, most often landing. The UAS operates within a smaller volume centered on the TASA node, set back from the Alert Boundary to provide sufficient reaction time for the UAS to reach a safe state. TASA can communicate with the UAS over LTE, radio, or can be connected to the UAS control station over

Ethernet. This approach works well for many applications where the UAS does not travel very far, but having a remote pilot and visual observers maintaining line of sight becomes prohibitively expensive. For example, agricultural inspection, work site management and facility security are all applicable. This approach was evaluated under this contract at Virginia Tech's UAS test site, Kentland Farm.

2.3 Multi Node Perimeter Use Case
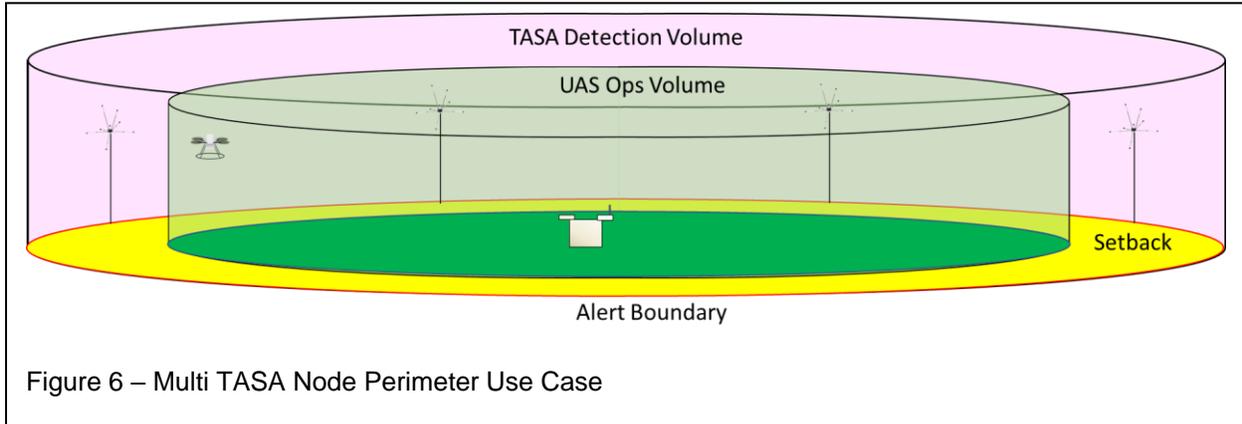
Figure 6 – Multi TASA Node Perimeter Use Case

Three or more TASA nodes may be set up around an operating area on the Alert Boundary itself. This allows the UAS operational volume to grow arbitrarily large by adding more TASA nodes. It also enables sensor fusion approaches, where neighboring TASA nodes can corroborate aircraft detections and reject false alerts. In this approach, TASA nodes transmit their information over LTE to a TASA user terminal. The terminal then fuses the individual sensor feeds and asses if there is an aircraft within the ZCA or not. The TASA terminal then sends commands to avoid straight to the UAS, to the remote pilot, or both.

2.4 Multi Node Triangulation Use Case
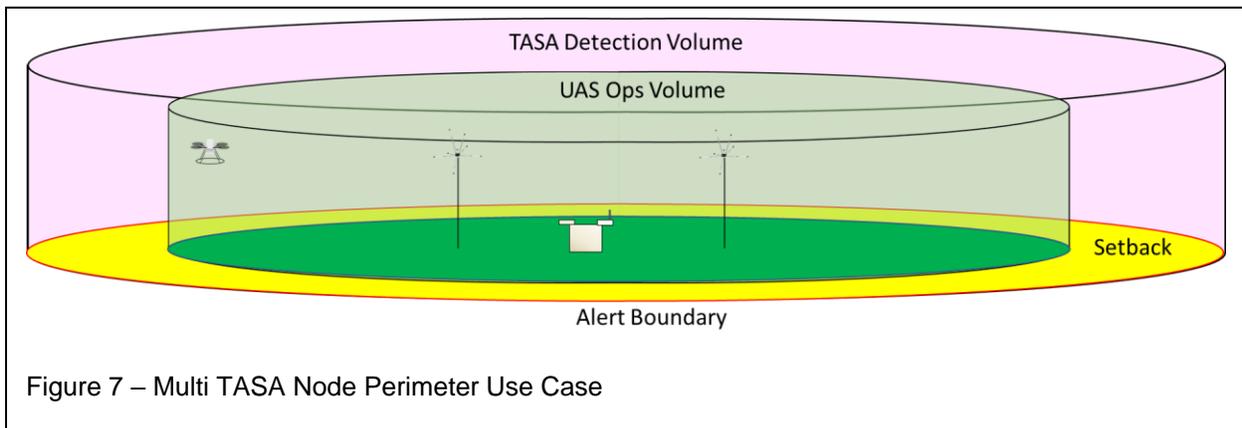
Figure 7 – Multi TASA Node Perimeter Use Case

The newest use case for TASA networking is Multi Node Triangulation. This approach uses two or more TASA nodes placed within the Alert Boundary. The TASA nodes are placed with overlapping coverage, such that the position of an approaching aircraft can be triangulated. This approach provides the most accurate position and velocity information as well as providing new means of rejecting false alerts. This is an exciting approach that shows good initial performance, but is still under development, with an expected release in the next few months. By providing position and velocity tracks, this approach lends itself to more advanced use cases, such as integration with John's Hopkins Universities ACAS sXu, which would enable use cases beyond a ZCA, where UAS could stay airborne and remain well clear of manned air traffic.

3.0   TYPICAL INSTALLATION PROCESS BASED ON UAS OPS

Typically, a UAS operator approaches SARA with a desire to fly a specific set of UAS operations BVLOS. The best fit for initial BVLOS waivers using TASA as the DAA system are UAS operations over private property, in Class G airspace below 400' AGL.   SARA works with the UAS operators to understand the flight paths and the maneuverability of the UAS.   SARA then recommends a pre-defined avoidance maneuver that can be completed safely, repeatably, and within a reasonable time budget. Based on this time budget, SARA then identifies the number of TASA nodes required, their locations, and the best use case for TASA node fusion. SARA performs a site survey to determine TASA node locations and assists with node installation and integration with the UAS. SARA then works with the UAS operator to verify that the installed TASA network is meeting the ASTM DAA Performance Standard by recording targets of opportunity or conducting scripted encounters with a hired manned aircraft. The UAS operator must perform testing to verify that their UAS can execute the avoidance maneuver repeatably within the time budget. All this information is then gathered into a data package that can be submitted to the FAA along with the BVLOS waiver application. We have found this approach to work well and to be necessary in the near term, because passive acoustics is unfamiliar to most UAS operators and they lack the experience to perform the setup, integration and verification themselves. To make the technology more scalable in the future, SARA is developing guidelines and best practices that would streamline the installation of new TASA networks based on similarity.

4.0   TASA INSTALLATION NEAR BLACKSBURG, VA

The TASA installation in Virginia under this contract was atypical because there were no specific UAS operations. TASA nodes did not have to be placed around a specific UAS operating area, so the specific node placements were less constrained than usual. Because the sole intent was to validate and verify the TASA system, TASA node locations were selected from the available properties owned by Virginia Tech near Blacksburg, VA. This resulted in a single TASA node at Kentland Farm and four TASA nodes in the Price's Fork area.

4.1   Single TASA node at Kentland Farm

Figure 8 – TASA Node at Kentland Farm

One TASA node was installed on a hilltop at Kentland Farm. A single TASA node provides sufficient range to cover the entire property and beyond, and the area is rural enough that we expected a single TASA node to achieve a low false alert rate. Accordingly, the single node use case described in Section 2.2 was implemented and evaluated here. The measured performance was more than sufficient to achieve the ASTM DAA Performance Standard risk ratios, but false alert rate was slightly higher than expected.

4.2 Four TASA node Perimeter at Price's Fork

Four TASA nodes were installed in the Price's Fork area, roughly in a diamond shape. Figure 9 shows a satellite image of the Price's Fork area on the Western outskirts of Blacksburg, VA. Each TASA node location is identified with a yellow pin and the serial number of the TASA node (Serial numbers 21, 22, 24 and 26). The space between each pair of TASA nodes is indicated. Figure 10 shows a photograph of each installation location. Price's Fork Road runs East to West near TASA nodes 24 and 21. This road carries 10,000 vehicles per day past the TASA nodes, according to VA DOT measurements. TASA node 26 is roughly 3km from the Virginia Tech Montgomery Executive Airport runway, providing targets of opportunity. In October, 2020, flight testing was conducted with hired manned aircraft flying through the TASA perimeter. The multi-node perimeter use case described in Section 2.3 was evaluated during this time. In the following months, the multi-node triangulation use case described in Section 2.4 was developed and SARA was able to conduct a limited evaluation in post processing.
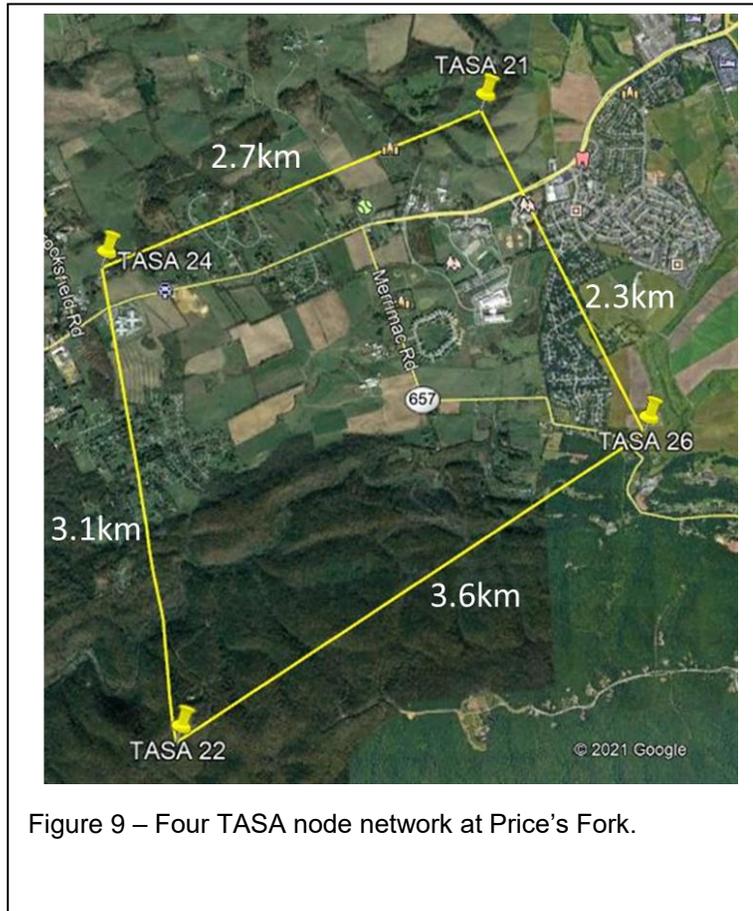

Figure 9 – Four TASA node network at Price's Fork.

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Figure 10 – TASA node locations at Price's Fork

4.3   Portable Masts

All five TASA nodes were mounted on portable masts which performed very well during the project. Telescoping aluminum segments allow the mast to be adjusted to any height between 10' and 47'. While some larger masts require concrete footings or other site improvements, these small masts were immediately deployable with no site improvements. Once raised, the mast is supported by a series of nylon rope guy wires. The mast was easily transported in a pickup truck and required minimal training to erect. The aluminum mast withstood the elements with no issue and teardown was completed in under an hour.

4.4   Solar Power

All five TASA nodes were equipped with a solar panel, charge controller and battery pack, as shown in Figure 11. This power system allowed the TASA nodes to operate 24/7 without regular maintenance.

Figure 11 – Solar power being installed on TASA node.

5.0   FLIGHT TESTING

Flight testing was conducted on October 6-8, 2020 to evaluate TASA detection range, bearing accuracy and field of regard. Test results were very favorable, showing good performance when using both the single TASA node use case and the multi node perimeter use case. The multi node perimeter use case particularly excelled at achieving a very low false alert rate. Detailed results were provided in a fight test report and are summarized here.

5.1   Test Aircraft

Figure 12 – A Cessna 172 and a Robinson R44 were flown as encounter aircraft

A Cessna 172 was selected as a representative single-engine fixed-wing aircraft. More Cessna 172 airplanes have been produced than any other aircraft. A Robinson R44 helicopter was selected as the second test aircraft. This is one of the more acoustically challenging helicopters currently operating in the National Airspace System. Test aircraft were flown one at a time. The airspace was not restricted an occasional general aviation traffic was encountered as well.

5.2   Flight profiles

The primary flight pattern flown over the Kentland Farm node, evaluating the single-node use case, was a "wagon wheel" pattern, shown in Figure 13. The intruder aircraft started 6km away from the TASA node and flew straight
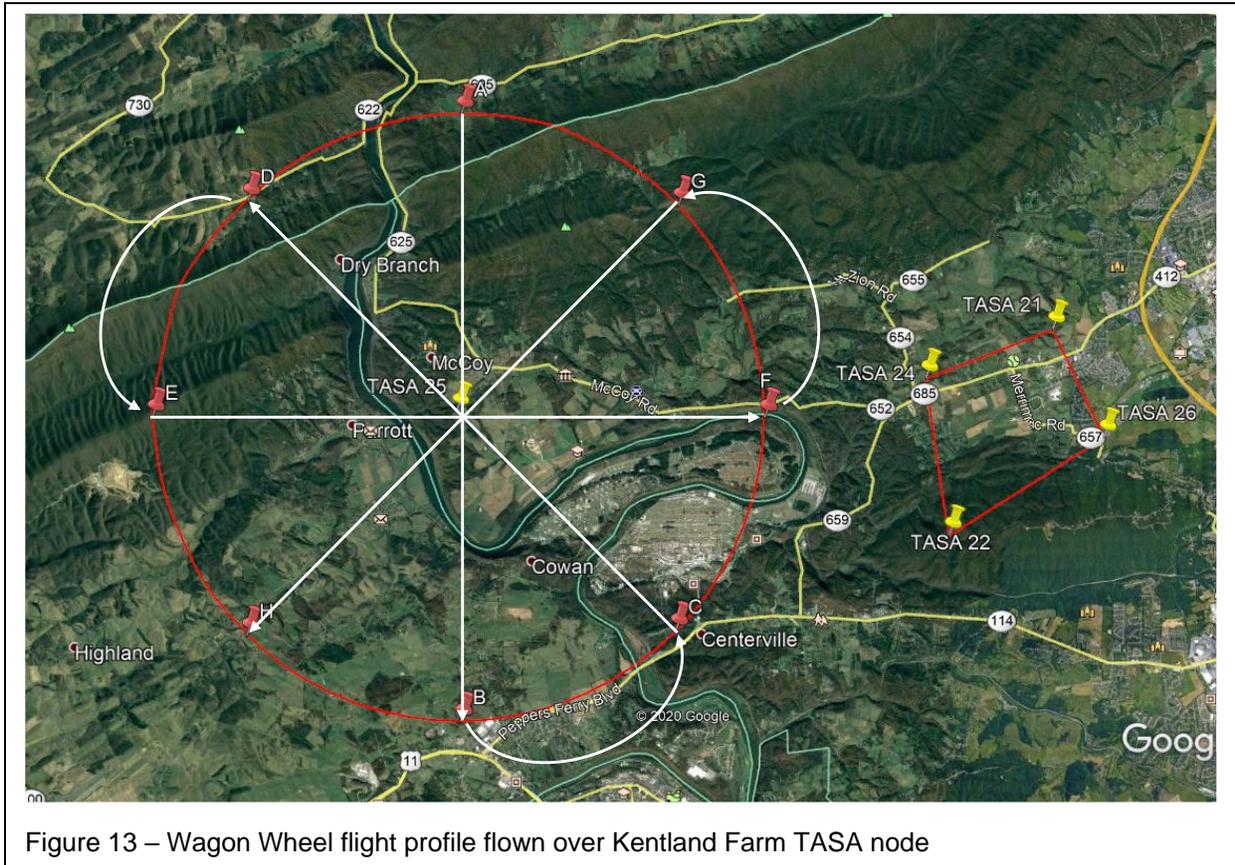
Figure 13 – Wagon Wheel flight profile flown over Kentland Farm TASA node

and level toward the TASA node at 500' AGL. Because of the varied terrain the altitude MSL varied based on the approach direction. After the encounter aircraft flew over the TASA node it continued straight past the node until it was 6km away. At this point it would circle around to approach from another direction. This is a good flight pattern for evaluating detection range, bearing accuracy and field of regard.

The two most important flight profiles flown over the Price's Fork TASA network were crossing patterns that tested the alert capability of the network when crossing each segment of the alert boundary. These profiles are shown in Figure 14. The intruder aircraft attempted to fly straight and level at 500' AGL, but due to the sloped terrain several segments of flight included climbs and descents. The encounter aircraft would fly across the alert boundary, straight through the ZCA and out across the opposite boundary.

Both at Kentland Farm and Price's Fork, no UAS were flown. Typically, SARA would ensure the UAS operator implements an effective collision avoidance maneuver and tests it thoroughly. Most of this testing can be done with a simulated encounter aircraft, but a few end-to-end tests are always recommended, where the intruder approaches, TASA alerts and the UAS avoids to remain well clear.

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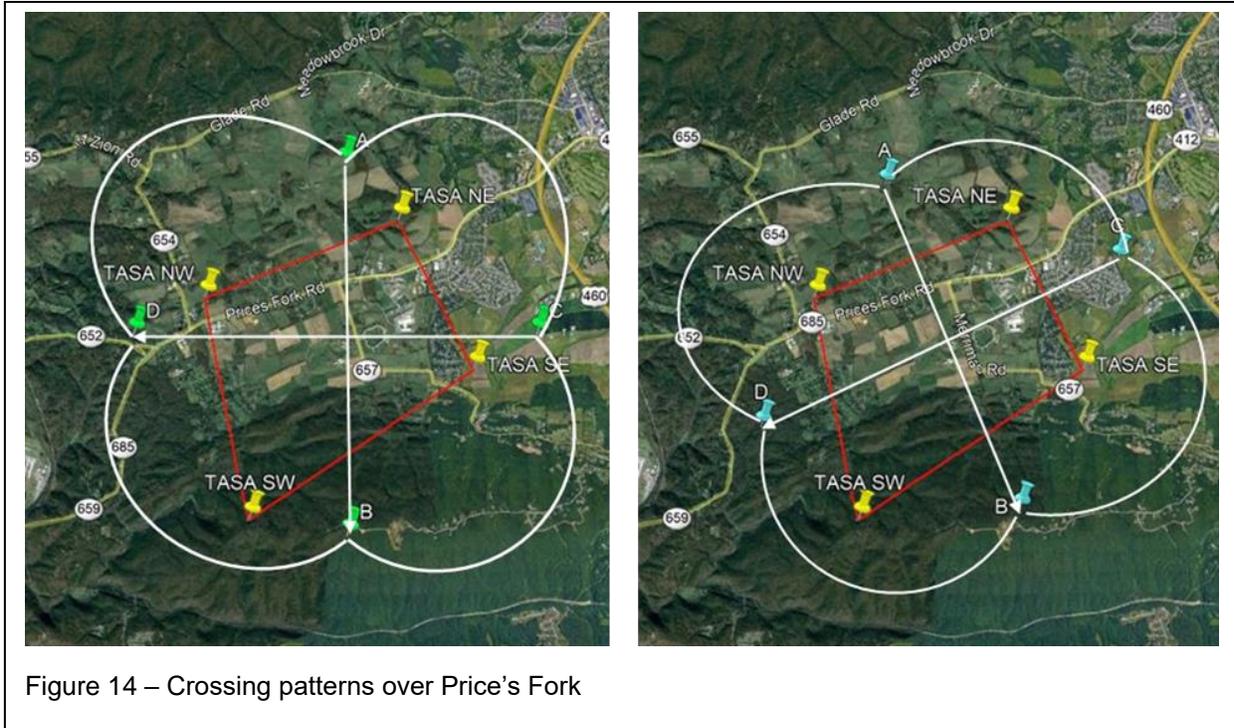
Figure 14 – Crossing patterns over Price's Fork

5.3   Weather Conditions

Testing was targeted to begin at sunrise, but morning fog delayed the start of testing. Testing began as soon as the pilots were comfortable with the weather. The remaining patchy fog presented a good opportunity to demonstrate TASA's ability to work regardless of visibility conditions, as shown in Figure 15.
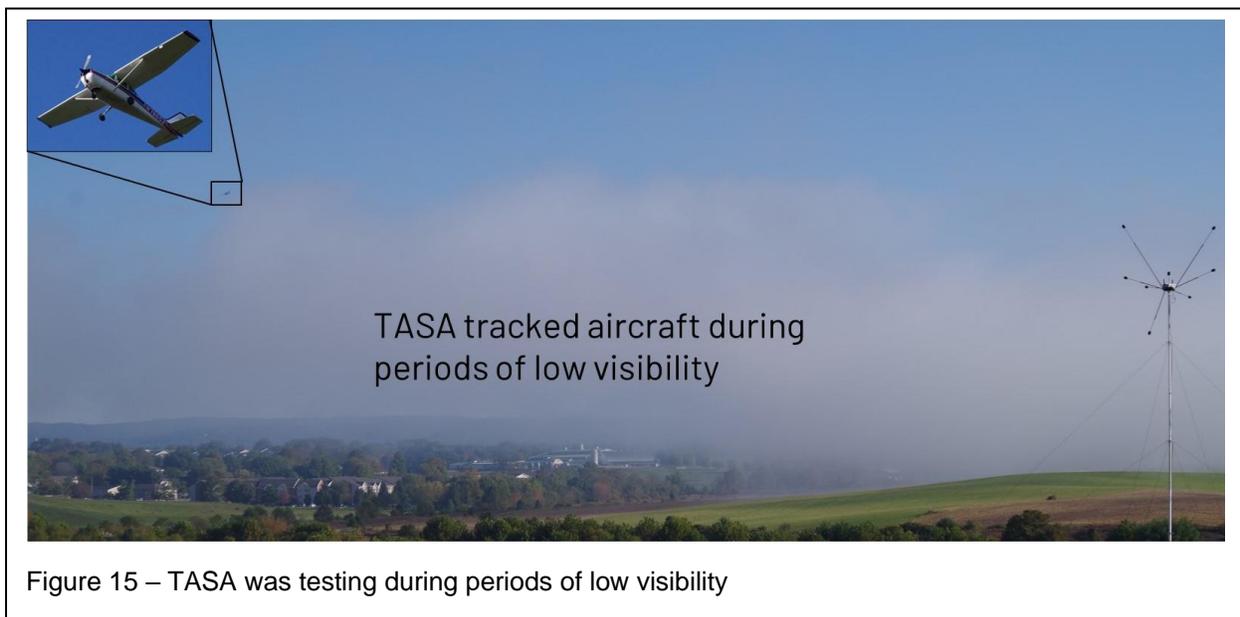

Figure 15 – TASA was testing during periods of low visibility

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6.0 TEST RESULTS

During flight testing, the TASA flight terminal displayed system health and aircraft detections in real time. Detailed logs were also automatically saved for post-test analysis. Analysis concluded that the node spacings tested at Price's Fork, 2.3km to 3.6km, was effective at achieving a high level of safety and a low false alert rate. Test results from Kentland Farm indicated that TASA node spacings in rural areas could be 7km or more while still providing the required level of safety. The observation here is that single TASA nodes achieve a sufficiently low false alert rate in rural areas to enable BVLOS operations, but in more suburban areas overlapping coverage from two TASA nodes is required to reject false alerts. Key performance metrics for the single node use case are reported in Table 1.

Metric	Cessna-172	Robinson R44
Probability of Detection	100% (20 approaches)	100% (20 approaches)
Field of Regard	360°	360°
Detection Range	6.07km avg	4.25km avg
Bearing Accuracy	0.4° Avg, 6.4° STD over all tracks	0.3° Avg, 5.1° STD over all tracks
False Alert Rate	4/hr alerts on trains & vehicles	4/hr alerts on trains & vehicles

Table 1 – Performance of single TASA node use case at Kentland Farm

Probability of detection, field of regard, detection range and bearing accuracy results were in line with previous test results and all very good. The false alert rate, while lower than some competing systems, was higher than SARA has observed in previous testing. While there were likely multiple factors contributing to this, all of which may not be known, some of this can be attributed to a higher-than-expected occurrence of train and vehicle noise in this area.

Key performance metrics for the multi-node perimeter use case are reported in Table 2. The perimeter was easily

Metric	Performance (Applies to Cessna & Robinson)
Probability of detection	100% (40/40 approaches) probability of detecting a perimeter crossing
Field of Regard	All segments of perimeter, 360° around each node
Alert Range	Alerts upon perimeter crossing
Bearing Accuracy	2.4° avg, 7.0° STD
False Alert Rate	0 alerts recorded on autos or other ground clutter. Consistent false alerts on nearby non-hazard aircraft

Table 2 – Performance of multi TASA node perimeter use case at Price's Fork

monitored with node spacings used, achieving 100% probability of detection over all segments of the alert boundary. The most exciting result was the very low false alert rate achieved. Though two TASA nodes were placed next to a busy road where semi-tractor trailers caused false tracks, the other two TASA nodes were far enough away from this road that semis were never heard. Then, by comparing the feeds of all four TASA nodes, false alerts on semis or other ground clutter were completely removed.

The Robinson R44 flew patterns over the Price's Fork TASA network twice; once with the TASA nodes at 50' AGL and once with the TASA nodes lowered to 20' AGL. Analysis of these results showed no discernable difference in performance. This is an exciting result, as shorter mounting heights reduce the cost of masts, reducing the already-low installation cost of a TASA network.

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7.0 EXTENDED OPERATIONS

The TASA network was operated 24/7 over a span of eight months. Virginia Tech's Mid Atlantic Aviation Partnership (MAAP) performed weekly inspections and gathered detailed performance logs which are stored locally at each TASA node. These logs are not used operationally, but they contain valuable information that allowed SARA to perform detailed analysis of TASA performance to further develop the system. MAAP and SARA both had copies of the TASA user terminal, which allowed real-time inspection of the TASA network health, as well as displaying aircraft detections. With these tools, SARA was able to identify issues and release software updates during scheduled site visits. Three TASA software versions were tested on the TASA nodes and more than 20 TASA terminal software versions were tested remotely.

After initial fielding, SARA observed periods of high latency in the system. The time required for a TASA node to transmit an aircraft detection up to the cloud and down to the TASA user terminal could take several seconds during particularly bad periods. SARA undertook a large effort to identify the cause of these latencies and resolve them. SARA was successful at reducing TASA latencies such that the average latency is now 270 ms. This is comprised of 254 ms to upload data from the TASA nodes in Virginia to the cloud and 15 ms to download the data from the cloud to the TASA user terminal. The distribution about these average results is shown in Figure 16.
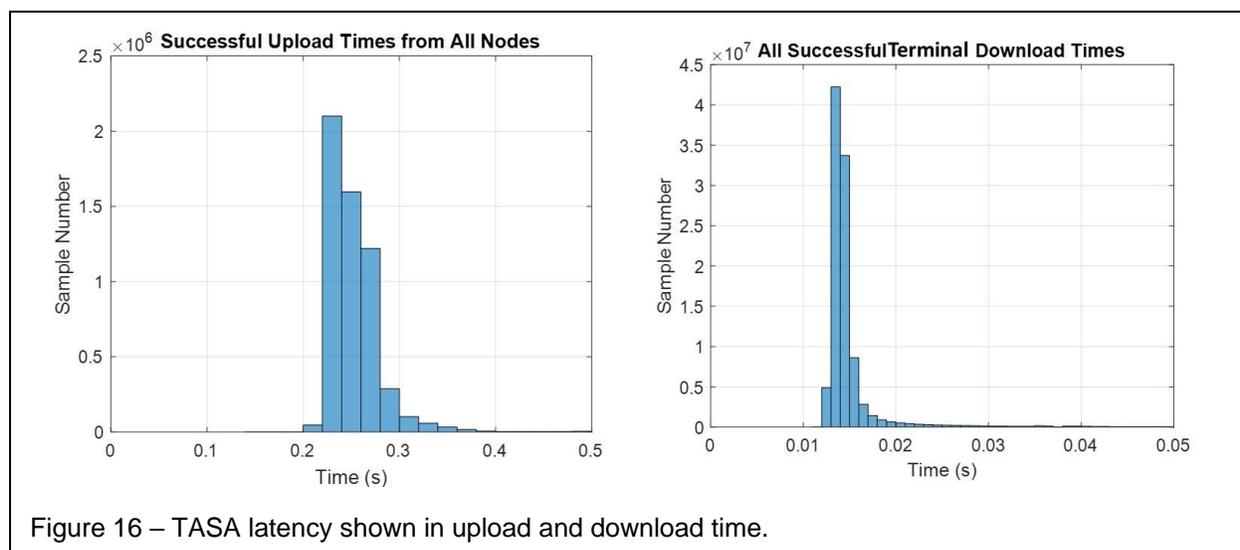

Figure 16 – TASA latency shown in upload and download time.

During extended operations the TASA hardware performed well in all visibility, wind and temperature conditions. Operations did reveal a faulty gasket around one connector on the TASA enclosure that allowed for some water ingress. The faulty gasket was identified and remedied, resulting in a new gasket being selected for future TASA builds. In general SARA and MAAP observed that no regular maintenance was required. The TASA windscreens, an inexpensive foam sleeve around each acoustic probe, did show some deterioration from birds pecking at them and would likely require replacement on a case-by-case basis after 2-3 years.

As mentioned earlier, diagnostic logs are stored locally at each TASA node. These logs are not used operationally but are valuable for SARA development. Because the TASA nodes were mounted out on masts out of reach, COTS USB extenders were used so data could be written to a flash drive at ground level. These USB extenders proved to fail intermittently throughout the fielding period. After trying several fixes and multiple USB extender brands, SARA concluded that these devices are not reliable enough to write continuously over long durations. Even with this issue, several terabytes of data was collected by MAAP and provided to SARA for analysis. This is more than enough for our development purposes and will continue to be a valuable resource advancing future software development.

8.0 ASTM RISK RATIO CALCULATIONS

For a typical application where SARA provides a TASA DAA system to a UAS operator, SARA would identify the UAS operating area, identify an avoidance maneuver, measure the time required for the UAS to reach a safe state, select a TASA use case, then specify where the TASA nodes must be installed. Under this contract, the opposite approach was required. The TASA node location options were extremely limited and based on what property Virginia Tech owned in the area. After selecting the best available TASA node locations, and since there were no actual UAS operations planned, SARA evaluated several TASA use cases generically, with the flexibility to specify a UAS operating area. A Data Analysis Plan was submitted near the beginning of the contract that provides much more detail about the risk ratio calculations.

8.1 Risk Ratios

SARA has been evaluating our DAA systems against the ASTM Standard Specification for Detect and Avoid System Performance Requirements. The main requirements in this standard are two *risk ratios*:

- RR is defined as the sum of encounters resulting in a near midair collision (NMAC) when mitigated by a DAA system, divided by the sum of encounters resulting in NMAC when not mitigated.
- LR is defined as the sum of encounters resulting in a loss of well clear (LoWC) when mitigated by a DAA system, divided by the sum of encounters resulting in LoWC when not mitigated.

For non-cooperative aircraft, those that are not broadcasting their position, the requirement is for RR≤0.3 and LR≤0.5.

8.2 Test-Anchored Simulation

The flight test results described in Section 6.0 provide measured statistical distributions of TASA detection range, probability of detection and bearing accuracy. The DAA Standard requires a statistically significant set of encounters be used to calculate the risk ratios and indicates that risk ratio calculations are usually performed through test-anchored simulation. SARA has developed such a test-anchored simulation that captures the unique attributes of the TASA DAA system and evaluates each of the three use cases reported on below.

8.3 Single Node Use Case

The single TASA node use case is powerful because a single TASA node can cover a relatively large area. The Price's Fork four-node network encompasses an area easily covered by a single TASA node, as shown in Figure 17. In rural areas, the single node use case is very effective. In areas with more acoustic clutter, the false alert rate can get too high and a multi-node approach becomes more effective.

Table 3 below shows the RR and LR performance of a single TASA node, enabling a UAS to fly at 400' AGL or lower out to a range of 1.5 km from the TASA node. We simulate a landing maneuver with a descent speed of 4 m/s. These results are in line with previous flight tests and analyses SARA has performed on the single node use case.
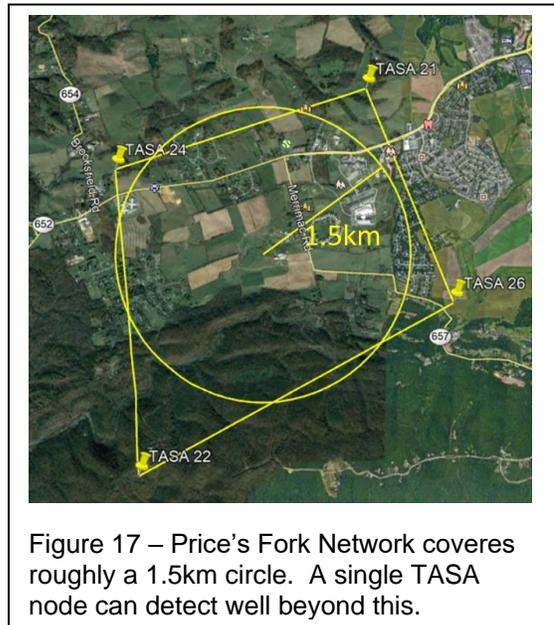

Figure 17 – Price's Fork Network covers roughly a 1.5km circle. A single TASA node can detect well beyond this.

Aircraft	RR (requirement is RR≤0.3)	LR (requirement is LR≤0.5)
Cessna 172	0.097	0.163
Robinson R44	0.11	0.20

Table 3 – Risk Ratios for Single TASA Node Use Case

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8.4 Multi Node Perimeter Use Case

This use case best fits applications where the UAS will travel over a large site, traveling several kilometers away from the launch point. The setback, shown in Figure 6, is a critical safety feature. When UAS operators have the option to place TASA nodes beyond the UAS operating area, this use case performs very well, not only meeting the risk ratio requirements but achieving extremely low false alert rates.
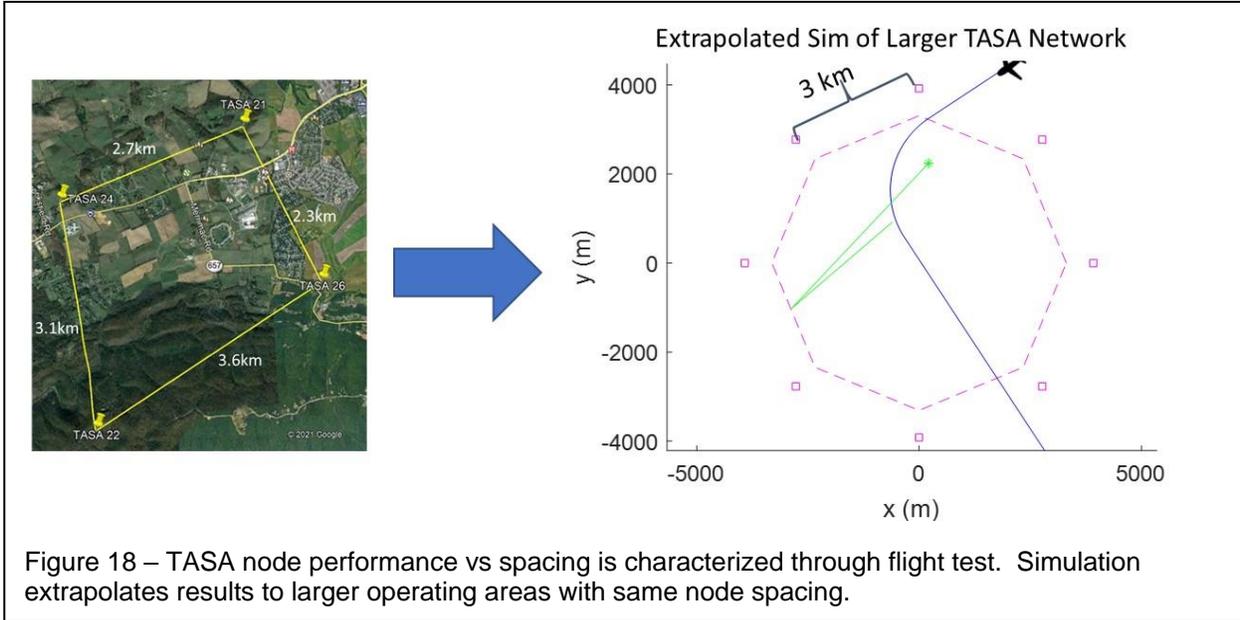

Figure 18 – TASA node performance vs spacing is characterized through flight test. Simulation extrapolates results to larger operating areas with same node spacing.

Table 4 below shows the RR and LR performance of a multi TASA node perimeter use case, enabling a UAS to fly at 400' AGL or lower in an operating area bounded by the TASA nodes. The setback between the alert boundary and the UAS operating area defined the time budget allocated to the UAS for completing an avoidance maneuver. For this simulation we selected a 609m setback.

Aircraft	RR (requirement is RR≤0.3)	LR (requirement is LR≤0.5)
Cessna 172	0.28	0.39
Robinson R44	0.22	0.30

Table 4 – Risk Ratios for Single TASA Node Use Case

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8.5   Multi Node Triangulation Use Case

The multi node triangulation approach is intriguing because it allows the TASA nodes to be placed inside or outside the UAS operating area, making installation much more flexible. This appears to also be the best use case for the Price's Fork installation positions. Figure 19 shows an example test run where the triangulation use case was able to track the position and velocity of the test aircraft as it approached, traversed and exited the ZCA. The test aircraft was a Cessna-172 carrying a GPS data logger onboard. GPS tracks are plotted as a gray line and gray circles. In this example the UAS operations boundary is drawn in green and placed directly at the TASA node locations; no setback is required. An alert boundary is drawn beyond the TASA nodes with a dotted gray line.

 Because the UAS operating area and alert boundary can be defined so flexibly with this approach, we are able to simulate many configurations. For the risk ratio evaluation, we chose a TASA layout similar to the Price's Fork site; a diamond shape with 3km spacing between TASA nodes. The UAS operating area is inset by 609m. We model the UAS as flying any altitude below 400' AGL and the automatically triggered avoidance maneuver is to descend at 4 m/s and land.   Table 5 below shows the RR and LR performance of a multi node TASA network running the triangulation use case. The simulation setup is shown in Figure 20. Evaluation of the multi node triangulation use case is ongoing. We have been able to calculate risk ratios for the Cessna 172 but have insufficient time to remaining on the contract to calculate the Robinson R44 risk ratios. We expect the two results to be similar.

Aircraft	RR (requirement is RR≤0.3)	LR (requirement is LR≤0.5)
Cessna 172	0.21	0.33

Table 5 – Risk Ratios for Single TASA Node Use Case
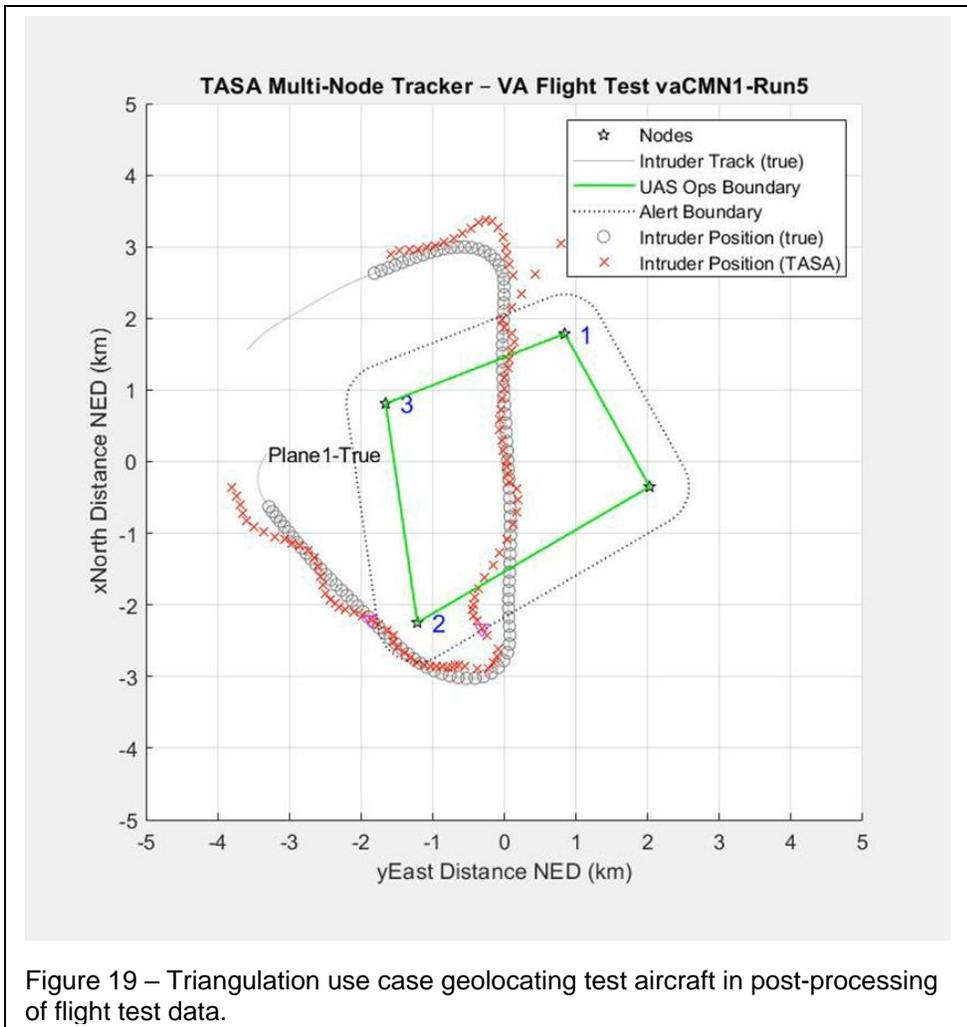
Figure 19 – Triangulation use case geolocating test aircraft in post-processing of flight test data.

Figure 20 – Risk Ratio simulation setup for triangulation use case
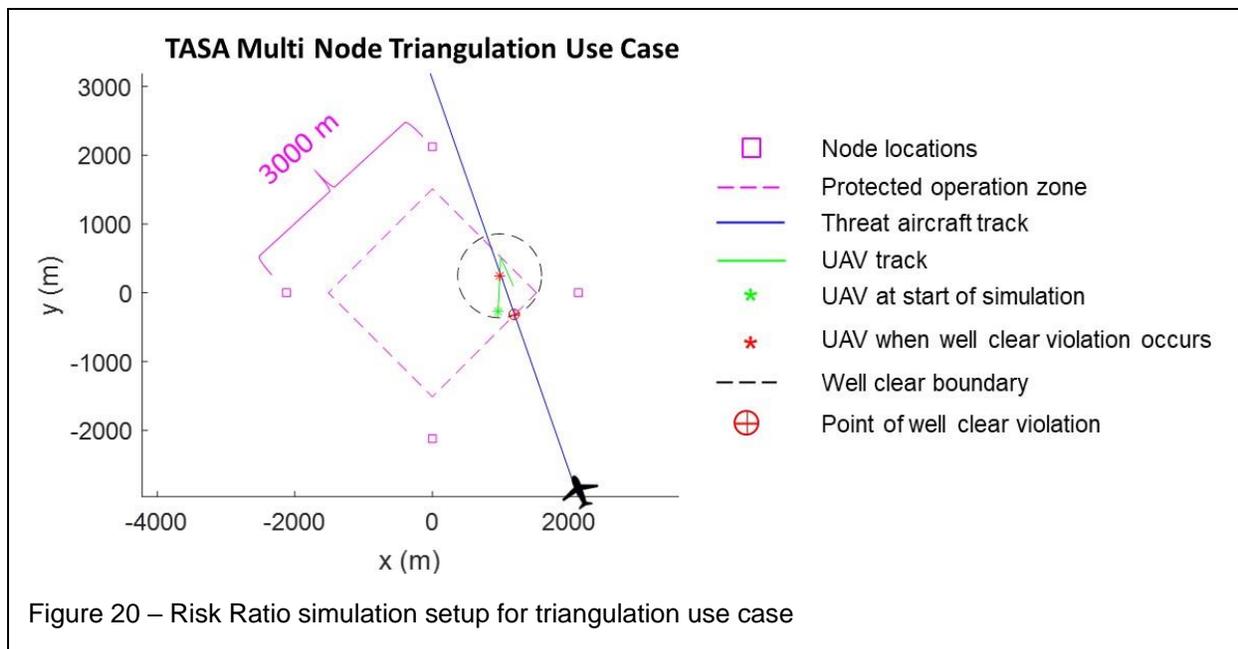
9.0   LESSONS LEARNED

This effort produced many lessons learned, from system-level findings to low-level engineering details. A TASA Operations Summary Report, delivered under the contract, provides additional details on lessons learned. The most salient lessons are summarized here:

- Using multiple TASA nodes with overlapping, or partially overlapping coverage is a powerful tool to dramatically reduce false positives.
- We observed no detection range reduction from lowering the TASA nodes from 50' to 20' AGL.
- Solar power operation is reliable for 24/7 operation and is a good approach moving forward
- Telescoping aluminum masts are a convenient and affordable mounting option for non-permanent installation

10.0   RECOMMENDATIONS

10.1   Process for Approvals at New Sites

Between the various TASA use cases characterized during this effort, SARA will be able to quickly deploy TASA networks at new customer sites. SARA would like to work with the FAA to define a process by which TASA installations may be approved by similarity. SARA has several companies wishing to fly BVLOS with a TASA network deployed at their operating sites. So far, our thinking is that SARA would perform the installation at each site to ensure the locations are appropriate. SARA would work with operators to vet the UAS avoidance maneuver and assist the operators in pursuing FAA approvals. We are unclear if flight testing must be performed at each site or if the existing test results can be applied to similar use cases.

10.2   Investigate New Avoidance Maneuvers

SARA has been considering the most conservative avoidance maneuvers, where the UAS descends and lands at the closest safe landing zone. With the multi-node TASA triangulation approach, it is likely possible that incrementally more advanced avoidance maneuvers could be proven effective. For example, if a manned aircraft enters into the zero-conflict airspace but is on a trajectory to remain well clear of the UAS, the UAS may be able to descend and loiter near a safe landing zone until the manned aircraft clears the airspace, at which point the UAS could resume its mission.

11.0   CONCLUSIONS

This contract has been a great opportunity for SARA to validate and verify the TASA DAA system with the FAA and with the Mid Atlantic Aviation Partnership. We have tested multi-node use cases that are fully ready to support safe BVLOS operations in the NAS. We have made great progress maturing the multi-node TASA triangulation use case and we believe this will be ready for operations very soon. We hope to find additional opportunities to continue working with the FAA in the future.