Design of Sense-and-Avoid Standards for RQ-7B Shadow under Loss-Link

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Abstract - Since 2008, the demand for Unmanned Aircraft Systems (UAS) within the National Airspace System (NAS) has more than doubled. The Congressional Mandate of 2012 tasked the Secretary of Transportation to develop a comprehensive plan to safely accelerate the integration of UAS into the NAS by 2014. A major concern with integration is Sense-and-Avoid (SAA) capabilities of UAS. This paper describes the design for the standard for onboard UAS sensors which meet the Target Level of Safety (TLS) of 10^{-7}, or 1 incident in 10,000,000 flight hours, set forth by the Federal Aviation Administration's (FAA) System Safety Handbook (SSH). To successfully perform SAA the RQ-7B Shadow needs a total of 5.73 seconds to detect and maneuver safely to avoid an incident with another aircraft. The hardware to satisfy these design requirements is the POP300D sensor.

I. Context

A. National Airspace System

The National Airspace System (NAS) is a collection of procedures, regulations, infrastructure, aircraft and personnel comprising the national air transportation system in the United States. It is governed by US law and Federal Aviation Regulations (FAR) set forth by the Federal Aviation Administration (FAA), which govern the design and operation of aircraft which operate within the NAS. The FAA is granted the authority to set rules and regulations which guide the NAS by Title 49 of the United States Code (49 U.S.C.) [1]. Subtitle 1 of 49 U.S.C. governs Department of Transportation, where the FAA resides and Subtitle VII governs aviation programs.

B. Expanding Roles of UAS's

The Unmanned Aircraft System (UAS) is an invention created to maintain air superiority since man first took to the skies. Major Norman E. Wells wrote: "to win, you must control the skies – particularly the skies over your own territory. Air power does not guarantee that you will win a war, as in the cases of Korea and Vietnam; but without it, modern armies are destined to lose" [2]. UAS are a mechanism utilized to achieve air superiority, making their applications primarily military; however, UAS can also serve in a variety of other capacities including remote sensing for terrain mapping, meteorology monitoring and precision agriculture, disaster response, homeland security, through surveillance of traffic along borders and the coast, search and rescue, cargo transport, and delivery of water to firefighting efforts or chemicals for crop dusting [3]. UAS are capable of performing these and many more missions without a pilot on board. This has led to a constant rise in demand for advancements in UAS technology across the globe. As the demand for UAS's increases, the number of flight hours has also increased, shown below in Fig. 1 [4]. It is projected that by 2013, the Department of Defense (DoD) will perform over one million flight hours of UAS operations.
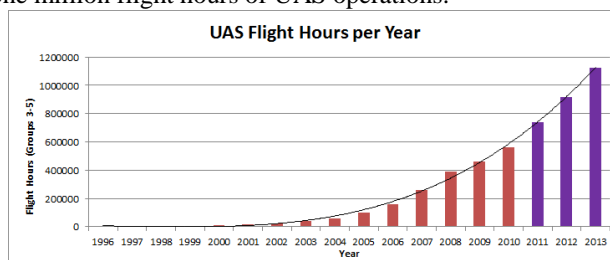

Figure 1: UAS Flight Hours

C. Key Issues

The increase in demand for UAS's and corresponding increase in flight hours within the NAS leads to a number of key issues which must be addressed. Many of these issues stem from the fact that there is no pilot onboard the UAS. A UAS places the pilot at a Ground Control Station (GCS) and controls the aircraft through a command-and-control (C2) link. Figure 2 depicts the differences between manned and unmanned systems. The biggest key issue then is that the pilot of the UAS cannot perform see-and-avoid maneuvers, the last line of defense in collision avoidance and the responsibility of the pilot, in the same manner as a manned aircraft. Because UAS lack the ability to perform see-and-avoid, the GCS pilot must rely on the onboard sensors that the UAS is equipped with to perform sense-and-avoid (SAA) maneuvers.

Another issue that arises from the need for SAA capabilities is the possibility of losing the C2 link while the UAS is in flight. To account for this possibility, UAS operators create a set of pre-programmed procedures for the UAS to execute if a loss of link occurs.

These issues complicate the next key issue: there are no set standards or regulations for the manufacturing & certification or operation of UAS in the NAS. A manned aircraft is issued an airworthiness certificate based on FAA regulations set in the FAR that allows the aircraft to fly in the NAS. However, there are no standards to determine that a UAS is airworthy. FAA Order 7610.4K: Special Military Operations gave the DoD a Certificate of Authorization (COA) which allows them to operate UAS in the NAS, but the COA does not ensure the UAS is airworthy [5]. This lack of standardization creates a gap that the FAA must address.
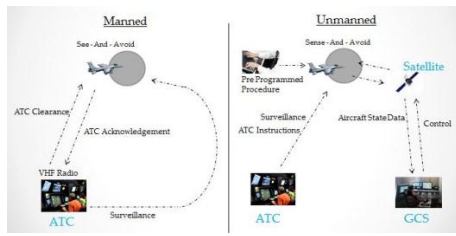
Figure 2: Manned VS Unmanned

D. Effort towards UAS Integration

The FAA Reauthorization Bill, passed in 2011, tasked the FAA to develop a comprehensive plan to safely integrate commercial UAS into the NAS [6]. This general order for the FAA was given a time schedule by Congressional Mandate in the FAA Modernization and Reform Act of 2012 to safely accelerate UAS integration into the NAS [7]. The Congressional Mandate pointed out three major areas to tackle for integration to become a reality: standards for operation, civil UAS certifications, and SAA capabilities.

E. Sense and Avoid

The FAA defined SAA in 2009 as "the capability of a UAS to remain well clear and avoid collisions with other airborne traffic" [8]. The sense half of SAA, is defined by the azimuth, elevation and detection range of onboard sensors. The avoid half of SAA, is accomplished by programming the UAS to make decisions after detecting an intruder aircraft according to 14 CFR 91.113: Right-of-Way Rules: Except Water Operations [9].

SAA capabilities will be at an acceptable level when a UAS can remain well clear and avoid not only collisions but also conflicts, when there are less than 500 feet separating the UAS from another aircraft.

F. Target Level of Safety (TLS)

To assess UAS SAA capabilities in terms of safety, or risk of collision, a clear understanding of how the FAA defines risk in the NAS is needed. The FAA Systems Safety Handbook (SSH) defines risk as "the likelihood of an accident, and the severity of the potential consequences" [10]. The likelihood of an accident is measured by the number of incidents per flight hour expressed as an order of magnitude, separated into four classifications. The likelihood of an accident ranges from a 'probably' event, or 1 accident per 1,000 flights hours, to an 'extremely improbable' event, or 1 accident per 1,000,000,000 flight hours. The FAA SSH has set a Target Level of Safety (TLS) for all operations in the NAS to keep accidents in the 'extremely remote' range. This corresponds to a 10^{-7} order of magnitude, or less than 1 accident per 10,000,000 flight hours. UAS operations must achieve this TLS before the FAA will allow full integration of manned and unmanned flights in the NAS.

II. STAKEHOLDER ANALYSIS

There is an effort from Congress and the FAA to integrate UAS into the NAS. Current demands for UAS in the NAS need accommodation from the FAA. Main agencies include the DoD, DHS, and NASA need UAS's to in fly in

NAS in order to carry out their missions (shown in Figure 4). Specifically these missions include the following:

The DoD reports the use of 146 UAS based at 63 continental United States locations. By 2015, it is estimated to have 197 units at 105 locations [4]. In order for the DoD to maintain combat readiness, military agencies need to perform specific missions that require access to the NAS. Missions for UAS's require real world conditions for crewmember, pilot, and maintainer training.

The DHS intends to use UAS in the NAS for border protection for terrorism prevention, illegal drug or contraband trafficking, or other criminal offences.

National Aeronautics and Space Administration (NASA) demand UAS operations for aeronautical and scientific research. These missions include atmospheric sampling, hurricane science, and earth surface measurements.

A. Key Issues

The FAA faces challenging safety concerns that hold back the integration for UAS's to fly in the NAS. These issues include the following:

1. Currently there is no standardization requirements for SSA procedures
2. Current SSA technology is not as good as See and Avoid procedures on a manned aircraft.
3. Economic issues that include cost in development, awareness, and education.

B. Tensions and Conflicts

As the use of UAS increases and the need to access civilian airspace is prevalent, the concern of safety is the main tension before the FAA can implement this integration. Other conflicts include the workload on the air traffic controller, and the robustness of SAA procedures. Unions such as the ACLU and AOPA oppose the widespread operations of drones and create tension (voyeurism, discriminatory targeting, and institutional abuse) with the FAA. Figure 3 below shows the conflicts and tensions among stakeholders. Other stakeholders include Air Traffic Controllers, Ground Station Pilots and Manned Aircrafts.
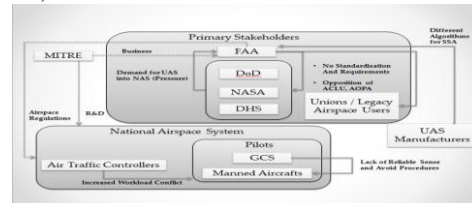

Figure 3: Stakeholder Interactions

III. PROBLEM STATEMENT

Since the task of identifying possible conflicts and avoiding them is the responsibility of the human operator, a UAS operating under a loss of link scenario must have Sense-and-Avoid capabilities which, when performed automatically, meet the 10^{-7} TLS set forth by the FAA SSH

A. Gap

SAA capabilities fail to ensure the TLS set by the FAA SSH. This creates a gap between UAS capabilities to

maintain the TLS set forth by the FAA SSH. This gap can be shown in the figure below.
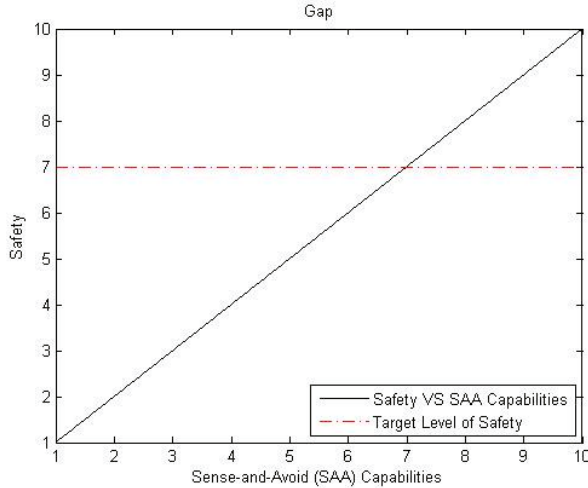

Figure 4: Gap Shown between SAA Capabilities and the TLS.

B. Need Statement

There is a need for SAA methodology that allows for UAS operating under loss-of-link to detect and avoid other aircraft allowing UAS to maintain the TLS of 10^{-7} set forth by the FAA while flying in the NAS.

IV. SCOPE AND PROJECT REQUIREMENTS

To analyze SAA capabilities with sufficient accuracy to give recommendations to improve collision risk in the NAS, a few assumptions need to be made which define the scope of the project. This design is scoped by the following three constraints.

A. Airspace Classification

For the scope of the project, all aircraft will be operating within Class E airspace [11].

B. UAS Selection

The UAS selected for the scope of the project is the RQ-7B Shadow. The RQ-7B Shadow is the primary airborne intelligence, reconnaissance and surveillance (ISR) UAS for the Army, Marine Corp and USCOMM units. The RQ-7B flies between 3,000 ft. AGL and 18,000 ft. AGL, placing it completely within Class E airspace [4]. The RQ-7B will be operating under a loss of link. In other words, the RQ-7B will have to perform SAA automatically, with no input from the GCS pilot. Other aircraft are assumed to be uncooperative and will not perform see-and-avoid maneuvers.

C. Electro-Optic / Infrared Sensors

Electro-Optic Infrared Sensors work in tandem as a complete system. The Electro Optic sensor takes pictures in the visible light spectrum with a charged coupled device (CCD) camera. The infrared sensor takes pictures within the infrared spectrum, making detections based on temperature differentiation. The largest factors in the cost of a complete E-O/IR sensor system are the weight and resolution. Since the RQ-7B can carry up to 110 lbs. E-O/IR sensor, any representative sensor must not exceed this limitation [4].

Resolution is the only factor affecting the UAS ability to detect intruder aircraft. An ideal E-O/IR sensor would have a full 360° Field of View (FOV) and infinite detection range; however, this is entirely infeasible. In actuality, resolution is set, and a tradeoff exists between the FOV and detection range. Simply put, if the E-O/IR sensor is given a large FOV versus a small FOV to passively scan, the distance at which it can detect an object will decrease.

V. DESIGN ALTERNATIVES

The RQ-7B Shadow is currently equipped with the POP 300 EO/IR sensor which has the parameters shown in Table 1. In addition, the table shows the parameters for the POP300D, a higher resolution sensor also produced by Israel Aerospace Industries Inc. (IAI). The POP300 and POP300D sensors will be used to conduct the sensitivity analysis by varying the sensors' azimuth and detection range.

Table 1: POP300 vs. POP300D Sensor Configuration Parameters [12], [13]

E-O/IR Model	POP300	POP300D
Manufacturer	IAI	IAI
IR Detector	640x480	1280x1204
E-O TV Lines	480	1204
Weight	35 lbs. (16.3 kg)	51 lbs.(20 kg)

VI. METHOD OF ANALYSIS

The Method of Analysis has three main components: Phase 1 Simulation, Gas Model of Aircraft Collisions and Phase 2 Model of detection sensor performance. Phase 1 is a Monte Carlo simulation of an airspace which generates probabilities and distributions for use in the Gas Model and Phase 2 Model. The Gas Model of Aircraft Collisions uses the distribution of relative velocities of simulated aircraft to predict the Expected Level of Safety (ELS) of the airspace. Phase 2 is a model which provides the ELS for each design alternative.

A. Phase 1 Simulation Assumptions

The model has 7 assumptions. First, all aircraft are operating in the x-y plane, meaning that they are in level flight and do not change altitude. The number of aircraft, N, in the airspace is 2 at all times. The velocity of other aircraft will have a normal distribution with a mean of 126.5 knots and a standard deviation of 22.5 knots. The horizontal dimension of other aircraft will have a normal distribution with a mean of 891.2 ft^2 and a standard deviation of 12.8 ft^2 [14]. The initial locations of aircraft entering the airspace will have a uniform distribution between 0 and 359 degrees. In addition, there will at all times be only 2 aircraft occupying the airspace. Finally, the aircraft entry headings will also be uniformly distributed between varying ranges depending on what side of the airspace they enter.

B. Phase 1

Phase 1 is a Monte Carlo Simulation with the following input parameters:
- Initial coordinates - (x,y)

- UAS and manned aircraft velocities – v
- Aircraft headings – p
- Diameters of the aircraft – g.

The UAS will always be located at the center of the airspace for the simulation with coordinates (0, 0), a constant velocity of 70 NM/h, a constant heading of 90º N, and a diameter of 14 ft.

The simulation begins by generating an aircraft with values for its velocity, v, and its area g. The simulation then randomly chooses a side of the airspace that the aircraft will enter from, and uses that value to determine its initial x and y coordinates as well as its heading p.

Using these inputs Phase 1 simulates 10,000,000 hours of flight time for the RQ-7B Shadow. Throughout the simulation all relative velocities between the RQ-7B and another aircraft were found using the following equation [15].

$$V_r = (v_i^2 + v_j^2 - 2v_iv_j \cos \beta)^{1/2} \quad (1)$$

The relative angle of the two aircrafts, β, is calculated by projecting the vector of aircraft j, onto aircraft i. The outputs from Phase 1 are shown below:

- Expected Relative Velocity – E[V_r]
- Number of Near Mid-Air Collisions (NMAC)
- Total Number of Aircraft Generated in Phase 1

Expected Relative Velocity, E[V_r], was calculated by simply averaging all of the recorded relative velocities for each generated aircraft with respect to the RQ-7B Shadow. Near midair collisions (NMAC) are defined as any incidence where a manned aircraft comes within 500 ft. of the RQ-7B Shadow. Finally, the Actual Level of Safety (ALS) for the airspace is defined as the probability of a collision, shown below in equation 2.

$$P(collision) = \frac{\# \; collisions}{\# \; total \; flight \; hours} \quad (2)$$

C. The Gas Model [15]

The Gas Model of Aircraft Collisions is a prediction of the airspace's ELS as a comparison to the ALS. The Gas Model uses the following inputs to calculate the ELS.

- E[V_r]
- E[g] - Expected area of aircrafts in airspace
- N - Number of aircraft in airspace
- A - Area of airspace

With these values the Gas Model applies the following formula to determine the ELS.

$$ELS = (N - 1) \frac{2 * g * E[V_r]}{A} \quad (3)$$

The difference between the ALS and ELS represents the gap which can be closed by improved technology and utilization of that technology. If the ELS is found to be greater than the ALS then the Phase 1 simulation data will be deemed invalid.

D. Phase 2

The goal for Phase 2 is to determine a sensor, or sensors, which allow the RQ-7B Shadow to detect intruding aircraft with enough time to make a maneuver. Phase 2 analyzes the fraction of NMACs detected by each design alternative as well as the remaining time until the detected aircraft becomes a NMAC. The fraction of NMACs detected is calculated by equation 4. If an aircraft does not enter the sensors FOV or is outside the detection range, it is not possible for the sensor to detect the aircraft.

$$Fraction \; NMACs \; Detected = \frac{\# \; NMAC \; Detected}{Total \; \# \; of \; NMAC} \quad (4)$$

Equation 5 represents the total time it takes for the RQ-7B to perform SAA, comprised of the time it takes to detect an aircraft, make a decision and execute that decision [16].

$$t_{total} = t_{detect} + t_{warn} + t_{turn} \quad (5)$$

Since E-O/IR sensors scan the FOV passively, it is assumed that t_{detect} is instantaneous. Because the RQ-7B is performing SAA automatically with no C2 link, the time required to relay information to the GCS pilot, t_{warn}, is also assumed to be instantaneous. Therefore, the total time required to perform SAA while operating under a loss of link is given by the time required to execute a turn, calculated by equation 6.

$$t_{turn} = 5.6 * \sqrt{\frac{\pi}{2} - \phi} \quad (6)$$

The banking angle of the RQ-7B, ϕ, is assumed to be 30°, which represents a load factor of 1.2, well within load factor limitations for small aircraft [17]. With this value for the banking angle, the time needed to make a turn to avoid a NMAC is 5.73 seconds, found using equation 6. Therefore, t_{total}, or the total time needed for the RQ-7B Shadow to detect and avoid an aircraft is 5.73 seconds.

E. Sensor Analysis

The POP 300 sensor has an IR detector lens that is 640 pixels x 480 TVL [12]. The POP300D sensor has an IR detector lens that is 1280 pixels x 1204 TVL [13]. The assumption that all aircraft operate only in the x-y plane implies that the z-plane will not be visible to our sensor. So the IR lens for the POP300 sensor is reduced to 1 pixel x 480 TVL and the POP300D sensor is reduced to 1 pixel x 1204 TVL. TV Lines are a bit smaller than pixels. TV Lines can be converted to pixels using:

$$1 \; TVL = 0.75 \; pixels \quad (7)$$

Equation 7 gives the number of pixels that will be used for each sensor to analyze its detection performance. Using the provided sensor parameters, manned aircraft velocities, and manned aircraft areas the maximum distance that the POP300/POP300D sensors can detect an intruding aircraft can be found. For the analysis it is assumed that the only object that will be large enough for detection is the other aircraft in the airspace with the RQ-7B Shadow.

First, the minimum detection threshold, Ω, is defined as the minimum projected angle that the manned aircraft subtends onto the pixel array grid [18]. For this simulation, the minimum detection threshold is one pixel; therefore, Ω for each design alternative is found using equation 8.

$$\Omega = \frac{1}{(\# \; sensors) * (\frac{pixels}{sensor})} \quad (8)$$

In addition to Ω, it is necessary to find the degrees per pixel for each design alternative. The FOV represents the

number of degrees which the E-O/IR sensor must passively observe. Equation 9 divides the total degrees in the FOV by the number of pixels for the design alternatives. The degrees per pixel represent the minimum angle that will be subtended onto the sensor lens which allows the RQ-7B Shadow to detect an aircraft.

$$\frac{FOV}{pixels} = \theta \left(\frac{^\circ}{pixel}\right) \quad (9)$$

Each aircraft which becomes a NMAC during the Phase 1 simulation has a particular aircraft dimension generated by the distribution of g when the aircraft was created. Equation 10 calculates the detection range as a function of θ and the horizontal dimension of the NMAC. Figure 5 depicts graphically how this equation is derived.
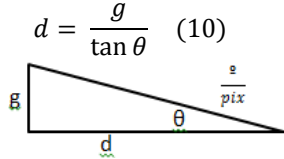
$$d = \frac{g}{\tan \theta} \quad (10)$$

Figure 5: Detection Range Derivation

VII. RESULTS

A. Phase 1 Results

The simulation of 10,000,000 flight hours led to 24,471,439 aircraft being generated, resulting in 56,887 NMACs. This corresponds to a probability of a NMAC, P(N), of 5.56E-03. In other words, approximately 5 in every 1000 aircraft will fly within 500 feet of the UAS.

3,095 of the 56,887 NMACs resulted in a collision. This corresponds to an ALS of 3.03E-04 for the simulated airspace when the RQ-7B Shadow does not perform any SAA maneuvers.

Finally, the probability of a collision given a NMAC, P(C|N) is found using Bayes' Theorem, assuming the probability of a NMAC given a collision is 1, seen in equation 11.

$$P(C|N) = \frac{P(N|C) * ALS}{P(N)} \quad (11)$$

Figure 6 is a plot of NMACs at when the manned aircraft breaches the 500ft range and becomes a conflict. The plot has X, Y ranges that are just large enough to show the 189,573 ft^2 conflict zone in the airspace surrounding the RQ-7B Shadow.
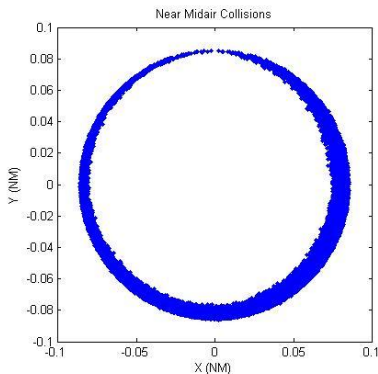
Figure 6: NMACs resulting from non-overtaking aircraft

B. Gas Model Results

The Phase 1 simulation generated an E[V_r] of 120.70 NM/hr. Using equation 3, the Gas Model predicts an ELS of 4.89E-05. Since the ELS is smaller than the ALS, our Phase 1 results can be considered valid and improvement to safety in the simulated airspace is possible through SAA.

C. Phase 2 Results

Phase 2 models the ELS for each design alternative based on their resolution and azimuth. Table 2 depicts the design alternatives analyzed. The sensor and resolution columns describe which sensor was used and how many were analyzed. The azimuth column describes the number of degrees left and right of the nose the sensor(s) passively scanned. These design alternatives resulted in the fraction of NMACs detected based on the azimuth and the time remaining before the aircraft becomes a NMAC based on detection range.

Table 2: Table of Sensor Performance

Sensor	Resolution	Azimuth	% NMACs Det.	TBN (Seconds)
POP300	640	90	0.1812	8.88
POP300	640	110	0.3150	7.19
POP300	640	130	0.4941	5.90
2x POP300	1280	130	0.4956	12.91
2x POP300	1280	150	0.7091	11.09
2x POP300	1280	170	0.9295	9.73
POP300D	1605	180	0.9999	11.92
2x POP300D	3210	180	0.9999	25.10

The results for a single POP300 sensor at 90, 110 and 130 degrees azimuth verify that as azimuth increases, the fraction of NMACs detected increases while the time before the aircraft becomes a NMAC decreases. At 130°, a single POP300 sensor detects approximately half of the NMACs and barely provides enough time to execute an avoidance maneuver.

Next, an analysis was performed with two POP300 sensors at 130, 150 and 170 degrees azimuth. The percentage of NMACs detected increases to approximately 93%; however, the average time remaining before the aircraft becomes a NMAC is only 9.73 seconds.

Finally, the POP300D sensor was analyzed with an azimuth of 180°, its design specification. A single POP300D detected nearly 100% of NMACs, and provided an average of 11.92 seconds to perform an avoidance maneuver. When two POP300D's were equipped, the time to perform an avoidance maneuver increased to 25.10 seconds. While this is certainly preferable, the cost to increase the detection range by adding a second POP300D sensor may exceed what UAS manufacturers wish to spend if a single sensor meets the TLS.

To determine which of these alternatives meet the TLS, the ELS for each design alternative were calculated using equation 12.

$$ELS = (1 - \%NMACs\ Det.) * P(C|N) * ALS \quad (12)$$

As you can see in Table 3 below, only the POP300D meets the TLS, with ELS of 2.03E-09.

Table 3: ELS for RQ-7B Shadow SAA Capabilities

Sensor	Resolution	Azimuth	% NMACs Det.	TBN (s)	ELS
POP300	640	90	0.1812	8.88	1.35E-05
POP300	640	110	0.3150	7.19	1.13E-05
POP300	640	130	0.4941	5.90	8.33E-06
2x POP300	1280	130	0.4956	12.91	8.30E-06
2x POP300	1280	150	0.7091	11.09	4.79E-06
2x POP300	1280	170	0.9295	9.73	1.16E-06
POP300D	1605	180	0.9999	11.92	2.03E-09
2x POP300D	3210	180	0.9999	25.10	2.03E-09

VIII. CONCLUSIONS AND RECOMMENDATIONS

The RQ-7B Shadow has a cruising speed much slower than other aircraft present in the airspace and most NMACs happened from aircraft approaching the UAS from behind. Because of this reality, the RQ-7B needs to be able to scan a 360° FOV to assure it meets the TLS. The POP300D was the only sensor that allowed the RQ-7B to scan a full 360° FOV with enough time remaining to avoid NMACs and consequently avoid collisions. Therefore, the POP300D is the only design alternative which assures the RQ-7B Shadow can achieve the TLS set forth by the FAA. We recommend all RQ-7B Shadows be equipped with this sensor.

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