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Establishing a Risk-Based Separation Standard for Unmanned Aircraft Self Separation

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Abstract—**Unmanned Aircraft Systems require an ability to sense and avoid other air traffic to gain access to civil airspace and meet requirements in civil aviation regulations. One sense and avoid function is self separation, which requires that aircraft remain "well clear." An approach is proposed in this paper to treat well clear as a separation standard, thus posing it as a relative state between aircraft where the risk of collision first reaches an unacceptable level. By this approach, an analytically-derived boundary for well clear can be derived that supports rigorous safety assessment. A preliminary boundary is proposed in both time and distance for the well clear separation standard, and recommendations for future work are made.**

Keywords- Unmanned Aircraft, Sense and Avoid, Separation Standards, Safety, Well Clear

I. INTRODUCTION

There has been significant effort in gaining civil airspace access for Unmanned Aircraft Systems (UAS). A key challenge to achieving airspace access is the ability to provide an acceptably safe means of compliance with regulations to see and avoid other aircraft. Without a pilot onboard the aircraft, other operational or technical means are required to detect and resolve potential conflicts.

The ability to perform the function of sense and avoid has been defined in the U.S. [1] and internationally [2] as the performance of two separate functions: self separation and collision avoidance. Self separation is the ability to remain "well clear" of other aircraft, typically through gentle, right-of-way compliant maneuvers. Collision avoidance is a function executed to prevent an imminent collision, and is typically more aggressive. The requirement to maintain well clear derives from regulatory language in U.S. Federal Aviation Regulations governing general flight rules.

Methods have been well-established to evaluate the safety performance of technical collision avoidance systems, most notably the Traffic Alert and Collision Avoidance System (TCAS) [3]. These evaluation methods have been extended to UAS [4]. There has been a lack of similar performance evaluation methods for self-separation systems due to the lack of an analytical definition of the term well clear.

An analytical approach to defining a well clear threshold to evaluate self-separation performance is proposed in this paper. The approach rests on the premise that well clear is, fundamentally, a separation standard for which the UAS is the separating agent. When viewed as a separation standard, accepted risk-based analyses for separation minima can be applied. By standard approach, the appropriate threshold is that which maintains an acceptable risk of collision. Such an analytically-derived definition of well clear will gain increased importance beyond UAS, and can benefit future NextGen and SESAR concepts that envision delegated self separation to airspace users.

The structure of the paper will be as follows. First, the basis for defining well clear as a separation standard will be discussed, along with the necessity of having an analytically-derived boundary to evaluate system performance. Second, a methodology will be described that utilizes fast-time simulation and airspace encounter models to derive the well clear boundary as a function of risk. Finally, results for candidate definitions of well clear boundaries will be presented and discussed.

II. UAS WELL CLEAR SEPARATION STANDARD METHODOLOGY

U.S. Federal Aviation Regulations require that pilots pass well clear of other aircraft when encounters occur in airspace. The term is used without a more detailed definition. Well clear is a separation standard with a subjective definition. In order for a technical system to perform maneuvers that maintain well clear, a quantitative definition is desirable.

A. The Need for an Analytical Definition of Well Clear

The FAA-sponsored Sense and Avoid Workshop defines well clear as "the state of being able to maintain a safe distance from other aircraft so as not to cause the initiation of a collision avoidance maneuver [1]." This definition is difficult to implement, as it requires the characterization of the performance of a collision avoidance system to define a threshold for which another system may act. Furthermore, collision avoidance performance varies by system, including pilot implementation of collision avoidance. This could result in different definitions as new collision avoidance logic or systems are implemented.

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Regulatory language, from which the concept of well clear is derived does not support an analytical definition and is subjective. Subjectivity was likely intentional, to allow pilot judgment in implementation. However, if a technical system is to perform an equivalent function to pilots, it is necessary to have an unambiguous, implementable definition of the separation the system seeks to maintain with other aircraft. Additionally, defining well clear allows for quantitative evaluation of safety performance. This would allow an encounter between two aircraft to be characterized either as maintaining well clear or violating well clear. By this approach, many synthetic encounters may be generated to assess system performance against a threshold. This approach has been accepted by regulators through many phases of development of TCAS. An analytical definition could therefore support a rigorous, validated approach to evaluating the safety of UAS sense and avoid systems.

An analytically-derived definition would offer additional benefits beyond UAS airspace access. Future technologies or operations where separation authority is transferred from air traffic control will benefit from an established definition. Changes to airspace or types of operation can also allow the definition to be revisited using a similar analytical methodology.

B. *Well Clear as a Separation Standard*

To derive an analytical definition of well clear, it must be recognized that a well clear threshold is fundamentally a separation standard. ICAO has defined a separation standard as “the minimum displacements between an aircraft and a hazard which maintain the risk of collision at an acceptable level of safety [5].” This is consistent with U.S. federal aviation regulations that require that aircraft not operate so close as to create a “collision hazard.” The well clear displacement depends upon many factors, including the relative encounter geometry and the performance characteristics of each aircraft.

Current ICAO guidance in establishing airborne separation standards recognizes two methods to determine appropriate standards. The first approach is by comparison to a reference system. In this approach, a new separation method is designed to meet the performance of an existing, accepted system. This approach has been followed in recent assessments of ADS-B separation [6]. The second approach is to compare assessed risk against a threshold, such as a target level of safety (TLS). This has been performed for past separation changes where the predominant technical contribution to collision risk is due to navigation error (for supporting analysis, see reference [7]).

In past assessments, collision risk has been analyzed considering end-to-end system performance. When assessing to a level of risk, a separation standard is typically proposed and evaluated such that the contribution of successive events is quantified and aggregated into a level of risk. This establishes a level of risk associated with the separation standard. By this general approach, a separation standard is a therefore a relative state between aircraft that when violated is assumed to no longer be acceptably safe. This relative state does not need to be distance-based. It could be measured by other parameters, such as time.

In the analysis discussed in this paper, well clear is framed as a relative state between aircraft for which the risk of collision is acceptable. The relative state could be defined by many potential variables. This analysis has limited the variables to time to closest point of approach, or tau; and distance. The risk and relative state relationship is illustrated conceptually in Figure 1. As shown in the figure, two aircraft have a future evolution of relative states along their flight paths. A general relationship between relative state and collision risk can be derived through several means. A predictive model of future trajectories could consider risk associated with each trajectory and formulate the risk of being in the state. Alternately, observed or generated trajectories could be examined to determine the proportion of time aircraft come into conflict when first passing through the relative state. The goal of such an examination is to derive a descriptive relationship that allows a threshold on acceptable risk to be translated to a relative state definition.

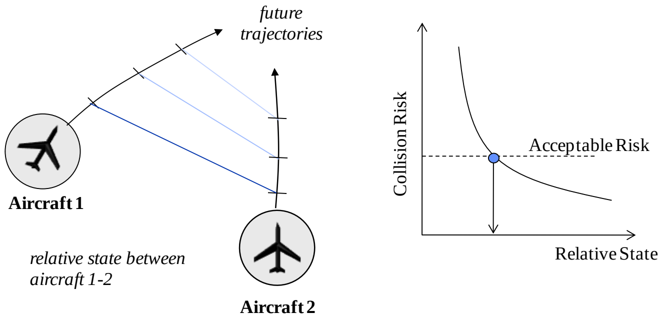

Figure 1. Relative state and risk

The analysis applied in this paper follows the intent of ICAO airspace analysis guidance, but does not derive performance to a specific target level of safety. A comparative approach is taken to current manned aircraft separation to derive an expected point at which self-separation would need to be initiated. Currently, the decision a manned pilot applies to maneuver well clear can be described based on a perceived future collision risk. A pilot would maneuver when he believes that the risk of continuing along the current trajectory would be unacceptable, given his knowledge of another aircraft’s position and intent.

C. *State-Based Measures of Well Clear*

To determine a well clear threshold definition, collision risk can be measured as the conditional probability of a Near Midair Collision (NMAC) given that two aircraft are at a relative state. A near midair collision is defined here using the TCAS-standard, as an event that occurs when two aircraft’s center of masses pass less than 500 ft and 100 ft vertically. The risk of collision after NMAC is assumed to be the same for all situations. Therefore NMAC risk will be proportional to collision risk.

The relative state between aircraft is investigated by two measures in this analysis: relative range and bearing, and time to Closest Point of Approach (CPA), commonly denoted as tau (τ). Choosing an appropriate measure will be a balance between simplicity and descriptiveness. A measure should be simple enough to be implemented as an unambiguous criterion to evaluate systems. It must also adequately capture the primary drivers of risk, thus being descriptive of risk.

The analysis performed also includes additional considerations for an analytical threshold defining well clear. First, it is unreasonable to expect pilots to see and avoid if they are unable to visually detect an aircraft. A model of visual acquisition could be used to examine the probability of detection of aircraft. to derive the threshold at which aircraft cannot be visually detected. This visual detection threshold could then be used as a basis for well clear. This approach may be considered for future work.

Defining well clear separation in terms of time to a given separation has been recommended by experts [1], as it simplifies the inclusion of multiple factors such as relative geometry and closing speed. It is also desirable for a UAS sense and avoid system to be interoperable with current collision avoidance systems. The most widespread collision avoidance system, TCAS, uses tau-based alerting criteria. Following similar methods could simplify interoperability by using established thresholds for generation of a collision avoidance advisory. Ensuring tau for well clear is always greater than tau for collision avoidance would ensure that TCAS does not issue a resolution advisory before violation of well clear.

III. COLLISION RISK MODELING APPROACH

The MIT Lincoln Laboratory (MIT LL) uncorrelated encounter model was used to generate a large number of statistically representative encounters at distances of 3 nm. Fast time simulation was then conducted using millions of the generated encounters to examine unmitigated collision risk.

A. *Encounter Simulation Methodology*

A statistical encounter model of air traffic is used to generate encounters with representative behavior of two aircraft in close proximity. For this step, the MIT LL uncorrelated encounter model was used. The uncorrelated encounter model captures the behavior of air traffic operating under Visual Flight Rules (VFR). The initial encounter conditions are expected to be uncorrelated between aircraft as they are not under common air traffic control. Their behavior during the encounter is statistically representative of VFR aircraft maneuvering in enroute airspace. The uncorrelated encounter model was built from one year of radar data from the continental United States. Additional detail on the development of the model and other model products can be found in reference [8].

Ten million complimentary pairs of aircraft trajectories were generated using Monte Carlo fast-time simulation. Each intruder is initialized on the surface of a cylinder with radius of 3 nm and height of 2,000 ft, with ownship trajectory at the origin. Initial locations were representative of traffic of uniform density. Cylinder dimensions were chosen to adequately capture behavior prior to crossing a well clear threshold while limiting computational complexity. A representative altitude of 7,500 ft was used. At this altitude, TCAS operates at sensitivity level 5, with a tau value for a resolution advisory of 25 s and DMOD value of 0.55 nm (3,340 ft) [10].

The state of each aircraft in the encounter is calculated and discretized for use in aggregate statistics. State variables inspected include range, bearing, relative altitude, and time to CPA (tau). For each encounter, statistics were collected to determine the frequency with which trajectories through given states resulted in an NMAC. These results can then form the conditional probability of NMAC given an aircraft passes through the state. A notional illustration is shown in Figure 2. The aircraft on the right does not intersect the NMAC region, while the aircraft on the left does. Both aircraft pass through the highlighted state of interest. If these were the only two encounters generated that passed through the highlighted state, its conditional probability of NMAC would be 50%. The process illustrated here is performed across multiple state definitions, using millions of encounter pairs to arrive at representative collision likelihoods.

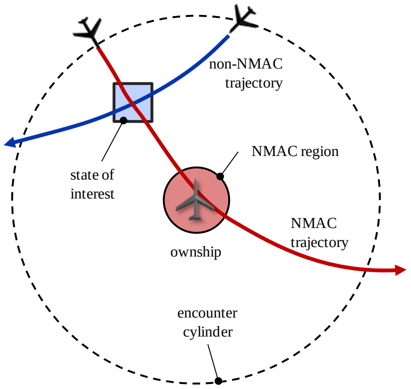

Figure 2. Encounter trajectories in two dimensions

Encounters were modeled using the MIT LL Collision Avoidance and System Safety Assessment Tool (CASSATT) [4]. The tool also implements a vendor-provided model of TCAS logic. The model assumes a TCAS version 7.1 sensitivity level 5. CASSAT also includes a validated visual acquisition model developed by Andrews [9]. As discussed previously, that model was not utilized.

The resulting probability of NMAC represents an unmitigated risk of collision. This is the risk that is incurred crossing a relative state given that no other action would take place. It therefore represents a marginal increase in collision risk assumed by reaching that relative state.

B. *Assumptions and Limitations*

Regulatory requirements to see and avoid apply to operation under both Visual Flight Rules (VFR) and Instrument Flight Rules IFR. Therefore, the well clear separation standard for performing a self-separation function would apply under both conditions. Under IFR in controlled airspace, there are established separation standards between IFR traffic. It has not yet been determined whether these separation standards sufficiently define well clear under IFR. Application to IFR would require an analysis of the effect of Air Traffic Control.

Under VFR, similar separation standards have not been defined. The goal of UAS operators is to achieve additional operational flexibility though VFR-like operations. For this reason, well clear is initially modeled in the VFR context. The use of the uncorrelated encounter model therefore creates the assumption that aircraft are not under direct air traffic control.

It has also been assumed that no avoidance actions are undertaken. Encounters are modeled that represent aircraft randomly "blundering" into NMAC. No attempt has been made to model the effects of visual acquisition and avoidance. It is likely that pilot maneuvering would reduce the collision risk shown in results. However, in some cases, pilot maneuvering would induce conflicts where none existed before, requiring a more detailed avoidance model to determine more accurate collision risk estimates. This assumption is appropriate for the purposes of defining well clear. The separation standard should indicate when a pilot would maneuver due to increased risk. It can be assumed that neither aircraft maneuvers prior to this maneuver threshold.

The MIT LL encounter models were built from radar-surveilled performance of existing aircraft under the current structure of the NAS. The ownship modeled in simulations is sampled randomly from the model. It does not reflect UAS performance where it may vary significantly from existing aircraft (e.g. with a slower cruise speed, higher climb rate, etc). The results also may not apply if significant changes to airspace operating rules cause aircraft behavior to change. This is not expected to have a significant effect on the uncorrelated encounter model.

The results for collision risk under this approach do not take into consideration several other factors that are relevant to a separation standard. An example is the likelihood of encountering wake, and the associated risk to aircraft and occupants. Wake vortex would also need to be considered for a complete definition of well clear.

IV. RESULTS

Results of the encounter simulation are shown in the form of contours of collision risk with respect to relevant state variables. Each contour indicates the conditional probability of NMAC given that an aircraft crosses the state contour. In each figure, ownship is located at the origin with the velocity vector oriented north. State variables examined include relative position in three dimensions and time to CPA (tau). In addition, the characteristics of TCAS resolution advisories are also examined.

A. Collision Risk Contours

Conditional collision risk results in the horizontal plane are shown in Figure 3. Following discussion of these characteristics, vertical characteristics will be treated separately. Each contour is drawn with the associated value of conditional probability of NMAC given an aircraft crosses the contour. The horizontal slice shows collision risk only for co-altitude encounters. As an example, if an intruder aircraft is 4,000 ft directly ahead of ownship, there is a 10% probability that the aircraft will violate the NMAC cylinder at some point in each aircraft's trajectory given that no other mitigating avoidance actions are taken.

NMAC risk contours of 1, 0.5, 0.2, 0.1, and 0.05 are shown in Figure 3. There is insufficient data resolution in the horizontal plane to obtain the 0.01 contour. The reader may note that there is a probability of 1 that an aircraft is an NMAC within the 500 ft. horizontal boundary defining an NMAC and risk decreases as range from the aircraft increases.

The asymmetric collision risk contours for likelihoods above 0.5 suggest that conflicts that occur less frequently are dominated by traffic approaching head-on. Very few overtaking conflicts are present. This is due to several factors. Fewer tracks are initialized behind the aircraft's direction of travel, due to a lower likelihood of encountering overtaking traffic. Also due to the forward speed of ownship, aircraft that are in conflict from behind have lower closing speeds. Traffic in the uncorrelated model is more likely to maneuver out of conflict horizontally during the encounter.

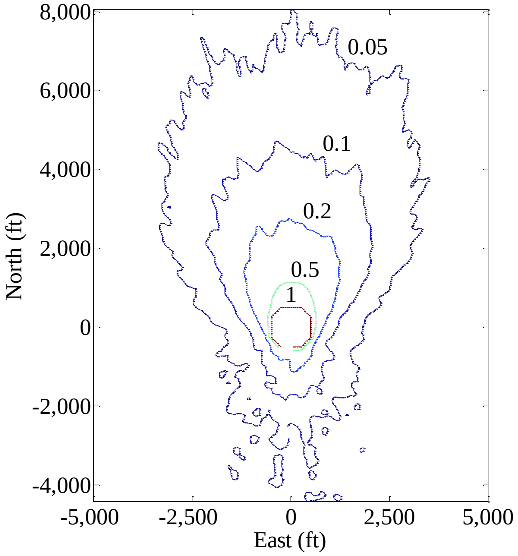

Figure 3. Contours of conditional NMAC risk in the horizontal plane

A vertical view of conditional NMAC risk is shown in Figure 4 for contours from 1 to 0.01. Similar to results evident in the horizontal plane, there are a larger proportion of head-on encounters evident at lower risk levels. Noise in the 0.01 and 0.05 contours behind ownship is due to the limited sample resolution available because of computation time limits on the number of encounters.

In altitude, the 0.05 contour extends to approximately 200 ft above the aircraft and 8,000 ft. ahead. The vertical slope of the contour is shallow, suggesting that a constant altitude limit may be a good approximation of the well clear boundary. The shape of the 0.01 contour is very different from the 0.05 contour. The bulges in altitude ahead and below suggest climbing and descending traffic are entering conflict in this region. Limited resolution of data behind the aircraft exhibit similar characteristics to those ahead, except at shorter distances.

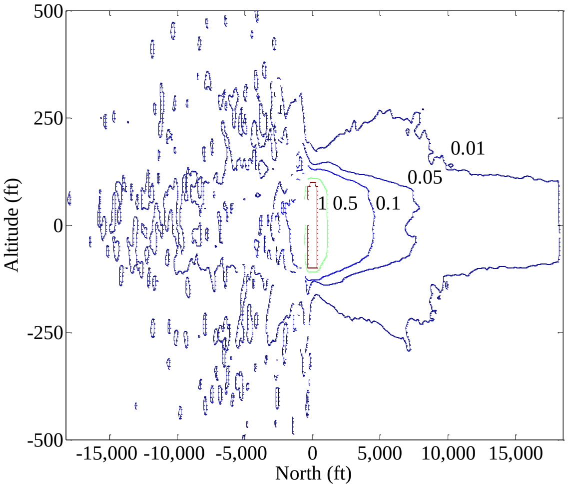

Figure 4. Contours of conditional NMAC risk in the vertical plane

B. *Time to Closest Point of Approach and TCAS Resolution Advisories*

The relative state between aircraft was also parameterized by the time to CPA, denoted as tau or τ. Results showing the average tau values of aircraft passing at a given range and bearing is shown in Figure 5. By inspection, the contours are similar to the collision risk contours shown in Figure 3. Ahead of the aircraft, a tau of approximately 45 seconds represents the same collision risk as the 0.05 contour, but widens beyond the collision risk contour to the side of the aircraft. This is due to aircraft approaching ownship, but turning out of conflict. A similarly elongated tail trails the aircraft, reflecting slower closing encounters.

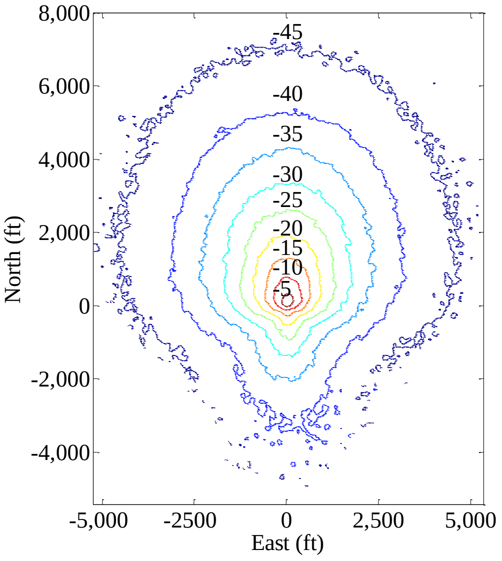

Figure 5. Mean time to closest point of approach (s)

Aggregating all results, a simple relationship between tau and the probability of NMAC can be derived irrespective of other relative states such as distance. This obscures the variability discussed above, but shows a similar correspondence between an average tau of 45 s and a corresponding P(NMAC) of 0.05.

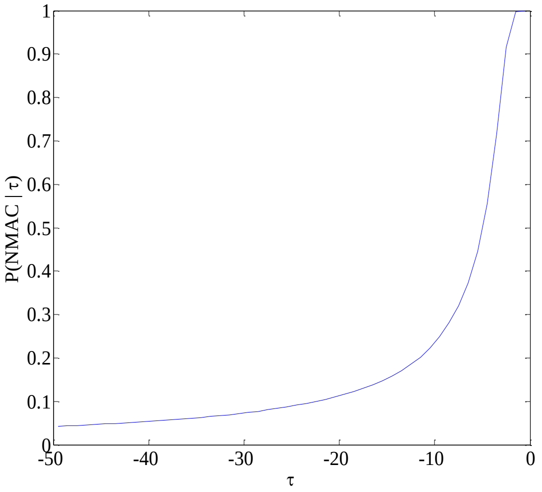

Figure 6. Probability of NMAC given time to closest point of approach (s)

To consider interoperability with TCAS, the likelihood of issuing a resolution advisory on an intruder aircraft was also examined. To calculate the probability of TCAS RA given relative position, one aircraft was equipped with TCAS, but did not change trajectory to comply with maneuvers. This approach was taken simply to analyze the initiation of an RA if an aircraft was equipped with TCAS without skewing collision risk results due to the effects of TCAS. The altitude was selected with TCAS at sensitivity level 5 to reduce variability in TCAS response. Each sensitivity level corresponds with several TCAS threshold parameters that will be discussed in more detail along with results.

At this sensitivity level, the tau threshold for issuing a resolution advisory is 25 s. Horizontal results for TCAS RA likelihood are shown in Figure 7. At the 0.01 contour, 1% of aircraft passing through the contour have a tau equal to 25 s, and 99% have a tau greater than 25 s. This view can be contrasted to Figure 5, to compare variability to mean results. The results are insightful in considering TCAS interoperability with well clear. If it becomes necessary to not issue TCAS RAs within the well clear boundary, it will need to be extended far beyond a low collision risk threshold. However, the results are representative of VFR operations, where the assumption of TCAS equipage among a large proportion of aircraft may not be valid.

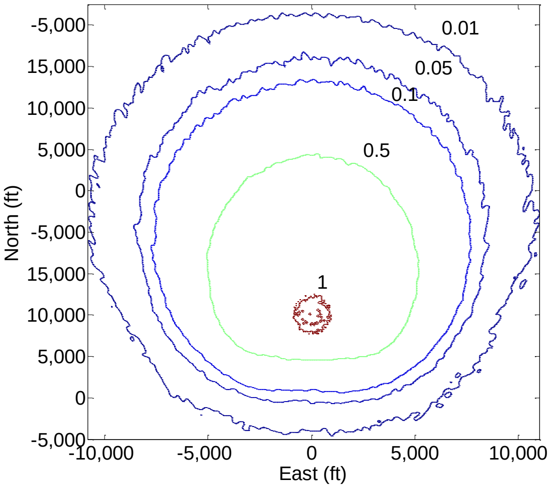

Figure 7. Likelihood of TCAS RA issuance, horizontal view

Figure 8 shows vertical contours of the likelihood of issuing a TCAS RA. The box-type shape reflects the setting of a vertical parameter in TCAS, which alerts when aircraft will cross within 600 ft. This setting is known to cause false alerts between VFR and IFR traffic offset by 500 ft. The results indicate that defining well clear to be less than 600 ft vertically would result in a substantial number of TCAS alerts.

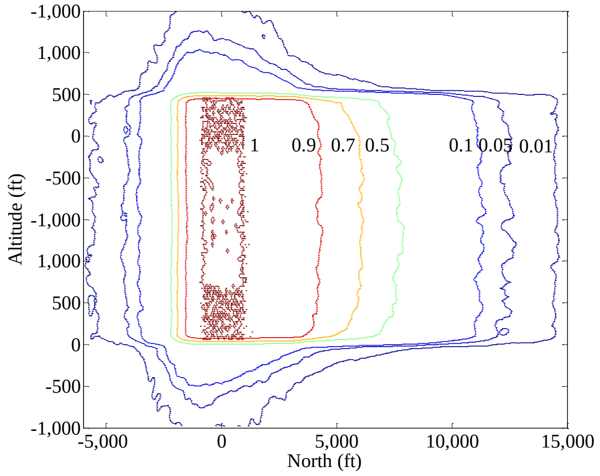

Figure 8. Likelihood of TCAS RA issuance, vertical view

V. CONCLUSIONS

The modeling performed above demonstrates an analytical approach to defining the regulatory boundary of well clear. By framing the threshold as a separation standard, boundaries can be derived based on an acceptable threshold of risk that is incurred from violating the threshold. This has the additional advantage of being comparable to the expected decision-making of pilots in executing self-separation. In the discussion below, a potential well clear boundary is proposed, and additional considerations and future work are outlined.

A. *Proposed Well Clear Boundary*

The lowest conditional likelihood of NMAC computationally feasible is 0.05, and has been used to consider potential contours of collision risk. The horizontal contours of 5% collision risk suggest that a well clear boundary based on this threshold would extend approximately 8,000 ft ahead of an aircraft, 3,000 ft. laterally, and 3,000 ft behind. A simplification of the complex shape would need to be derived that reflects the acorn-like shape ahead of the aircraft. In the vertical, altitude offsets of 300 ft, and equivalent limits ahead and behind the aircraft approximate the 5% risk contour, with some additional buffer. These boundaries would include some likelihood of issuing a TCAS RA. Assuring that no RA would be issued would require the boundary to be increased further.

B. *Implementation and Assessment of Well Clear*

An analytical definition of well clear, such as the one proposed above would be implemented in a UAS collision avoidance system as a desired avoidance boundary. Avoidance actions would be designed to be executed by automated systems or a human in the loop who would seek to maintain well clear through horizontal or vertical maneuvers. At the long time horizons required to achieve large separations, avoidance actions would likely not be aggressive, and it would be desirable for them to be compliant with existing right of way rules.

Well clear performance would be assessed through safety assessment, as part of an overall target level of safety analysis for midair collision. An unambiguous boundary provides a clear measure of when execution of well clear separation has failed. This failure rate may have its own accepted risk level, or would represent one node in a fault tree of multiple failures leading to a potential collision.

C. *Future Work*

The results presented here represent a preliminary analysis to test an approach to defining well clear. Other approaches may be possible, and additional considerations will be required before the approach can be used to establish a separation standard.

A novel approach to implementing well clear could consider avoiding a state with an assigned collision risk without using a surrogate measure. Such an approach has been used in development of future collision avoidance logic for TCAS by Kochenderfer [11]. The approach uses a Markov model of state transition, encounter models of air traffic, and a cost function to computer optimize collision avoidance logic based on state estimation. By this formulation, the function of self separation would be to maintain a relative state that avoids incurring a cost associated with some probability of collision.

Provided that the conditional probability approach is accepted by the community, additional analysis will be required to determine the appropriate risk threshold to define the separation standard. This risk threshold can be determined in the context of a target level of safety analysis, considering the failure of multiple mitigating factors before arriving at a collision.

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