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Characteristics of a Well Clear Definition and Alerting Criteria for Encounters between UAS and Manned Aircraft in Class E Airspace

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Abstract— **Unmanned aircraft systems will be required to equip with a detect-and-avoid (DAA) system in order to satisfy the federal aviation regulations to remain well clear of other aircraft. For a DAA system to satisfy the requirement to stay well clear of other airborne traffic, a quantitative definition of well clear needs to be defined and evaluated. This study investigates the implications of UAS using proposed well clear definitions as a separation standard for conducting operations in the national airspace system. The first analysis considers three well clear definitions and presents the relative state conditions of intruder aircraft as they encroach upon the well clear boundary. The second analysis focuses on the definition of the alerting criteria needed to inform the UAS operator of a potential loss of well clear. All analyses are conducted in a NAS-wide fast-time simulation environment using UAS aircraft models, proposed UAS missions, and historical air defense radar data to populate the background traffic operating under visual flight rules. The results presented in this study inform the safety case, requirements development, and the operational environment for DAA minimum operational performance standards.**

Keywords- unmanned system; airspace integration; detect and avoid; separation standard

I. Introduction

Regulations that establish operational and performance requirements for unmanned aircraft systems (UAS) are being developed by a consortium of government, industry and academic institutions. Those requirements will apply to detect-and-avoid (DAA) systems and other equipment necessary to integrate UAS with the National Airspace System (NAS) and are determined according to their contribution to the overall level of safety required to operate in the airspace. Several key gaps must be addressed in order to link equipment requirements to an airspace level of safety. Foremost among these is the calculation of the relative effectiveness of a particular system to mitigate violations of a separation standard with other aircraft, which is known as the system's "risk ratio [1]." The risk ratio is calculated as the probability of mid-air collision with a DAA system divided by the probability of mid-air collision without a DAA system. The risk ratio of a DAA system, in combination with risk ratios of other collision avoidance mitigations, will determine the overall safety of the airspace measured in terms of the number of mid-air collisions per flight hour. The second gap is the lack of a quantitative definition of a separation standard that the DAA system is intended to maintain [2], without which a risk ratio cannot be calculated. A third gap is the alerting criteria needed for a UAS operator to gain situation awareness and remain well clear of other aircraft. Defining and evaluating the risk ratios as a function of the DAA system parameters, the UAS separation standard, and the alerting criteria requires a simulation capability that incorporates UAS aerodynamic performance and mission characteristics of future UAS operations that will be conducted in areas that interact with current operations. Together, the UAS characteristics and DAA separation standard will allow determination of the frequency and types of encounters expected between UAS and manned aircraft that are necessary to calculate the risk ratio, develop the safety case, and develop performance requirements of the DAA system.

Previous research investigated the rate and characteristics of aircraft encountering each other [3]. In these studies the safety of new collision avoidance methods has largely been focused on existing airspace and aircraft using the existing separation standards. This research established the risk ratio metric as a valid method of demonstrating that a safety standard had been met. Standards for collision avoidance systems and air traffic control (ATC)-provided separation were based on the performance of existing transponder and radar systems, respectively, along with human performance. Separation standards for DAA systems cannot be determined in the same manner since there are no current operational or performance requirements for such systems. Recent approaches have focused on an acceptable risk of collision without a DAA system [4],[5]. A distance-based separation minima has been proposed by EUROCONTROL for military UAS operating in non-segregated airspace [6]. Recently, the UAS Executive Committee Science and Research Panel (SaRP) evaluated three candidate separation standards which incorporate time and distance criteria, however risk ratios have not been evaluated using these definitions [2]. Aircraft mission and aerodynamic performance parameters that are central to calculating risk ratios have also been based on existing airspace operations [1]; they do not incorporate a wide range of new UAS aircraft performance and mission characteristics [7]. These characteristics are necessary because most manned aircraft in en-route and transition airspace fly from origin to

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destination along fixed airways, while many unmanned aircraft need to perform "mission-oriented" operations (e.g. flying a loitering pattern, grid pattern, or non-predetermined missions with frequently changing flight plans). This difference in mission profiles may create different conflict situations between unmanned and manned aircraft. Several studies have investigated the airspace impact of a single UAS mission in northern California, but these analyses have not been extended to other geographic areas or included other UAS aircraft types or missions [8]. The key to demonstrating the requirements for safely integrating UAS with the NAS will be to extend such analyses to a representative set of UAS types and missions over a broad geographic area using candidate separation standards so that a collision mitigation risk ratio for DAA systems may be calculated. Complementary to the research presented in this paper, human-in-the-loop experiments simulating UAS operations using a DAA system and Monte Carlo simulations with DAA models are currently being examined to investigate the numerator of the risk ratio for a DAA system.

The original contribution of the research reported in this paper is the denominator of the risk ratio for a DAA system: the rate at which the DAA separation standard is violated given no separation mitigation methods are employed. The simulations used to collect these statistics considered thousands of UAS flight plans and tens of thousands of UAS flight hours in a range of geographic areas so that the results would be more broadly representative of potential domestic operations in the continental United States. A second contribution of the analysis is the representation of the relative states between aircraft when the separation standard is violated. This information may be used to determine DAA surveillance system requirements, establish initial conditions in Monte Carlo aircraft interaction simulations, provide guidelines for the design of DAA traffic displays for UAS pilots, and indicate the interoperability between the DAA separation standard and existing separation standards. A third contribution of this work is to inform the influence of the alerting logic on the UAS operator's ability to maintain well clear of other aircraft. In particular, the timeliness, frequency, and reliability of the alerts presented to the UAS operator are evaluated. This information can be used to inform the DAA sensor requirements and the design of DAA traffic displays. The results presented in this paper represent an essential contribution to a safety case for a DAA system and therefore an important step in the design of systems and procedures that will support safe integration of UAS with the NAS.

The rest of the paper is organized as follows: Section II introduces the well clear definitions and alerting logic used in subsequent analyses; Section III outlines the two analyses. The first analysis instantiates three well clear definitions and evaluates the relative state information when there is a loss of well clear. The second analysis focuses on the alerting criteria and the characteristics at the instance of first alert. Section IV details the simulation methodology including the simulation platform, traffic scenarios, UAS missions and models; Section V presents the results of the two analyses; and Section VI provides the concluding remarks.

II. Definitions for Well Clear Analysis

The FAA-sponsored Sense-and-Avoid (SAA) Workshop [1] defines SAA as "the capability of a UAS to remain well clear from, and avoid collisions with, other airborne traffic. SAA provides the intended functions of self separation and collision avoidance compatible with expected behavior of aircraft operating in the NAS." The self-separation (SS) function of an SAA system is intended as a means of compliance with the regulatory requirements (14CFR Part 91, §91.111 and §91.113) to "see and avoid" and to remain "well clear" of other aircraft. Since the publication of that workshop report, the UAS community has shifted to using the term "detect and avoid" rather than "sense and avoid," a distinction without a difference. This paper will use DAA for consistency.

The concept of well clear has been proposed as an airborne separation standard to which a DAA system must adhere, and performing SS correctly means remaining well clear of other aircraft. The well clear definition is a separation standard used by the SS function to determine what action is necessary to remain an appropriate distance from other aircraft. The standard will require a UAS be able to detect and avoid other aircraft in sufficient time as to avoid creating a collision hazard. The time or distance thresholds defining a loss of well clear could be unique for each intruder based on closure rate, performance characteristics, encounter geometry, and other variables. Therefore, it is necessary to define an explicit and quantitative definition of well clear so that the contribution of the SS function to the overall safety for a given airspace can be unambiguously determined.

The second SAA workshop [1] defines "well clear" as the state of maintaining a safe distance from other aircraft that would not normally cause the initiation of a collision avoidance (CA) maneuver by either aircraft. The following DAA interoperability implementation principles could also be utilized to define the well clear standard: (1) Separation should be large enough to avoid corrective maneuvers from intruders (e.g., resolution advisories for TCAS-equipped intruders), to minimize traffic alert issuances by controllers, and to avoid excessive concern for proximate see-and-avoid pilots; (2) Deviations should be small enough to avoid disruptions to traffic flow and vary appropriately with encounter geometry and operational areas (e.g. terminal, transition, enroute).

Ongoing research efforts are evaluating DAA interoperability criteria; however assessing the overall impact to operations in the NAS is still an open research area. This paper aims to investigate the impact on operations in the NAS due to new separation standards and UAS conflict alerting criteria. This study will determine how frequently aircraft operating in class E airspace and transiting to class A airspace encounter UAS as a function of the well clear boundary definition and the characteristics of the UAS mission profiles. The proposed definitions are taken from a recent FAA report [1], a dedicated US Government workshop on well clear [2], and variations on methods used by TCAS II [4],[9].

A metric originally used in the Traffic Alert and Collision Avoidance System (TCAS) collision detection logic to estimate the time to closest point of approach (CPA) between two aircraft is based on the concept of "tau," which is calculated as the ratio of slant range between aircraft to their range rate and measured in seconds. The TCAS detection logic also includes a vertical metric that approximates the time until both aircraft will be at co-altitude. This metric is referred to as vertical tau and is calculated as the ratio of the difference in altitude to the vertical range rate and measured in seconds:

$$\tau_{vert} = -\Delta h / \Delta \dot{h}. \tag{1}$$

One issue with the tau metric occurs for encounters where the rate of closure is very low, as described in the TCAS II Manual [4]. The calculated tau may be large for these encounters while the physical separation may be quite small. In such a situation, the calculated tau value no longer assures adequate separation because a sudden acceleration that increases the closure rate (e.g., a turn) would not give sufficient alerting time to avoid a loss of well clear. To provide protection in these types of encounters, a modified alerting threshold, often referred to as "modified tau," is used by TCAS II. This metric uses a new parameter, "distance modification" (DMOD), to provide a minimum range at which to alert regardless of the calculated value of tau. Modified tau is computed as

$$\tau_{\mathrm{mod}} = \begin{cases} -\frac{(\mathrm{r}^2\text{-}\mathrm{DMOD}^2)}{\mathrm{r}\dot{\mathrm{r}}} & \text{for } \mathrm{r} \geq \mathrm{DMOD} \\ 0 & \text{for } \mathrm{r} < \mathrm{DMOD} \end{cases}, \tag{2}$$

where the distance modification represents a threat boundary encircling the ownship aircraft that triggers an alert when the boundary is violated. The modified tau metric was introduced to address the slow closure rate scenarios that caused a collision hazard not identified by the tau metric, however modified tau also has limitations. For situations in which aircraft are on converging paths with a high rate of closure and a large miss distance, the modified tau metric will indicate an alert is required. TCAS II addresses this limitation in the tau and modified tau measures by applying a horizontal miss distance (HMD) filter at CPA. This filter removes alerts for encounters in which separation at CPA is greater than the HMD parameter.

The modified tau and vertical tau metrics will form the basis for the two definitions used in this study. The first definition presented in this study considers three proposed configurations that quantify a loss of well clear, while the second definition considers the alerting criteria used to alert the UAS operator of a potential collision with another aircraft.

A. Definition 1: Loss of Well Clear

The following definitions are considered qualitative definitions of well clear. These definitions are the criteria to determine if the separation standard has been violated with another aircraft. Definition 1 is similar to the detection logic in TCAS II and consists of a set of criteria based on the time to co-altitude and modified tau definitions. This definition consists of temporal and distance-based criteria in the horizontal dimension as

$$C1\colon\ 0 \leq \tau_{mod} \leq \tau^*_{mod} \quad AND \quad r_{xy}(t_{CPA}) \leq HMD^*, \tag{3}$$

and criteria in the vertical dimension as

$$C\,2\colon\ 0 \leq \tau_{vert} \leq \tau^*_{vert} \quad OR \quad |\Delta h| \leq ZTHR, \tag{4}$$

where HMD^* is the horizontal miss distance threshold, $ZTHR$ is the altitude separation threshold, Δh is the current altitude separation, $r_{xy}(t_{CPA})$ is the predicted horizontal miss distance at CPA, $\tau^*_{mod}, \tau^*_{vert}$ denote constant values that are thresholds for the time to co-altitude and modified tau calculations, and τ_{mod}, τ_{vert} denote the time to co-altitude calculations and modified tau given by (1) and (2), respectively. From (3) and (4), a loss of well clear (LOWC) is defined as

$$LOWC\colon\ C1\ is\ true\ \ AND\ C2\ is\ true. \tag{5}$$

This study considers three definition configurations, which are based on the well clear definitions proposed by the SaRP and the Radio Technical Commission for Aeronautics (RTCA) Special Committee 228 DAA Working group. The RTCA SC-228 is an organization developing minimum operational performance standards (MOPS) for DAA systems. For two definitions (D1.1, D1.2), the SaRP tuned parameter values to meet a common threshold of 1.5% for unmitigated near mid-air collision (NMAC) risk using an Uncorrelated Encounter Model [10]. The third definition that is considered in this study (D1.3) has the same parameters as D1.2, except that the altitude separation threshold, denoted as ZTHR, is less than the distance that air traffic controllers would consider as operationally acceptable separation between aircraft operating under visual flight rules and instrument flight rules (500 ft according to FAAO JO 7110.65, Para. 7-7-3). The threat boundary defined by DMOD and HMD for the third definition is comparable to the distance-based separation minima proposed by EUROCONTROL [6] (0.5 nmi horizontal separation and 500 ft vertical separation). Three well clear definition parameter configurations are detailed in Table 1.

Table 1: Well Clear Boundary Configuration Parameters.

Configurations	τ^*_{mod} [s]	τ^*_{vert} [s]	DMOD [ft]	ZTHR [ft]	HMD [ft]
D1.1	30	20	6000	475	6000
D1.2	35	0	4000	700	4000
D1.3	35	0	4000	450	4000

B. Definition 2: Alerting Criteria

Another important factor in safe operations is the UAS operator's ability to gain situation awareness of a conflict and have sufficient time to avoid a LOWC with an intruding aircraft. Definition 2 considers the temporal threshold, referred to as the self-separation threshold (SST), at which the DAA system should alert the pilot of an imminent threat. The definition is the same as the definition given by Criteria 1 and 2 in (3) and (4), respectively. The parameters for the modified tau-alerting criteria are detailed in Table 2.

Table 2: Alerting Criteria Configuration Parameters.

Configurations	SST: τ^*_{mod} [s]	τ^*_{vert} [s]	DMOD [ft]	ZTHR [ft]	HMD [ft]
D2.1	90	0	4000	450	4000
D2.2	90	0	4000	700	4000
D2.3	110	0	4000	700	4000
D2.4	70	0	4000	700	4000
D2.5	90	0	6000	700	6000
D2.6	90	0	6000	900	6000

III. Analyses of Well Clear Definitions

This study focuses on encounters between UAS and aircraft operating under visual flight rules (VFR) carrying a transponder squawking transponder code Mode A 1200 (referred to as cooperative VFR aircraft). Two analyses of well clear definitions and alerting criteria are considered in this study.

Analysis 1: Characterizing encounters at the well clear boundaries.

This analysis focuses on the characteristics of UAS encounters with manned cooperative VFR aircraft, including range rates, relative heading and range. The objective of this analysis is to study the relative time and distance separations between aircraft at the boundary of a well clear definition.

Analysis 2: Evaluating the alerting criteria.

This analysis considers criteria for alerting the UAS operator that action is necessary to avoid a loss of well clear. The parameters of each definition are varied and the analysis focuses on the relative state information at the first alert. In particular the range rates, relative heading and range are of interest, as well as the percentage of alerts that do not result in a LOWC. This analysis informs the minimum sensor range required based on the alerting criteria, as well as the rate of nuisance alerts due to buffers added to the alerting parameters.

IV. Methodology

A. Simulation Platform

The Airspace Concept Evaluation System (ACES) is a National Airspace System (NAS)-wide fast-time simulation tool [11]. The ACES platform models and simulates the NAS using interacting agents representing center control, terminal flow management, airports, individual flights, and other NAS elements. These agents exchange messages between one another to model real-world information flows. This distributed agent-based system is designed to emulate the highly interconnected nature of the NAS, making it a suitable tool to evaluate current and envisioned airspace concepts. The approach of this study is to use ACES to investigate the effects of well clear definitions for UAS DAA systems in enroute and transition airspace. The ACES platform provides a large set of four-degree-of-freedom aircraft models, including many models that mimic the flight characteristics of UAS aircraft (such as Global Hawk, Reaper, Shadow, etc.).

One of the inputs to ACES is the flight demand set, which consists of all of the flights to be simulated with their aircraft type, their origin and destination airports, their departure times and their flight plans. In this study, UAS mission flight demand sets are used as inputs to the ACES platform, as well as VFR aircraft. The VFR aircraft flight data sets are synthesized from air defense radar data.

B. Traffic Scenarios

For this study, manned VFR traffic and unmanned aircraft performing a variety of representative missions at different altitudes were simulated in ACES. The 84th Radar Evaluation Squadron (RADES) at Hill Air Force Base, Utah, collected radar surveillance of VFR traffic. The RADES collects data through the Eastern and Western Defense sectors and provides the data to a variety of government entities, including the FAA and Department of Defense. The RADES provides track updates on both cooperative and non-cooperative aircraft, however this study focuses on encounters between UAS and cooperative VFR aircraft. The raw radar-return data includes: time, the four-digit Mode A identifying code squawked by the aircraft, quantized pressure altitude measurements reported by the target, and range and azimuth measurements. To build tracks for use in the ACES simulation, the raw radar measurements were fused together into a single track for each target using a minimum-spanning tree clustering algorithm [12]. A Kalman filter was then used to smooth the tracks, and flight plan waypoints were extracted from the smoothed trajectory. The ACES platform requires each aircraft to have a origin and destination airport, thus airports are added to the beginning and end of each VFR smoothed track to run in the simulation.

Twenty-four days were chosen across the four months (January, April, July, and October) of 2012 on days in which no adverse meteorological conditions were impacting the VFR traffic densities. Different days of the week and different weeks in each of the months were selected to account for variability in weekday and seasonal traffic densities. The total number of flights per day ranges from 20,000 to 28,000 and on averages is approximately 23,000.

C. UAS Missions and Aircraft Models

The FAA's UAS Integration Concept of Operations requires that UAS operate under instrument flight rules (IFR) and conduct operations in airspace not segregated from manned air traffic. One key challenge for UAS integration into the NAS is that the operations and flight characteristics typical of UAS differ from those of most manned IFR aircraft. While manned IFR aircraft usually fly from origin to destination along fixed airways and jet routes at a single cruise altitude, UAS are expected to fly "mission oriented" flight plans that can include many turns and altitude changes within a limited geographic area. The differences in flight plans between UAS and manned IFR aircraft will create different encounter rates and characteristics. Modeling expected UAS operations is necessary in order to accurately predict the safety of DAA systems while operating in the NAS. The mission characteristics used in this study are consistent with the missions outlined in the FAA CONOPS [14], RTCA DO-320 [15], and a recent Volpe Report [16]. Intelligent Automation Inc. developed the mission sets, in collaboration with and under the supervision of NASA [17],[18].

The proposed UAS missions were identified by the stakeholder community and literature reviews, constructed by talking to subject matter experts, socio-economic analysis, and stakeholder input, and verified through simulation. This study used the following nine missions to be representative of potential future operations in the NAS: cargo transport, autonomous and remotely piloted on demand air taxi, strategic and tactical fire monitoring, atmospheric sampling, air quality monitoring flood inundation mapping and stream flow monitoring. Each mission consists of a set of flights that have altitude, speed, aircraft performance, takeoff times, duration, and geographic constraints that are dictated by that mission's requirements and objectives. The UAS flight data set consists of approximately 18,000 flights and 26,000 flight hours over a 24-hour period. This study does not include a mitigation to separate aircraft; therefore the UAS missions will come within close proximity to VFR traffic and other UAS. For this study, interactions between UAS are not analyzed and do not affect the encounter statistics. Each UAS flight is independent of the others in analysis and simulation; therefore all UAS missions were combined in a single flight data set, which was run in simulation against different days of VFR traffic.

The UAS aircraft models used in this study are derived using performance data and follow the Base of Aircraft Data (BADA) model formats. The BADA-formatted models were generated from industry data [19] and validated by Intelligent Automation Inc. (IAI) [20]. The performance specifications required to operate given UAS missions are conducted with representative aircraft types whose performance would at least meet that which is required for the particular mission.

V. Simulation Results

A. Analysis 1

Analysis 1 introduces a well clear definition as a separation standard and investigates the rate of losses of well clear and relative state characteristics at the instance of violation of that separation standard. This analysis will consider three definitions of well clear as outlined in Section II.A. All three definitions are based on the modified tau calculation with a horizontal miss distance at the predicted CPA as detailed in (3)-(4).

The aggregate statistics are outlined in Table 3, where it is clear that the well clear definition D1.3 yields the fewest losses of well clear. Additionally the simulation produced 270 NMAC over the 24 simulation days and yielded a probability of NMAC given a LOWC of approximately 1.5% and 1.6% for the D1.1 and D1.2 well clear definitions, respectively. The SaRP tuned the D1.1 and D1.2 definitions to a 1.5% unmitigated risk of NMAC given a LOWC using the MIT Lincoln Lab's Uncorrelated Encounter Model, and the results from the ACES simulation are consistent with the tuned unmitigated risk from the encounter model. D1.3 is based on the parameters of D1.2 but decreases the ZTHR value to 450 ft, and this yields an unmitigated risk of NMAC given a loss of well clear of 2.2%.

Table 3: Aggregate statistics for well clear definitions over 24 simulated days

Statistics	D1.1	D1.2	D1.3
UAS Flight Hours	25,734	25,734	25,734
Losses of Well Clear	18,139	16,867	11,938
NMAC	270	270	270
$P(NMAC\|LOWC)$	1.5%	1.6%	2.2%
Probability of TCAS II resolution advisories (RA) prior to LOWC	4.8%	0.9%	8.6%

One interoperability consideration for a well clear definition is how often an intruder's TCAS II would alert prior to a loss of well clear. The premise is that if TCAS II is alerting either the UAS operator or the intruder aircraft, then there has been a LOWC between the aircraft. The TCAS II alert in Table 3 is the combination of the preventative alerts and corrective alerts. From the statistics it is clear that D1.2 produces the lowest probability of a TCAS II alert, whereas D1.3 produces the highest. In today's operations, IFR and VFR aircraft are legally separated by a 500 ft altitude difference. According to the proposed well clear definitions, D1.1 and D1.3 would not register a LOWC if aircraft were at this 500-ft altitude separation, however D1.2 would register a LOWC. Table 3 demonstrates the trade-off between the operational acceptability of having a definition that is less than 500-ft in the altitude separation, denoted by ZTHR, and the interoperability and unmitigated risk of an NMAC given a loss of well clear.

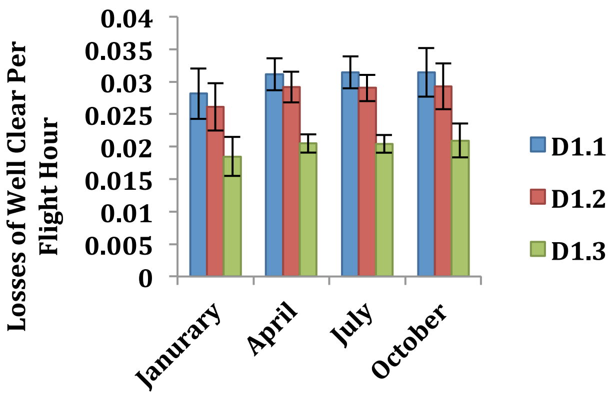

Figure 1: LOWC per flight hour for the well clear definitions (D1.1-D1.3).

Figure 1 depicts the rate of losses of well clear per flight hour grouped by the season for each of the three well clear definitions. It is clear from this bar chart that definition D1.1, which includes the time-to-co-altitude and the largest horizontal miss distance of the three definitions, has a much larger rate of losses of well clear, which is due to the larger airspace volume that is being protected by this definition. Since D1.1 and D1.2 were tuned to the same conditional probability of NMAC, it is expected that their rate of losses of well clear would be similar. When comparing D1.3 and D1.2 it is clear that the decrease in ZTHR to 450 ft in D1.3 has a large impact on the rate of losses of well clear (1 LOWC per 50 hours for D1.3 as compared to 1 LOWC per 40 hours for D1.2). It is also interesting to note that the seasonal effects have minimal impact on the rate of losses of well clear.

The three well clear definitions used in Analysis 1 have similarities to the alerting logic in TCAS II. The TCAS alerting logic established sensitivity levels, which vary the parameters of the definition based on altitude. These sensitivity levels were included to manage the tradeoff between necessary airspace protection and unnecessary advisories. Higher sensitivity levels, which produce larger protected airspace around each TCAS-equipped aircraft, are selected at higher altitudes to account for higher closure rates between aircraft. The well clear definitions (D1.1-D1.3) use a constant set of parameters for all altitudes. Figure 2 depicts the well clear violation rates as a function of altitude layer and demonstrates diminishing returns for protecting more airspace at higher altitudes, as the rates of losses of well clear violations are negligible. This result is largely due to the majority of VFR traffic operating below 10,000 ft.

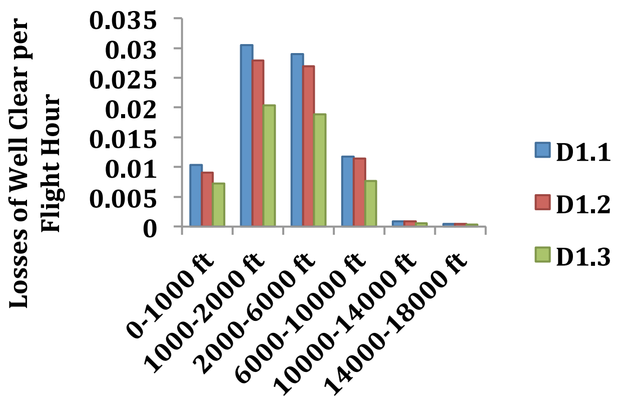

Figure 2: LOWC per flight hour for the well clear definitions (D1.1-2.3) per altitude (MSL) layer

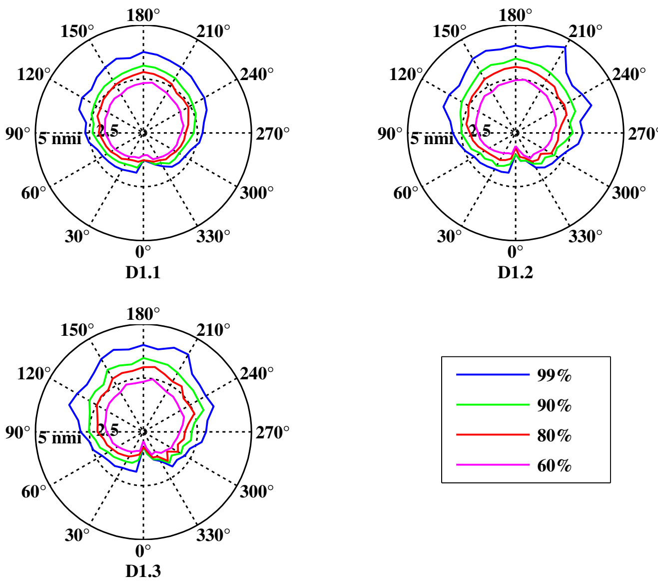

Figure 3: Relative heading for definitions D1.1-D1.3 where contours for the boundaries are shown for the 99%, 90%, 80%, and 60% of the LOWC.

The relative heading between an intruder aircraft and the UAS ownship aircraft is shown for the three well clear definitions D1.1-D1.3 in Figure 3. The orientation of the plot is such that the ownship is at the origin and a head on encounter is represented by the 180 degree tick mark, whereas an overtaking encounter is represented at the 0 degree tick mark. The figure depicts 99%, 90%, 80%, and 60% contours for each of the well clear definitions. These contours represent the percentage of data contained within the contour. For instance, in the D1.1 relative heading plot, the blue line indicates that 99% of the losses of well clear are within 4 nmi of the ownship. The three well clear definitions yield similar results, as all contours are less than 4 nmi. It can be concluded that in order to avoid a loss of well clear a DAA system would require a sensor that could see no less than 4-5 nmi in front of the aircraft. The shape of the contours implies that an intruder overtaking a UAS would yield a LOWC at a much closer range than an intruder and UAS in a head-on conflict. It can be concluded that the DAA system should be equipped with a sensor that can detect intruders behind the UAS at no less than 3 nmi in order to account for losses of well clear due to overtaking encounters. Additional surveillance range is needed beyond these minimums to account for aircraft maneuvering, coordination with ATC, and conflict alerting.

The subsequent figures will depict relationships between other parameters that define an encounter, however for brevity the plots will be shown only for definition D1.3, which is the well clear definition that has been proposed by the RTCA Special Committee 228 on Detect and Avoid Standards.

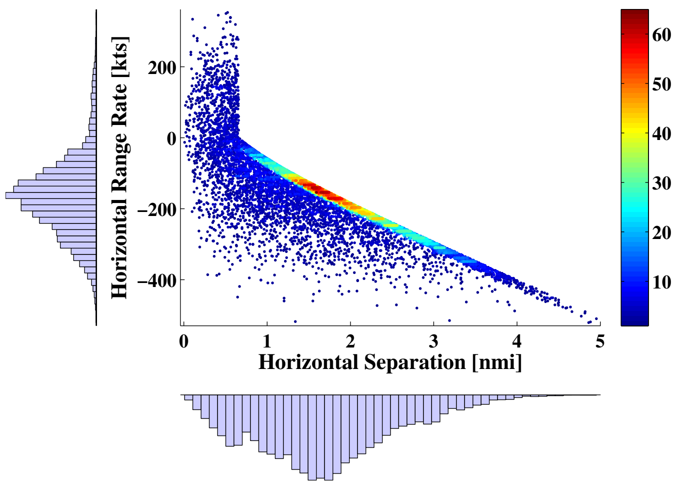

Figure 4: Scatter plot of horizontal separation and horizontal range rate for definition D1.3 at the first loss of well clear.

Figure 4 depicts the relationship between the horizontal range rate and the horizontal separation at LOWC for the D1.3 well clear definition. In this plot, horizontal range rate represents how timely aircraft are approaching each other, where the more negative the range rate the faster the aircraft are coming together, and a positive range rate implies the aircraft are on diverging paths. The histograms are provided on each of the axes and the color of the scatter plot corresponds to the density of aircraft pairs that had a LOWC. The scatter plot has roughly a linear relationship between 0.658 nmi and 5 nmi that represents the modified tau time threshold of 35 seconds. Encounters occurring between 0.658 nmi and 5 nmi separation and under the 35-second modified tau line represent violations that occured at a modified tau less than 35 seconds. The higher the range rate implies the lower the modified tau value at the LOWC. Points on the scatter plot that occurred closer than 0.658 nmi separation violated the threat boundary defined by a cylindrical volume with the radial as DMOD (0.658 nmi) and vertical distance as ZTHR (450 ft). Specifically, a subset of the losses of well clear at the threat boundary had a positive range rate. These cases represent aircraft that were climbing or descending behind the UAS within the threat boundary. Even though the aircraft have already passed each other and are on diverging paths, these cases would register to the DAA system as a LOWC and may prompt the UAS operator to initiate a collision avoidance maneuver.

A scatter plot of the altitude separation and vertical range rate for the D1.3 well clear definition is depicted in Figure 5, along with the histograms along each of the axes. In this plot, the losses of well clear occur along the vertical dimension of the threat boundary volume, denoted by ZTHR, and at a vertical range rate of zero feet per minute. This implies that a large portion of the losses of well clear occur while aircraft pairs are level with each other and vertically offset. The scatter plot also denotes a high-density area where the aircraft pairs are vertically converging at a rate of 1000 feet per minute and incurring a LOWC at the 450 ft altitude separation limit defined by ZTHR. These vertical closures are a relative measure and therefore could be caused from the intruder climb/descending on the ownship, the ownship climbing/descending on the intruder, or both the ownship and intruder climbing/descending into each other.

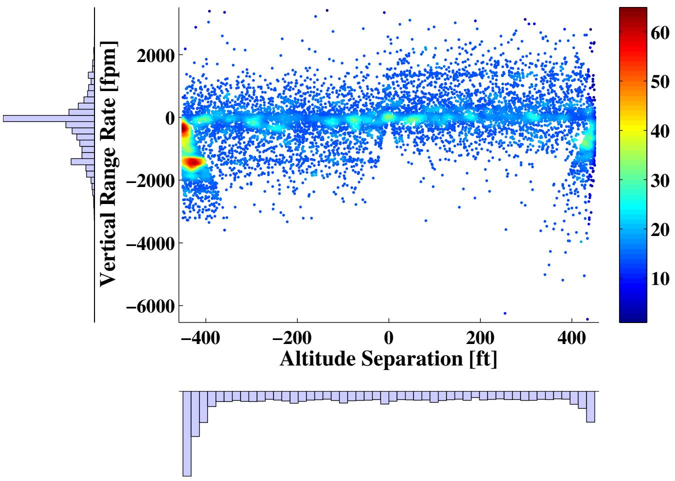

Figure 5: Scatter plot of altitude separation and vertical range rate for definition D1.3 at first loss of well clear.

In summary, Analysis 1 investigated the characteristics of encounters at the LOWC. This included the rate at which aircraft had a LOWC, the relative separation, heading, and range rates between a UAS and intruder aircraft. These results have implications to the safety of the well clear definition as they expose areas where the well clear boundary will be exercised based on current VFR traffic in the airspace. For comparison, the encounter rates for three well clear definitions were presented, however for brevity, the relative statistics were only presented for the D1.3 definition. It was observed that seasonal variation had limited influence on the rate of encounters, sensor ranges need to be chosen at a sufficient minimum distance as to capture most losses of well clear (3-5 nmi), and the DAA system may need logic to protect against alerting the pilot to losses of well clear that occur while the aircraft are on diverging paths. These results expose the need for effective alerting and vigilance by the UAS operator to maintain safety for UAS operations in the NAS.

B. *Analysis 2*

Analysis 2 investigates defining criteria to alert the UAS operator that action is necessary to avoid a potential LOWC. This analysis considers adding buffers to the well clear definition parameters for alerting, and parameters of the alerting definition will be varied. The analysis will focus on the relative state between the aircraft pairs in conflict at the first alert. In particular the range rates, relative heading and separation are of interest, as well as the percentage of alerts that did not result in a loss of well clear. While Analysis 1 assessed the safety implications of aircraft that had a LOWC, Analysis 2 will assess the impact to the UAS operator based on the frequency of alerts, their timeliness, and the relative state between the aircraft at the first alert. The relative state between a UAS and an intruder at an alert also has implications on DAA sensor requirements.

The definitions used in Analysis 2 are based on the well clear definition given by definition D1.3 and detailed in Table 2. The parameters that are varied in this analysis are: the self-separation threshold for modified tau, denoted as τ^*_{mod}, the altitude separation threshold, denoted by ZTHR, and the minimum miss distance modification variables DMOD and HMD. Definition D2.1 uses the definition for well clear in D1.3 and extends the self-separation threshold (SST) to 90 seconds. This in effect is adding a buffer on the temporal dimension. Definition D2.2 adds a buffer to D1.3 in both the time threshold of 90 seconds and the altitude threshold of 700 ft. The temporal aspect of the alerting criteria is anticipated to be the most impact, therefore D2.3 and D2.4 use the definition of D2.2 and extend the SST to 110 seconds and decrease the SST to 70 seconds, respectively. Definition D2.5 uses the definition D2.2 and extends the minimum separation thresholds to 6000 ft HMD and 0.987 nmi DMOD. The altitude separation threshold and minimum horizontal separation threshold are increased with respect to D2.2 in the D2.6 definition. The selection of the self-separation threshold will largely be driven by the minimum sufficient time required for the UAS operator to receive an alert, gain situation awareness, determine the threat and a possible resolution, if time permits contact air traffic control and request an amended clearance, command the UAS to perform a self-separation maneuver, and for the aircraft to execute the maneuver. An excessively large SST would produce frequent alerts to the pilot and a SST that is too small may give the pilot an insufficient amount of time to avoid a loss of well clear. The buffers added to the minimum horizontal and vertical separation thresholds are to account for sensor, navigation, and maneuver uncertainty.

Table 4: Aggregate statistics for alerting criteria over 24 simulated days

Statistics	D2.1	D2.2	D2.3	D2.4	D2.5	D2.6
SST Alert	21,319	29,230	35,754	23,712	37,182	44,116
LOWC	11,938	11,938	11,938	11,938	11,938	11,938
NMAC	270	270	270	270	270	270
$P(LOWC\|SST)$	55.9%	40.8%	33.3%	50.3%	32.1%	27.0%
$P(NMAC\|SST)$	1.26%	0.92%	0.75%	1.13%	0.72%	0.61%

The aggregated statistics for the number of alerts over the 24 simulated days are presented in Table 4. As expected, the number of alerts scale with the size of the airspace volume defined by the alerting criteria. The results show the smaller the buffered volume the larger the conditional probability of NMAC and larger the conditional probability of a LOWC. The unmitigated probability of LOWC given an alert due to an intruder crossing the SST and the probability of a NMAC given an SST alert are two metrics that are useful in the derivation of two risk ratios needed for the DAA safety cases. The subsequent figures will explore the characteristics of the encounters at the moment of first alert.

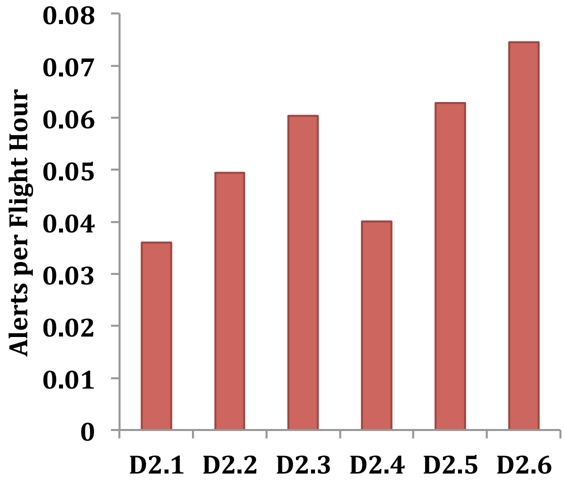

Figure 6: Rate of alerts issued per UAS flight hour

Figure 6 depicts a bar chart of the rate of alerts that were issued per UAS flight hour for each of the alerting definitions. It is interesting to note that the well clear definition D1.3 produced an unmitigated LOWC once every 50 hours, whereas extending the SST for alerting produced an alert rate at once every 28 hours, as shown by D2.1. By increasing the ZTHR in D2.2, an alert was issued once every 20 hours, as shown in D2.2. Comparing D2.2 alerting rate to D2.6, it can be observed that the threat boundary defined by DMOD, ZTHR and HMD have a large effect and produces an alert once every 13 hours when all parameters were increased as given by D2.6. Alerts can be distracting to a UAS operator if they occur too frequently. In addition, if alerts that are issued are not representative of an actual potential threat to the UAS then confidence in the automation can be lost. The SST is intended to alert the pilot that action is necessary to avoid an imminent threat. Therefore, if a UAS operator consistently is alerted to proximate aircraft that are not likely to pose an imminent threat, then the operator may determine that the alerting is inaccurate and adapt their behavior to disregard the alerts. While inaccurate alerts are not directly a safety concern it can raise the workload of the UAS operator, which could lead to a hazardous situation. In this work we define nuisance alerts as alerts that were predicted to be a LOWC at a future time but ultimately would not result in a LOWC when no action was taken by the UAS to separate from the threat aircraft.

Figure 7 depicts a bar chart of the percentage of nuisance alerts for each of the alerting definitions. As expected the larger buffered volume for alerting yields the larger percentage of nuisance alerts. It is clear from Figure 7 that the SST is a large driver in the nuisance alert percentage. Nuisance alerts can be caused by either a maneuvering intruder or ownship aircraft and a larger SST allows for a longer time horizon upon which either aircraft could maneuver. One disadvantage of the alerting logic is that both the UAS and intruder aircraft states are projected forward in time using dead reckoning, therefore if either aircraft is currently maneuvering alerts may be issued even though the aircraft have a minimal likelihood of resulting in a conflict. So while the alert is correct based on the alerting criteria using a dead reckoning trajectory projection, the lack of knowledge of intended flight path of the UAS would cause the alert to be issued when there is no imminent loss of well clear present. It is expected that the percentage of nuisance alerts would be lower if the trajectory intent of UAS ownship were considered in the alerting logic.

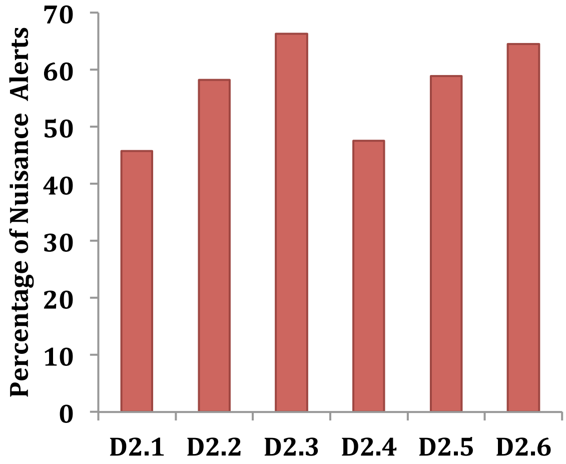

Figure 7: Percentage of nuisance alerts for each of the alerting definitions.

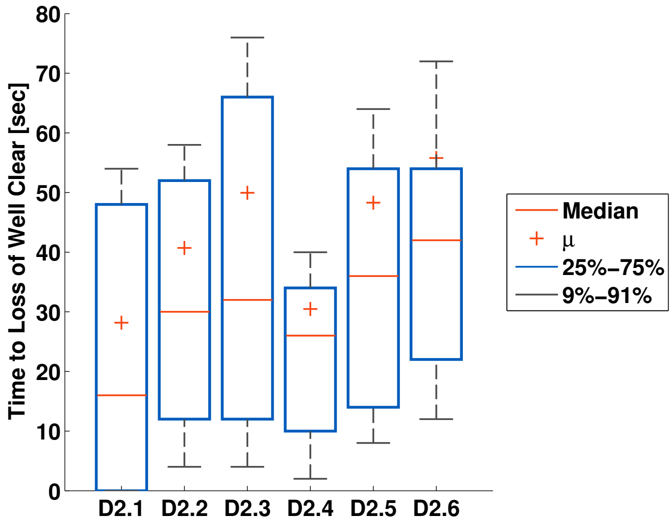

Figure 8: Time to LOWC at first alert for each of the alerting definitions.

In addition to the frequency and reliability of alerts, it is also important that the alerting is timely enough for the pilot to perform a maneuver prior to a LOWC. Figure 8 depicts a box-and-whiskers plot of the time until the LOWC. In this plot, the box represents the data between the 25^{th} and 75^{th} percentiles, the line inside the box represents the median, the plus symbol represents the mean and the solid black line represents the whiskers, which denote the 9^{th} and 91^{st} percentile values. Data outside the span of the whiskers are considered outliers and omitted from this plot. It is clear from D2.1 that when no buffers are present it is possible for aircraft to not pose a threat until after they are within 35 seconds modified tau, which is the boundary of the well clear definition. For a head-on encounter scenario, the definition D2.1 should yield a time to loss of well clear of 55 seconds, however it is clear that the mean (30 seconds) and median (17 seconds) are far below that value. This result demonstrates that due to maneuvering intruders relative to the UAS ownship, often aircraft will induce an alert at a measured value of modified tau, which is lower than the SST. Comparing D2.1 and D2.2 depicts the impact of the vertical buffering on ZTHR, where it is evident that the mean and median of the time to well clear increases. Adding a vertical buffer appears to be a necessity, as it increases both the mean and median of the alerts above 25 seconds. Increasing the alerting time expands the range of how early alerts are issued, however it is evident from D2.2-D2.6 that the percentage of alerts issued late is a function of the size of the buffers on their vertical (ZTHR) and horizontal minimum separation distances (HMD and DMOD).

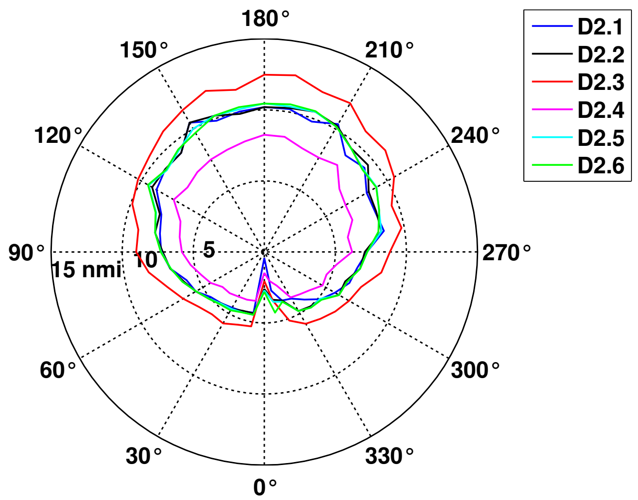

Figure 9: Relative heading at the first alert for all alerting definitions.

Another important aspect of the alerting logic that has implications for the sensor requirements is the relative range between the intruder and ownship at the first alert. While Figure 3 in Analysis 1 inferred the minimum range required of the sensor to detect all intruders at the well-clear boundary, Figure 9 informs the minimum sensor range requirements needed to detect an intruder for a given SST. Figure 9 depicts a relative heading plot where 99% of the data is contained within each contour for each alerting definition. In order to avoid a loss of well clear, the alerting logic needs to ensure that a UAS operator has sufficient time to detect and resolve the conflict. Future studies will consider a resolution algorithm and human-in-the-loop (HiTL) evaluation to determine whether the SST defined is sufficient to avoid a loss of well clear. Figure 9 illustrates when the SST is set to 70 seconds (D2.4) the sensor requirements would be 7 nmi head-on and 3 nmi in-trail, whereas if the SST is set to 110 seconds (D2.3) the sensor requirements are 12 nmi head-on and 5 nmi in-trail.

To provide more information about the characteristics of the intruder aircraft, the subsequent plot depicts the D2.2 definition relative heading at the time of first alert. Definition D2.2 represents a configuration discussed as a potential alerting criterion within the RTCA SC-228 working group, Figure 10 depicts the relative heading, where the contours represent the boundaries within which 99%, 90%, 80%, and 60% of the alerts are contained. In developing surveillance requirements, it is feasible that the results from HiTL and fast-time simulations may yield an SST range that is acceptable for avoiding a loss of well clear, however inherently extends the surveillance range beyond the limits of current technology. In this scenario, the standards may specify an acceptable number of late alerts to ease the burden on the surveillance requirements. Figure 10 indicates the percentage of alerts that would still be issued within a given contour and the subsequent reduced surveillance range requirement. The alerts that would have occurred between the required surveillance range dictated by SST and the reduced surveillance range dictated by the current surveillance technology would be considered late alerts. Further work is needed to determine the acceptable percentage of late alerts for a DAA system.

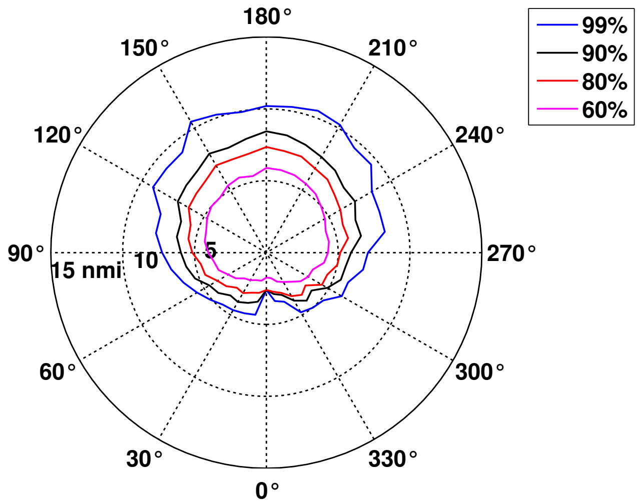

Figure 10: Relative heading for definitions D2.2 where contours for the boundaries are shown which contain 99%, 90%, 80%, and 60% of the alerts.

In summary, Analysis 2 was an initial investigation of the impact of parameters of the alerting criteria on the frequency of alerts and encounter characteristics. It was shown that the minimum horizontal and vertical separation distances had a meaningful impact on the frequency of alerting. It is evident that while adding buffer to the well clear definition for alerting is beneficial, as was shown on the increased time until loss of well clear box-and-whisker plots, making the buffers too large will produce more frequent alerts for the UAS operators and likely more nuisance alerts. Analysis 2 also presented data to inform the inferred sensor range detection requirements for a given SST, as well as inform the trade-off between sensor coverage and late alerts when there is a gap between required performance and technological state of the art for airborne surveillance.

VI. Conclusion

A UAS operation will have to comply with the regulatory see-and-avoid requirements by equipping with a DAA system. While manned aviation can rely on an onboard pilot to maintain a safe proximity or "well clear" of other aircraft based on their subjective judgment, a UAS must have a clear quantitative definition to establish the minimum separation that is allowable to safely operate in the NAS. The results presented in this work are predicated on the assumption that a quantitative definition of well clear is considered a separation standard between UAS operations in Class E airspace and other aircraft. Two analyses were conducted using a NAS-wide fast-time simulation platform. Nine UAS missions consisting of approximately 18,000 flights were simulated against twenty-four days of historical cooperative VFR aircraft traffic. The UAS and VFR aircraft received no mitigation to avoid separation conflicts.

Analysis 1 focused on the characteristics of encounters at the well clear definition boundary. Three different well clear definitions were considered, including the definition accepted by the RTCA Special Committee 228 DAA working group. The analysis established a minimum sensor range of 5 nmi head-on and 3 nmi in-trail required to detect all losses of well clear. This analysis will inform the stakeholder organizations making operational standards as to the characteristics of the traffic that will be encountered, the unmitigated risk associated with the well clear definition, contribute to the risk ratio calculation to evaluate the performance of the DAA system, as well as expose any strengths and weaknesses of the definition.

Analysis 2 focused on the alerting criteria used to inform the UAS operator of an imminent loss of well clear. This analysis investigated the impact of adding buffers to parameters of a well clear definition from Analysis 1 to use for alerting. Analysis 2 informs the impact to the UAS operator based on the frequency of alerting, the timeliness of alert, and the relative state between the aircraft at the first alert, which have implications for the DAA sensor performance requirements. A key result from this analysis is to motivate the need for buffers on the minimum horizontal and vertical separation in the well clear definitions, which allows alerts to get issued with more time for the UAS operator to initiate a resolution maneuver. It was also observed that the SST increases the span at which alerts are being issued, giving the pilot more time for maneuvering, but at the cost of requiring more capable sensors and the potential for more nuisance alerts. The two analyses presented help inform the DAA safety case, DAA requirements development, and operational environment for the DAA MOPS.

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