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Detect-and-Avoid Surveillance Range Requirements for Electro-Optical/Infra-Red Sensors

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Table of Contents

List of Abbreviations

ADS-B	Automatic Dependent Surveillance - Broadcast
AGL	Above Ground Level
ATAR	Air-To-Air Radar
ATC	Air Traffic Controller
DAA	Detect and Avoid
DAIDALUS	Detect and Avoid Alerting Logic for Unmanned Systems
DR	Declaration range
DWC	DAA Well Clear
EO/IR	Electro Optical or Infra-Red
FAA	Federal Aviation Administration
FoR	Field of regard
IFR	Instrument Flight Rules
KTAS	Knots True Airspeed
LoWC	Loss of DAA Well Clear
MOPS	Minimum Operational Performance Standards
MCR	Maneuver coordination range
MSL	Mean sea level
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NM	Nautical Mile(s)
NMAC	Near Mid Air Collision
NTRS	NASA Technical Reports Server
RTCA, Inc.	Radio Technical Commission for Aeronautics
SC	Special Committee
STI	NASA Scientific and Technical Information
SWaP	Size, Weight and Power
TM	Technical Memorandum
UA	Unmanned Aircraft
UAS	Unmanned Aircraft Systems
WG	Working Group

1 INTRODUCTION

A detect-and-avoid (DAA) system provides surveillance, alerting, and maneuver guidance (referred to as guidance in this report) that are critical to an unmanned aircraft system's (UAS) ability to maintain separation from manned aircraft and other unmanned aircraft. The last decade has seen significant progress in the development of DAA requirements, spearheaded by RTCA Special Committee 228 (SC-228) and subsequently by other standards organizations such as EUROCAE and ASTM. SC-228's development of DAA requirements assumes the UAS follows instrument flight rules (IFR) and has a remote pilot or operator in the loop. As of the publication of this document, the SC-228's latest Minimum Operational Performance Standards (MOPS) for DAA, versioned as DO-365B [1], DAA systems use onboard and/or ground surveillance systems to detect traffic. The surveillance systems must detect both cooperative and non-cooperative air traffic. Cooperative traffic are vehicles that have a broadcasting transponder, while non-cooperative traffic do not, and so must be detected via radar or other sensors. A DAA system's alerting and guidance functions alert the pilot/operator in the loop of potential hazards, such as intruder aircraft, and provide maneuver solutions which help the pilot/operator avoid or mitigate observed hazards. A UAS pilot is expected to coordinate with air traffic control (ATC) before executing a conflict avoidance maneuver if the type of alert is not urgent enough to require an immediate maneuver.

Electro-Optical/Infra-Red sensors (EO/IR) are candidate low size, weight, and power (SWaP) airborne sensors for DAA surveillance. EO/IR sensors operate in both visible and infrared wavelengths and provide situation awareness in both day and night conditions. Under favorable atmospheric conditions and suitable operational assumptions, EO/IR sensors can potentially fulfill the performance requirements of a sensor that detects non-cooperative traffic. In an effort to document the requirements for such a sensor to do so, RTCA SC-228 started working on an EO/IR MOPS for DAA systems in 2017.

This report documents the analysis and simulation that directly supports the development of the declaration range (DR) requirements for EO/IR sensors for DAA systems under the operational environment assumed by DO-365B. The resulting EO/IR MOPS will be published as DO-387 by RTCA. While both safety and operational suitability metrics are considered for the surveillance volume requirements of EO/IR sensors, operational suitability metrics, in particular those related to alerting time, turned out to be the primary drivers of the declaration range requirements. These considerations will be further discussed in subsequent sections.

This report is organized as follows: Section 2 describes general considerations about the surveillance volume of an onboard DAA sensor. Section 3 describes the approach to determining the DR requirements. Sections 4 and 5 describe results of Part 1 and Part 2 analyses, respectively. Section 6 concludes this report.

2 SURVEILANCE VOLUME CONSIDERATION

The required surveillance volume for a DAA sensor builds on a few key operational assumptions made by SC-228 for the DAA systems:

1. The UAS operates under IFR.
2. UAS pilots or operators are "in the loop" and actively controlling the vehicle.
3. The UAS follows a set of right-of-way rules called the Quantified Right of Way by SC-228. For example, the UAS does not need to maneuver if it is overtaken by an intruder aircraft.
4. The UAS flies like fixed-wing aircraft.

DO-365B requires the UAS to have an on-board Automatic Dependent Surveillance-Broadcast (ADS-B) receiver (ADS-B in) and active surveillance for detecting cooperative intruders. Cooperative intruders are those equipped with a Mode S transponder, a Mode C transponder, or an ADS-B transmitter. Non-Cooperative intruders, i.e., those that do not have a Mode S transponder, a Mode C transponder nor an ADS-B Out capability, are detected via additional onboard sensors or ground-based surveillance systems. The onboard sensors for detecting non-cooperative intruders are referred to as non-cooperative sensors by SC-228. Note that non-cooperative sensors actually detect both cooperative and non-cooperative intruders.

ADS-B In and active surveillance technologies generally provide for a sufficient surveillance volume for DAA systems under the operational assumptions made by SC-228. ADS-B In can be implemented in a small payload that can be carried by small drones or Part 105-compliant UAS. An active surveillance system's payload can be easily accommodated by large UAS such as NASA's Ikhana aircraft, but its sizable antenna can be a challenge for mid-sized UAS such as the NASC TigerShark. The surveillance volume for onboard non-cooperative sensors, on the other hand, poses a sizeable trade space for performance and SWaP considerations. For example, a large onboard air-to-air radar (ATAR) may meet the DR requirements of DAA, but is an infeasible option for many UAS missions due to the radar's large SWaP. Besides, such radar may be too costly for many UAS missions.

The surveillance volume of an onboard non-cooperative sensor is usually referred to as the field of regard (FoR). FoR is commonly expressed in terms of DR, bearing (or azimuth), and elevation of an intruder aircraft with respect to the UAS's airframe-centric coordinate systems. The requirements for bearing and elevation ranges in the EO/IR MOPS are inherited from those in the ATAR MOPS for DAA systems, defined in DO-366A [2]. The required range of bearing for ATAR (and hence EO/IR as well) is between -110° (negative is to the left of the UAS) and +110°. Intruders approaching from outside this bearing range are expected to be responsible for avoiding the UAS because the UAS has the right of way. The required range of elevation for the ATAR (and EO/IR) is between -15° (below the flight path angle) and +15°. Because the UAS flies like a fixed-wing aircraft, it has considerable horizontal speed (assumed to be ≥ 40 kts). Therefore, the probability of a non-cooperative intruder aircraft approaching from outside the elevation range of (-15°, +15°) is regarded as too low to impact safety. This leaves only the declaration range to be determined for EO/IR sensors.

The DR requirements for onboard non-cooperative sensors consider primarily the following two categories of metrics:

1. Safety: the DR should support the UAS pilot's ability to ensure safe separation from other traffic by following DAA alerts and guidance computed from surveillance data.
2. Operational suitability: the DR should support DAA alerts with a look-ahead time sufficient for the pilot/operator to coordinate conflict-avoidance maneuvers with ATC for encounters in which the intruder enters the sensor's FoR via the front side of DR.

The intention of DAA alerting and guidance is to help the UAS pilot maintain separation defined by the DAA Well Clear (DWC). For non-cooperative intruders, the DWC is a cylinder centered around the UAS defined by a horizontal radius of 2200 ft and vertical boundaries -450 and +450 ft below and above the UAS. For non-cooperative intruders, the DAA MOPS defines two levels of alert:[1] 1) corrective alerts provide sufficient time for the UAS pilot to coordinate with ATC for a conflict avoidance maneuver, 2) warning alerts increase the urgency of the conflict and ask the UAS pilots to maneuver immediately and notify ATC afterwards. Prior human-in-the-loop (HITL) simulations and flight tests showed that a UAS pilot needs 10 to 15 seconds to coordinate and initiate a maneuver with ATC in response to a corrective alert [2]. If responding to a warning alert, a UAS pilot needs 8 to 10 seconds to evaluate and initiate a

[1] The descriptions here applies to Classes 1 and 2 of the DAA equipment in DO-365B and omits the preventive alert. Class 3 DAA equipment has slightly different alerting nomenclature.

maneuver [2]. The initiation of a maneuver should take place while the UAS still has enough distance from the intruder in order to maintain DWC. For any specific encounter and UAS maneuverability parameters, there is a minimum horizontal distance, called minimum initiation range (MIR), below which the UAS will be unable to maintain DWC with any maneuver. Therefore, the warning alert should be raised at least 8 to 10 seconds before the MIR is reached. The duration of a corrective alert must be at least 15 seconds to be useful to a UAS pilot, and so a corrective alert should be raised at least 25 seconds before the MIR is reached.

Fast-time simulations [3], HITL [4] simulations, and flight test results [5] indicate that a UAS pilot is able to maintain separation given enough warning alert time before MIR. In these studies, alerting timelines were truncated by the simulated limited surveillance range. Despite short or no corrective alerts in these studies, the UAS pilot (or modeled pilot behavior in [3]) was able to maintain separation effectively. Short duration or lack of corrective alerts as a result of limited surveillance volume, however, is inconsistent with the IFR assumption which expects a UAS pilot to coordinate with ATC for conflict avoidance guidance in most situations, including encounters with non-cooperative intruders. A surveillance range that ensures safety but does not support ATC coordination time is deemed unacceptable by the FAA. As a result, the required DR is driven by operational suitability metrics, in particular, corrective alert timing.

An EO/IR sensor's track accuracy requirements are also important to the performance of the DAA system. Closed-loop simulations have been conducted to investigate these requirements. Results are published in a separate report [7].

3 APPROACH

The approach to determining the DR requirement for an EO/IR sensor consists of two parts:

1. Part 1 performs a baseline DR analysis assuming a 25 second window before MIR in which DAA issues alerts to a UAS pilot. The alert can be either Corrective or Warning. These results are directly applicable to the requirements for the low SWaP ATAR class.

2. Part 2 modifies the resulting DRs from Part 1 by considering what is achievable by current EO/IR technologies. The impact of this modification was evaluated using additional simulations that examined corrective alert time distributions resulting from the modified DRs. The modification was shown to result in minimum impact on the alerting performance and deemed acceptable by SC-228.

The following sections document Part 1 and Part 2 separately. Several assumptions are made for both parts of the analysis:

- Ownship (UAS):
  - Speed is assumed to be between 40 kts and 110 kts.
  - Turn rate is assumed to be 7 deg/sec.
  - Climb/descent rates are assumed to be 500 ft/sec.
- Non-cooperative intruder categories
  - Small: representative aircraft is a glider.
  - Medium: representative aircraft is a Cessna 172.
  - Large: representative aircraft is a Beechcraft B200 kts

Distinct DR requirements are derived for each intruder category. The reason of categorizing intruders by size is because an EO/IR sensor's detection range is strongly correlated with the aircraft's physical size.

An ATAR's detection range is also strongly correlated with an aircraft's physical size, although in a somewhat indirect way (it is the radar cross section that affects an ATAR's detection range). To be able to model intruder categories in encounters, DO-366A assumes larger aircraft fly faster. The following size-speed correlations are adopted by DO-366A and also assumed for this work:

- Small: intruders with speed at or below 100 kts
- Medium: intruders with speed at or below 130 kts
- Large: intruders with speed at or below 170 kts

Note that non-cooperative intruders rarely fly faster than 170 kts [6].

4 BASELINE DECLARATION RANGE ANALYSIS

This section describes the computation of the baseline EO/IR DRs as a function of intruder category and bearing ranges. Using fast-time simulations, the MIR between two aircraft required for the UA to start maneuvering to remain DWC is identified. For the non-cooperative DWC and UAS maneuverability considered for DAA, horizontal maneuvers are generally more robust and effective than vertical maneuvers in maintaining separation, in that MIRs resulting from a vertical maneuver are larger than MIRs resulting from horizontal maneuvers. Therefore, only horizontal maneuvers are considered in this work. Starting with the aircraft's positions at the MIR, linear extrapolation is then used to step the Unmanned Aircraft (UA) and intruder aircraft back by 25 seconds worth of distance. The resulting horizontal distance, called Maneuver Coordination Range (MCR), provides the remote pilot enough time to respond to alerts and potentially coordinate with ATC. MCR is a function of the ownship speed, intruder speed, intruder bearing, and intruder relative heading. MCRs will eventully flow up to DRs.

The encounter geometry is set up in such a way that a non-accelerating intruder aircraft is flying a course that will intercept the trajectory of the UA, resulting in a direct collision if no maneuver is performed. The intruder approaches from bearings of $\varphi = 0°, \pm30°, \pm60°$, and $\pm90°$ at airspeeds of 100, 130, and 170 kts corresponding to the maximum airspeed (and therefore most stressing case) of the non-cooperative intruder categories Small, Medium, and Large.

The UA performs a constant-rate turn towards the positive relative heading for all maneuvers in this analysis. A roll rate of 5 degrees/s is assumed for the transient period of the turn maneuver. Therefore, for all relative bearings less than zero the mitigation maneuver was performed away from the intruder, and for all relative bearings greater than zero the UA turned toward the intruder aircraft (Figure 1). The assumption of a positive heading for the UA's maneuver is taken with no loss of generality, since the same analysis results can be derived from mirror images of these encounters.

Figure 1 shows a graphical depiction of the encounter geometry. The figure shows an intruder with a positive bearing and an intruder with a negative bearing. To determine if a range is sufficient for the UA to remain DWC with the intruder, predicted constant-velocity trajectories were examined while the UA performed the level turn at every second until there was no projected loss of DWC. The variation in the resulting turn magnitude does not impact the derived DR values, but does have an impact on the minimum separation and flight path deviation.

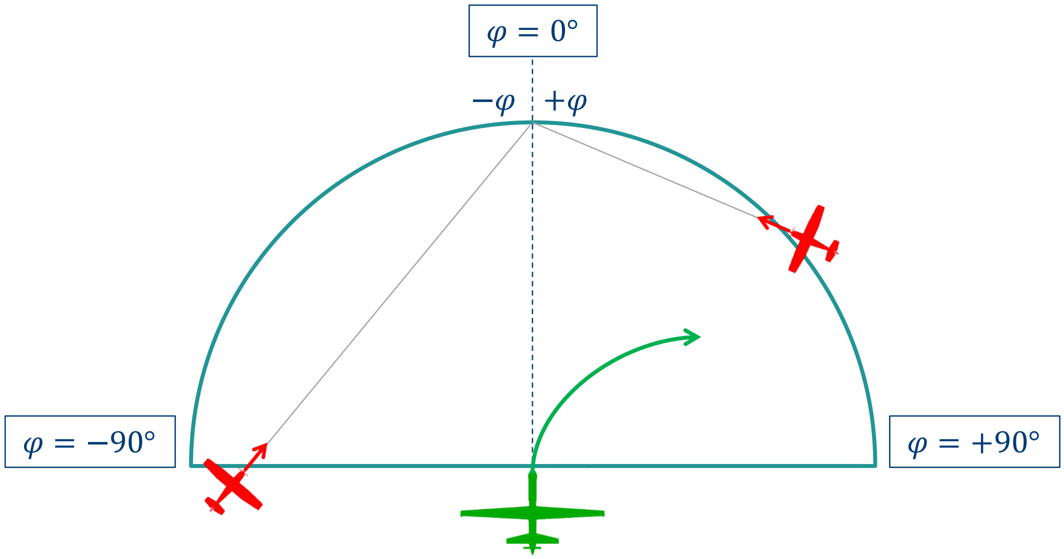

Figure 1: Encounter Geometry

The DRs are based on worst case scenarios that ensure that, for any ownship speed beween 40 and 110 kts, there is at least 25 seconds in which the DAA system can alert before the ownship reaches the MIR. As long as the ownship has not reached the MIR there is at least one turn maneuver (left or right) that can avoid the loss of DWC. The DRs are binned by bearing ranges and derived from MCRs as follows:

1. For a specific ownship speed and a specific intruder category (which maps to the upper bound of this category's intruder speed), compute the MCRs for the following 7 encounter geometries from a to d.

    a. Pick the MCR for the $\varphi=0°$ as the candidate DR for $|\varphi| < 30°$.

    b. Pick the smaller of the two MCR from the $\varphi=\pm30°$ results as the candidate DR for $30° \leq |\varphi| < 60°$.

    c. Pick the smaller of the two MCRs from the $\varphi=\pm60°$ results as the candidate DR for $60° \leq |\varphi| < 90°$.

    d. Pick the smaller of the two MCRs from the $\varphi=\pm90°$ results as the candidate DR for $90° \leq |\varphi| < 110°$.

2. Repeat the steps above (from a to d) for all ownship speeds in increments of 1 kts between 40 and 110 kts.

3. For each bearing range, pick the largest candidate DR from the candidates (computing with various ownship speeds) as the final DR for this bearing range.

4. Repeat the step for another intruder category.

Detailed results of this process are documented elsewhere [8]. For $|\varphi| < 60°$, the DRs are driven by values for the 110 kts ownship speed. For $60° \leq |\varphi| \leq 110°$, the DRs are driven by values for the 40 kts ownship speed. The DR values are expressed as the DR value for $|\varphi| < 30°$ and correction factors that represent ratios of these reduced DR values for larger $|\varphi|$ and the DR for $|\varphi| < 30°$. The results are shown in Table 1. A visual representation of the DRs is presented in Figure 2.

Table 1 Baseline DRs

Intruder Airspeed (kts)	DR (NM)	Correction Factor			
		|φ| < 30°	30° ≤ |φ| < 60°	60° ≤ |φ| < 90°	90° ≤ |φ| ≤ 110°
100	2.57	1.00	0.85	0.67	0.54
130	2.93	1.00	0.92	0.77	0.63
170	3.42	1.00	0.93	0.83	0.72

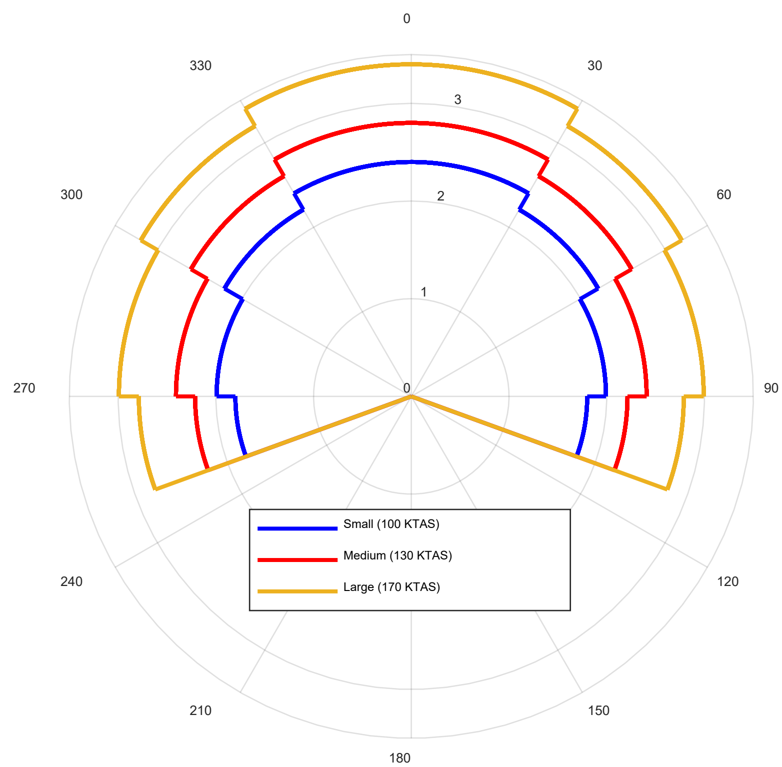

Figure 2 Notional Polar Plot of DRs. Numbers outside the circles and inside the circles represent bearings (degrees) and range (NM), respectively.

5 MODIFIED DECLARATION RANGES AND VALIDATION

The baseline DRs for the head-on intruders in Table 1 pose a challenge to current EO/IR technologies, particularly in the Small intruder category. Minor modifications to the DRs were proposed by a team of EO/IR subject matter experts as an attempt to better align the DR requirements with technical feasibility without degradation of DAA alerting performance. The modification reduces DRs for the |φ| < 30° range and compensates for this reduction by slightly increasing DRs for larger values of |φ|. The proposed modified DRs are given in Table 2. Figure 3 compares the modified DRs to the basline DRs.

Table 2 Modified DRs

Intruder Airspeed (kts)	Modified DR (NM)	Correction Factor			
		|φ| < 30°	30° ≤ |φ| < 60°	60° ≤ |φ| < 90°	90° ≤ |φ| ≤ 110°
100	2.4	1.00	0.92	0.83	0.75
130	2.8	1.00	0.93	0.86	0.79
170	3.4	1.00	0.94	0.88	0.82

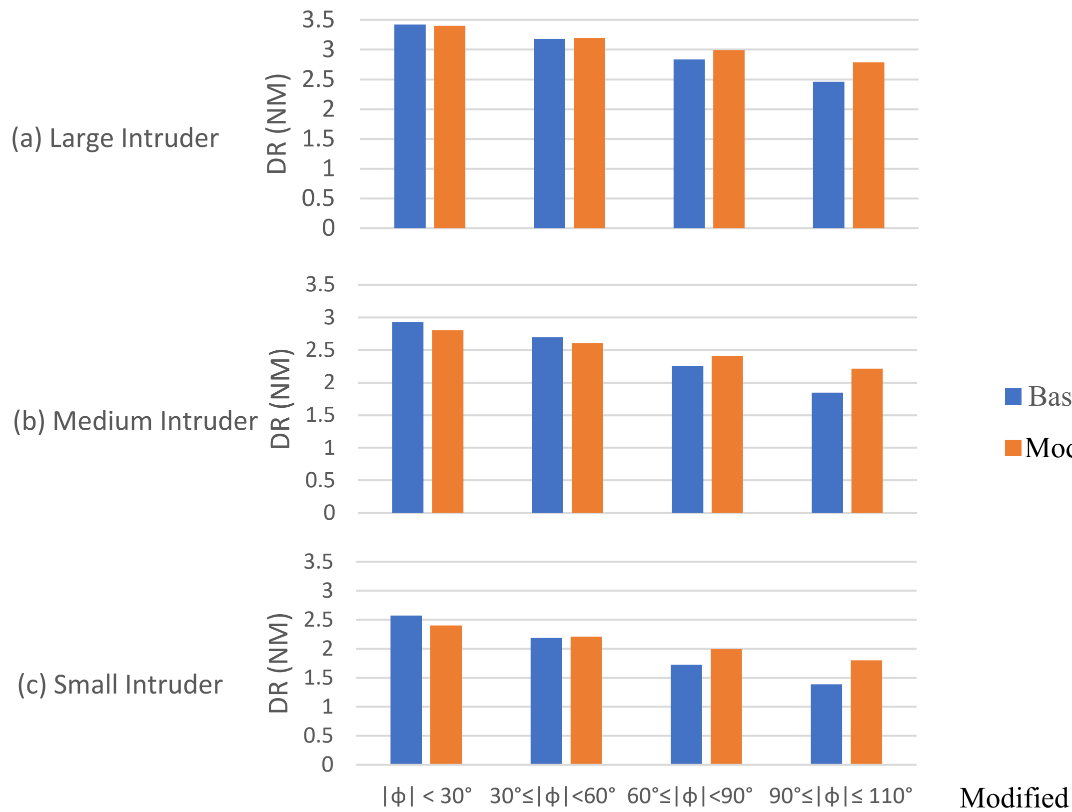

Figure 3: Comparison of modified DRs to baseline DRs

To evaluate the impact of this modification on alerting performance, fast-time simulations of a large number of representative encounters were conducted. The alerting metric used for evaluating the modified DRs is the following:

C20+C21 : the percentage of alerted encounters that have a corrective alert less than or equal to 14 seconds, including those with no corrective alert.

C20 and C21 were two metrics among many for informing the Federal Aviation Administration's (FAA's) safety risk management document. C20 represents the percentage of alerted encounters that have 1- to 14-second corrective alerts, and C21 represents the percentage of alerted encounters that have no corrective alerts. The lower C20+C21 is, the better. Simulations using larger DRs show this metric decreases with larger DRs but will not reach zero due to the existence of scenarios involving maneuvering aircraft. A non-accelerating encounter that has an intruder entering the EO/IR's FOR at full DR is less likely to contribute to C20+C21 because, if the DR is large enough, the intruder would trigger a corrective alert (>14 seconds) before the alert transitions to a warning alert. On the other hand, a worst-case intruder in the vicinity of the UAS may suddenly turn towards the UAS, leaving insufficient time for the pilot to maneuver away, let alone coordinate with ATC. The intruder may be well within the surveillance volume before it turns towards the UAS but won't trigger an alert until it turns.

The pairwise encounter set for the simulations was created by overlaying projected UAS mission trajectories with radar-recorded Visual Flight Rules (VFR) traffic across the entire continental US. Details of this encounter set are described elsewhere [7]. Figure 4 shows the altitude and speed distributions of the UAS and VFR traffic at their closest point of approach. Altitude and speed filters were applied to focus on non-cooperative intruders similar to the categories described above. Only encounters between 500 ft AGL and 10,000 ft MSL were analyzed. Only encounters in which the ownship flies at or below 110 kts and the intruder flies at or below 170 kts (a 95th-percentile speed for non-cooperative intruders) were analyzed. A total of approximately 80,000 encounters were analyzed. About 20,000 encounters triggered DAA alerts. Each encounter's intruder is categorized by its top speed. The percentages of encounters with Large, Medium, and Small intruders are 26%, 35% and 39%, respectively.

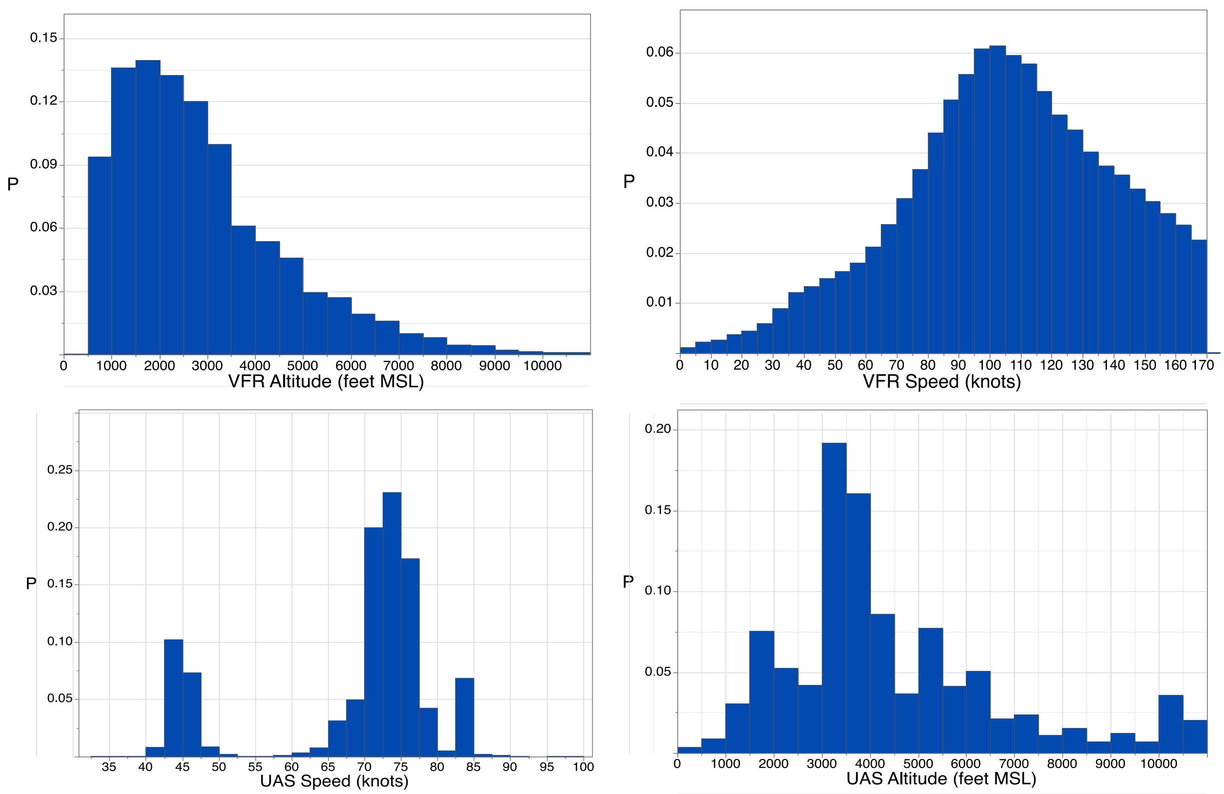

Figure 4 UAS and VFR Traffic Speed and Altitude distribution

Detect and Avoid Alerting Logic for Unmanned Systems (DAIDALUS) [8] Version 2.e, the reference DAA algorithm for RTCA DO-365B, was used for the simulations. All intruders were treated as non-cooperative aircraft, under the assumption that cooperative and non-cooperative aircraft have similar turn rates and frequencies [9]. The alerting volume is based on the non-cooperative DWC (DWC) definition. The DWC radius was increased by a factor of roughly 1.5 to guard against maneuvering intruders. Warning and corrective alerts were issued 30 and 60 seconds before the predicted time the UAS would penetrate the buffered DWC, assuming constant velocities for both aircraft. For non-accelerating encounters that lead to a direct collision and have the intruder entering the EO/IR's FoR at a full DR, the sequence of alerting events usually follow this order: first corrective alert, first warning alert, reaching the MIR, and a loss of DWC. For such encounters, the total time of alert before reaching MIR is expected to be at least 25 seconds according to the baseline DRs.

Table 3 and Table 4 show the results of C20+C21 computed using the modified DRs and the baseline DRs, respectively. The metric is further broken down by the bearing range in which the first alert is issued. The number of alerted encounters is also shown on the right. Figure 5 compares the metric in bar charts. For large intruders, C20+C21 is similar between the baseline DR and the modified one. For medium and small intruders, C20+C21 is degraded by ~30% for $|\varphi| < 30°$ range but improved by 10%-20% for $|\varphi| \geq 60°$. Aggregating over bearing ranges, C20+C21 for large intruders is almost identical between the two sets of DRs but slightly degraded for medium and small intruders. The overall aggregated result shows that the modified DR yields somewhat comparable although slightly degraded performance (32% vs. 30%) to the baseline DRs. The overall difference of 2% in C20+C21 is regarded acceptable by SC-228, and hence the modified DRs were accepted as the requirement for EO/IR.

Table 3 C20+C21 for the modified DRs

Intruder Type	C20+C21					Number of Alerted Encounters			
	All	**0-30°**	**30-60°**	**60-90°**	**90-110°**	**0-30°**	**30-60°**	**60-90°**	**90-110°**
Large	0.297	0.260	0.263	0.235	0.540	1869	1416	985	734
Medium	0.319	0.332	0.277	0.253	0.520	2717	1947	1197	627
Small	0.328	0.339	0.302	0.296	0.460	3712	2225	967	361
Overall	**0.317**								

Table 4 C20+C21 for the baseline DRs

Intruder Type	C20+C21					Number of Alerted Encounters			
	All	**0-30°**	**30-60°**	**60-90°**	**90-110°**	**0-30°**	**30-60°**	**60-90°**	**90-110°**
Large	0.302	0.253	0.273	0.249	0.552	1876	1407	977	732
Medium	0.290	0.244	0.276	0.287	0.554	2809	1941	1167	616
Small	0.295	0.242	0.313	0.382	0.561	3852	2213	903	326
Overall	**0.295**								

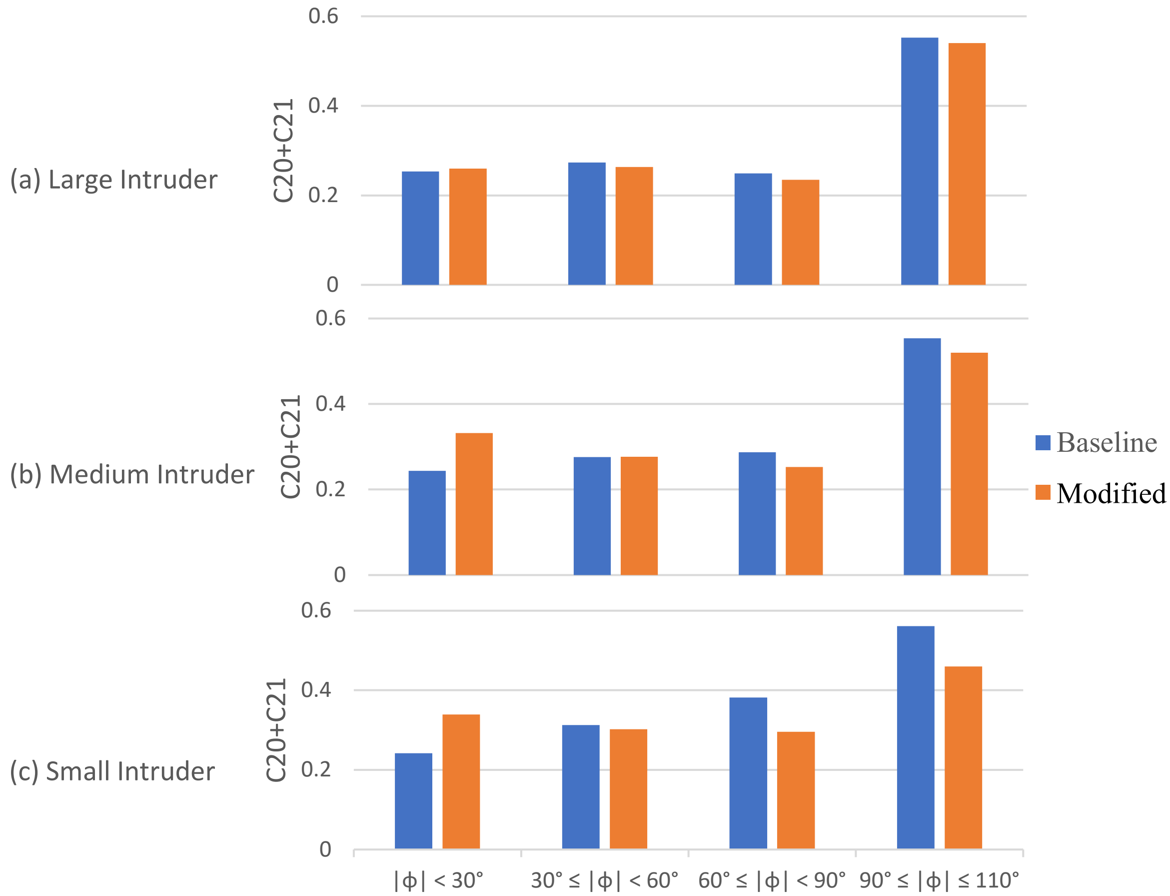

Figure 5: C20+C21 across the bearing range

The acceptance of the basline DRs as well as modified DRs by SC-228 indicates the FAA is willing to accept that about one third of the encounters between a UAS and a non-cooperative intruder may not leave enough time for pilots to coordinate a maneuver with ATC. The DRs, nonetheless, provide enough surveillance volume to not degrade safety. Further increase of the DRs can reduce the percentage of C20+C21. Simulations using the methodologies described in this report by increasing DRs to be based on 50 seconds beyond the MIR showed a reduction of C20+C21 metrics to 20%-25%. This slight improvement of C20+C21, however, will come at a cost of putting the required DRs out of reach from many low SWaP sensor technologies and is regarded by SC-228 as unnecessary operational suitability metric gain.

6 CONCLUSION

EO/IR sensors show promising performance as low SWaP non-cooperative sensors for a DAA system and are especially attractive for small and medium UAS that are subject to payload constraints. Nonetheless, the surveillance volume of EO/IR sensors must be able to support the performance requirements of DAA systems in terms of safety and operational suitability. Following operational assumptions for DAA systems established by RTCA's DAA MOPS, DO-365B and DO-366A, this report documents the derivation of declaration range (DR) requirements for EO/IR sensors for DAA systems. The baseline DRs are derived based on alerting time requirements and vehicle performance assumptions. These baseline DRs are then modified to better align with current state-of-the-art EO/IR sensor capability, and evaluated using the FAA's alerting time metrics. Results show the modified DRs impact the alerting time metrics only marginally and are deemed acceptable by SC-228. The DR requirements recommended by this work are written into RTCA's DO-387, the EO/IR MOPS for DAA systems.

The need to coordinate with ATC before executing a DAA maneuver is being reviewed by SC-228 in the Phase 3 work. The UAS community has expressed strong desire to fly UAS in a way similar to flying by visual flight rules that involves less ATC intervention. This extension of the DAA operational environment could potentially reduce the required alerting timeline and in turn lower the DR requirements for non-cooperative sensors.

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