Appendix A NAS-wide Encounter Rate Evaluation using Historical Radar Data and the Airspace Concept Evaluation System (ACES)

A.1 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. These 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 the 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.

Defining the risk ratio that the DAA system must provide to ensure the safety of the airspace requires: 1) an evaluation of the current airspace, and 2) a simulated evaluation that incorporates UAS aerodynamic performance and mission characteristics of future UAS operations that are projected to be conducted in areas where they could interact with current operations. Appendix A focuses on quantifying the frequency of encounters that exist in the current airspace and what could occur with the introduction of UAS. These results, combined with an evaluation of the unmitigated risk of collision and a desired level of safety of the airspace, will yield a required risk ratio of the DAA system.

A.2 Definition of Airborne Encounter

Appendix A quantifies the frequency of airborne encounters between aircraft in the absence of separation assurance mitigations. The unmitigated rate of encounters is investigated for interactions occurring in historical data as well as interactions that could occur from proposed UAS missions. An encounter is notionally determined by where the responsibility of a DAA system to mitigate a potential threat should begin, referred to as the Self-Separation Threshold (SST). Since manufacturers may have differing operational requirements, the SST value may be unique for each system. For this safety evaluation, the approach was to use a metric similar to the well clear definition, whose parameter values would yield encounters that were just prior to or outside of a generic SST definition. The proposed well clear definitions derived from a recent FAA report [1], a dedicated U.S. Government workshop on well clear [2], and variations on methods used by Traffic Alert and Collision Avoidance System (TCAS) II [3], [4] form the basis for defining an airborne encounter.

A metric originally used in the 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 (r) between aircraft to their range rate ($\dot{r}$) and measured in seconds:

$$\tau = -r/\dot{r}. \tag{1}$$

As described in the TCAS II Manual [3], one issue with the tau metric is that the calculated tau may be large even when the physical separation may be quite small because the rate of closure is very low (e.g., encounters where two flights are flying at approximately the same speed, on the same heading, offset by a small distance). 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 provide sufficient alerting time to avoid a loss of well clear. To provide protection for 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 (τ_{mod}) is computed as:

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

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 because they were not identified by the tau metric; however, modified tau also has limitations. For instance, in situations where aircraft are on converging paths with a high rate of closure and a large miss distance, the modified tau metric will indicate that an alert is required. TCAS II addresses this limitation in the tau and modified tau measures by applying a filter for the horizontal miss distance (HMD) at CPA. This filter removes alerts for encounters in which separation at CPA is greater than the HMD parameter.

The following definition is considered a qualitative definition of an airborne encounter between a pair of aircraft. This definition uses the modified tau calculation similar to the collision detection logic in TCAS II. It consists of a set of criteria based on temporal and spatial criteria.

The criterion in the horizontal dimension is specified as:

$$Criteria\ 1\colon\ 0 \ \leq \ \tau_{mod} \leq \tau^*_{mod}\ , \tag{3}$$

where τ_{mod} denotes the modified tau given by (2) and τ^*_{mod} denotes a constant value that is a threshold for the modified tau calculations.

The criterion in the vertical dimension is specified as:

$$Criteria\ 2\colon\quad |\Delta h| \ \leq ZTHR, \tag{4}$$

where Δh is the current altitude separation and $ZTHR$ denotes a constant value that is a threshold for altitude separation.

From (3) and (4), an airborne encounter is defined as:

$$Encounter\colon\ Criteria\ 1\ is\ true\ \ AND\ Criteria\ 2\ is\ true. \tag{5}$$

The parameters defining an airborne encounter were chosen such that they captured interactions between aircraft pairs prior to relative states that would constitute a loss of well clear. For reference, an encounter would be identified in a similar time horizon as when a DAA system may alert the pilot of a potential threat. The airborne encounter definition is not meant to imply formal criteria as to when alerting is expected; rather, it is defined to be sufficiently large to capture relevant interactions for the safety evaluation. The assumption is that a generic SST value would have a modified tau of 90 seconds, a DMOD of 4000 feet (ft), and a ZTHR of 1500 ft. Thus, the airborne encounter definition should yield parameters that are larger as to capture encounters just prior to an expected SST alert. The parameters of the airborne encounter definition used here are detailed in Table 1.

τ^*_{mod} [s]	DMOD [ft]	ZTHR [ft]
100	4000	2000

Table 1: Airborne encounter parameters.

A.3 Methodology

A.3.1 Analyses

The following section outlines the three analyses conducted in this study and describes the simulation platform and the data sources that are used in the evaluation. Analysis 1 evaluates the frequency of unmitigated encounters that currently exist in the airspace, and Analysis 2 determines the frequency of unmitigated encounters that could occur with the introduction of UAS. They are inputs to the calculation of the required risk ratio of the DAA system. One potential caveat of these analyses is that they may be affected by ATC-like mitigation for separation (5 nmi horizontal/1000 ft en route separation standard).

Analysis 3 investigates this for Analysis 2 in terms of the encounter rate and relative state data (i.e., encounter geometry characteristics).

A.3.1.1 Analysis 1: Determine Encounter Rates based on Historical Radar Data

This analysis evaluates the aggregate rate of airborne encounters that occur between aircraft operating under Instrument Flight Rules (IFR) and other aircraft operating under IFR as well as those operating under Visual Flight Rules (VFR). To facilitate this analysis, raw measurements from air defense radar data are processed and synthesized into tracks. Aircraft are categorized at the instance of encounter as operating under IFR, operating under VFR with a Mode 3/A identifying code of 1200, or operating under VFR with no transponder. The raw radar data contains various characteristics that needed to be overcome, such as: inconsistent/absent Mode 3/A identification, multiple position reports for the same aircraft from different radar locations, position reports without altitude measurements, data dropouts, asynchronous position reports, and missing position reports. The radar measurements are processed into tracks for each aircraft, which are then compared to identify instances when an airborne encounter occurred. Analysis 1 uses radar data from 21 days in 2012 and limits this data to aircraft position reports at or below FL180, above 500 ft (above ground level, or AGL), and within the continental United States (CONUS). Military formation flight operations are filtered from the data set since they intended to fly within close proximity and would otherwise skew the encounter data.

A.3.1.2 Analysis 2: Determine Encounter Rates based on Simulated UAS Missions

Fast-time simulations are conducted using the Airspace Concept Evaluation System (ACES) platform [5], [6] to estimate the rate of occurrence of encounters between UAS and VFR aircraft without mitigation. Each day of processed VFR radar track data from Analysis 1 is replayed in ACES as the simulation platform modeled UAS flights (about 20,000 in total, each performing one of 18 missions). The UAS and VFR data are compared to identify encounters and collect relative state data using the same filters as in Analysis 1. In addition, encounters where at least one flight is in ACES for less than 2 minutes are filtered out since these pop-up cases would have been prevented through pre-departure scheduling by air traffic control (ATC). Similarly, the calculation of UAS flight times to compute encounter rates started at two minutes after departure. It ended at arrival or the time of the last VFR flight track (whichever came first).

A.3.1.3 Analysis 3: Investigate Effect of ATC Mitigation on UAS-VFR Encounters

A potential caveat of the Analysis 2 simulations is that they do not include ATC-like mitigation for UAS-manned IFR aircraft conflicts for separation (5 nmi horizontal/1000 ft vertical en route separation standard). Maneuvering UAS for separation conflicts with manned IFR aircraft could affect UAS-VFR encounter rates and relative state data. As such, a second set of ACES simulations is run with ATC-like mitigation for UAS-manned IFR aircraft conflicts provided by a conflict detection and resolution algorithm named Autoresolver [7] for four of the days used in Analysis 2 to investigate this. As in Analysis 2, VFR radar track data is replayed in ACES as the simulation platform modeled UAS flights. In addition, manned IFR flights are simulated using flight schedule and flight plan information from Aircraft Situation Display to Industry (ASDI) data [8].

UAS-VFR encounters are identified and relative state data are collected as in Analysis 2 by applying the same analysis scripts. The encounter rates in the mitigated runs of Analysis 3 are compared directly with the encounter rates in the unmitigated runs of Analysis 2. With regard to the relative state data, the two-sample Kolmogorov-Smirnov (KS2) test is used as a coarse filter first to identify which state data had distributions that are different than their unmitigated counterparts. Then, CDF plots of these data are generated to determine which data are substantially different for practical purposes. If the UAS-VFR encounter rates and relative state data are similar with and without ATC-like mitigation, then the results from Analysis 2 can be used in the calculation of the required risk ratio of the DAA system. Otherwise, simulations with ATC-like mitigation will need to be run for the other 17 days of traffic data.

A.3.2 Simulation Platform: Airspace Concept Evaluation System (ACES)

ACES is a NAS-wide non-real-time simulation tool [5], [6] used in Analysis 2 and Analysis 3. 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. ACES has a large set of four-degree-of-freedom aircraft models that it uses to simulate flights, 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, origin and destination airports, departure times, and flight plans. In Analysis 2 and Analysis 3, UAS mission flight demand sets, described in A.3.3.2, are used as inputs to the ACES platform. In Analysis 3, manned IFR flight demand data sets derived from ASDI data, described in A.3.3.3, are also used. UAS-VFR encounter rates are calculated by overlaying historical VFR flights produced from air defense radar, described in A.3.3.1, with ACES-simulated UAS missions and/or manned IFR flights.

A.3.3 Traffic Scenarios

A.3.3.1 84th Radar Evaluation Squadron (RADES) Air Defense Radar Data

The VFR traffic data used in all analyses and the IFR traffic data used in Analysis 1 are collected from the 84th Radar Evaluation Squadron (RADES) at Hill Air Force Base, Utah. The RADES collect data through the Eastern and Western Defense sectors. They provide that data to a variety of government entities, including the FAA and the Department of Defense. They ensure that there is reliable and accurate sensor information to support military day-to-day operations, contingencies, and specialized activities (e.g. counter-narcotics, search and rescue, etc.). Continuous real-time feeds are maintained from short-range radars in the interior of the United States as well as long-range air route surveillance radars that cover the perimeter. The raw radar data return can include: time, the four-digit Mode 3/A identifying code squawked by aircraft, quantized altitude measurements reported by the target, and range and azimuth measurements. Note: Not all radar returns included the four-digit Mode 3/A identifying code and the altitude measurements.

For the purposes of this evaluation, aircraft whose radar data contain a four-digit discrete Mode 3/A transponder code (that is not 1200) are considered to be operating under IFR. On the other hand, aircraft squawking a Mode 3/A transponder code of 1200 are classified as cooperative aircraft operating under VFR. Likewise, when no Mode 3/A transponder code is present, the aircraft are classified as a non-cooperative aircraft operating under VFR. In the radar data set, an aircraft's transponder code may change (e.g., aircraft with a four-digit discrete transponder code begins squawking 1200) during portions of its flight for various reasons. Due to this characteristic of the data, when evaluating aircraft encounter events, the classification of an aircraft's flight rules and transponder status (IFR, cooperative VFR, or non-cooperative VFR) occurs at the initial instance of the encounter event.

To build tracks to use in the ACES simulation, several days of traffic data were processed from four different months in 2012. Two algorithms were used to process the raw radar measurements and fuse them into tracks. The first algorithm was developed to create tracks for the IFR and cooperative VFR traffic. This algorithm first collected the raw radar measurements that had Mode C transponder codes, which included altitude measurements. Then, for every 10-second section of data, a minimum-spanning tree clustering sub-algorithm classified the radar position reports within a +/- 60-second time window into groups of radar returns, where each group represents one aircraft [9]. It also associated unique aircraft reports by comparing consecutive time windows amongst aircraft classified by the clustering. Tracks for aircraft uniquely identified by the sub-algorithm are then smoothed using a Kalman filter.

Under a contract with NASA, Honeywell developed the complementary algorithm to create tracks for the non-cooperative VFR traffic. This algorithm processes raw radar returns from primary radar characterized as "search only," meaning the primary radar reported a target that was not reinforced with a beacon sensor report. In these reports, the altitude information is unknown and, thus, the altitude must be assigned for use in the simulations and evaluations. This algorithm uses a Kalman filter based on a track association method to identify and generate tracks from multiple returns, and a single cruise altitude from a gamma distribution was assigned to each aircraft. The gamma distribution was generated from available 3D Air Route Surveillance Radar-4 (ARSR-4) returns for non-cooperative VFR aircraft. ARSR-4 radars are used to control airspace mainly around the borders of the CONUS. An assumption was made that the gamma altitude distribution constructed from the ARSR-4 radar returns are representative of the aggregate altitude distribution across the entire CONUS. Furthermore, a limitation of the non-cooperative VFR traffic in this analysis is that they are assigned a single cruise altitude and, thus, encounters that would have occurred due to climbs and descents are not represented because of a lack of sufficient radar data.

Drop-outs and missing returns in the radar data lead to the creation of short flight segments during track generation by both algorithms. To overcome this limitation, a stitching algorithm is applied to connect flight segments. It is based on three criteria: 1) time between the end point of one track and the start point of another, 2) horizontal and altitude distance between those two points, and 3) the maximum allowable speed for traveling from the end point of one segment to the start point of the other segment. Further filters were applied to remove outliers associated with: 1) military formation flights, 2) flights under 20 minutes in duration, and 3) erroneous average speeds.

Twenty-one days were chosen across the four seasons of 2012 such that 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 selected days used in Analysis 1 and Analysis 2 are shown in Table 2. A subset of four days was used in Analysis 3 of UAS-VFR encounter rates and relative state data with ATC-like mitigation: January 11, April 21, July 17, and October 6, 2012.

January 2012

Su	M	Tu	W	Th	F	Sa
1	2	3	4	🟥 5	🟥 6	7
8	9	10	🟥 11	12	13	🟥 14
15	16	17	18	19	20	21
22	23	🟥 24	25	26	27	28
29	30	31				

April 2012

Su	M	Tu	W	Th	F	Sa
1	2	3	🟥 4	5	🟥 6	7
8	9	10	11	🟥 12	13	14
🟥 15	16	17	18	19	20	🟥 21
22	23	🟥 24	25	26	27	28
29	30					

July 2012

Su	M	Tu	W	Th	F	Sa
1	2	3	4	🟥 5	🟥 6	7
8	9	10	11	12	13	🟥 14
15	16	🟥 17	18	19	20	21
🟥 22	23	24	25	26	27	28
29	30	31				

October 2012

Su	M	Tu	W	Th	F	Sa
	1	2	3	4	5	🟥 6
7	8	9	10	11	🟥 12	13
14	15	🟥 16	17	18	19	20
🟥 21	22	23	🟥 24	25	26	27
28	29	30	31			

Table 2: Selected days in 2012 for VFR traffic scenarios.

A.3.3.2 Proposed UAS Missions

The FAA's UAS Integration Concept of Operations (FAA CONOPS) [10] requires that UAS operate under 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 aircraft will create different encounter rates and characteristics. Modeling expected UAS operations is necessary in order to accurately predict the safety of DAA systems during operations in the NAS. The mission characteristics used in this study are consistent with the missions outlined in the FAA CONOPS [10], RTCA DO-320 [11], and a recent Volpe Report [12]. Intelligent Automation, Inc. (IAI) developed the mission sets, in collaboration with and under the supervision of NASA [13], [14].

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. The 18 UAS missions used in this study were chosen to be representative of potential future operations in the NAS (e.g., 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, etc.). Each mission consists of a set of flights that have altitude, speed, aircraft performance, takeoff times, duration, and geographic constraints that are dictated by its distinct requirements and objectives. The UAS flight data set consists of approximately 20,000 flights and 26,000 flight hours over a 24-hour period (after applying the filters described in A.3.1).

None of the analyses included mitigation to separate UAS aircraft from aircraft operating under VFR; therefore, the UAS missions will come within close proximity to VFR traffic and other UAS. For this study, interactions between two 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 were simulated in ACES against different days of VFR traffic in Analysis 2 and Analysis 3.

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 [15] and validated by IAI [16]. UAS missions were simulated in ACES using representative UAS aircraft types whose performance would meet at least the minimum level required.

A.3.3.3 Aircraft Situation Display to Industry (ASDI)

ASDI data are processed into ACES input files to simulate NAS traffic operations in the ACES platform to measure the effect of ATC-like mitigation for UAS-manned IFR aircraft conflicts for separation on UAS-VFR encounter rates and relative state data (Analysis 3). For a particular day, the demand schedule and set of flight plans are generated by combining information from various NAS messages in ASDI data [8] and converted into an ACES flight input file [e.g., flight plan, cruise altitude, and cruise true airspeed data are extracted from the ASDI FZ (Flight Plan Information) message]. The last filed flight plan before takeoff for each aircraft is used as their respective desired route. ASDI data for any timespan can be converted into an ACES flight input file.

A.3.4 ATC-like Mitigation Model: Autoresolver

To investigate the effect of ATC-like mitigation for UAS-manned IFR aircraft conflicts for separation (5 nmi horizontal/1000 ft vertical en route separation standard) on UAS-VFR encounter rates and relative state data in Analysis 2, a set of ACES simulations is run with ATC-like mitigation provided by a conflict detection and resolution algorithm named Autoresolver in Analysis 3. Autoresolver has been used in both fast-time simulations [17] and real-time human-in-the-loop (HITL) simulations [18]. It attempts to resolve aircraft conflicts that are predicted to occur between 1 and 8 minutes in the future using a maneuver that causes the minimum amount of delay. It considers a variety of maneuver types, such as path stretch, direct-to, step altitude, temporary altitude, and speed change [7]. It also incorporates heuristics derived from controller feedback in HITL simulations to model ATC preferences when determining which aircraft to maneuver, such as:

- If aircraft A is an arrival and aircraft B is not an arrival, then Autoresolver prefers to maneuver aircraft B,

- If aircraft A has just reached its desired cruise altitude, then Autoresolver prefers to maneuver aircraft B
- If aircraft A is in cruise and aircraft B is not in cruise, then Autoresolver prefers to maneuver aircraft B
- If aircraft A was maneuvered for a previous conflict more recently than aircraft B, then Autoresolver prefers to maneuver aircraft B

The version of Autoresolver used in this study (specifically, in Analysis 3) is the legacy version that separates IFR-to-IFR conflict aircraft (both manned and UAS) to the ATC en route separation criteria (5 nmi horizontally/1000 ft vertically). In this study, Autoresolver is also configured such that conflict resolution maneuvers are required to maintain (secondary) separation of 1.5 nmi horizontally/500 ft vertically with (secondary) other IFR and VFR traffic. This legacy version of Autoresolver is not to be confused with the version adapted for UAS detect-and-avoid well clear separation known as Autoresolver-AD (Adapted for DAA) that is not used in this analysis.

A.3.5 Summary of Analysis Methodologies

Table 3 is a summary of the simulation platform (if any) and input data used in Analyses 1, 2, and 3.

Analysis	ACES	ATC-like mitigation (Autoresolver)	IFR radar data	VFR radar data	Proposed UAS missions	ASDI data
1	N	N	Y	Y	N	N
2	Y	N	N	Y	Y	N
3	Y	Y	N	Y	Y	Y

Table 3: Summary of simulation platform and input data.

A.4 Results

A.4.1 Analysis 1

This section focuses on the aggregate rates of airborne encounters between aircraft flying at or below FL180, above 500 ft AGL, and occurring within the CONUS. The aggregate rates are representative of a NAS-wide data set consisting of 21 days of historical data from four months (January, April, July, and October) in 2012.

Figure 1 depicts the aggregate rate of airborne encounters between two aircraft operating under IFR, between an aircraft operating under IFR and an aircraft operating under VFR squawking 1200 transponder code (cooperative VFR), and between an aircraft operating under IFR and an aircraft operating under VFR with no transponder (non-cooperative VFR). An airborne encounter, as defined in A.2, between two aircraft operating under IFR occurred about once every half hour. Likewise, an encounter between an IFR and a cooperative VFR aircraft occurred about once every 2.7 hours, and an encounter between an IFR and a non-cooperative VFR aircraft occurred about once every 5.7 hours.

The relative differences between these encounter rates are expected. Two aircraft operating under IFR are more likely to encounter each other due to the nature of the encounter definition—which provides a larger area buffer to detect conflicts given a larger closure rate between aircraft—and the nature of IFR aircraft, which generally fly faster than VFR aircraft. Furthermore, aircraft operating under IFR are more likely to fly fixed airways and naturally reduce their separation near airports. In contrast, VFR traffic typically occupy airspace altitude 10,000 ft and below and generate relatively slower closure rates with aircraft operating under IFR. Overall, given the definition of airborne encounter, an aircraft operating under IFR should expect to encounter another aircraft approximately once every 0.4 hours.

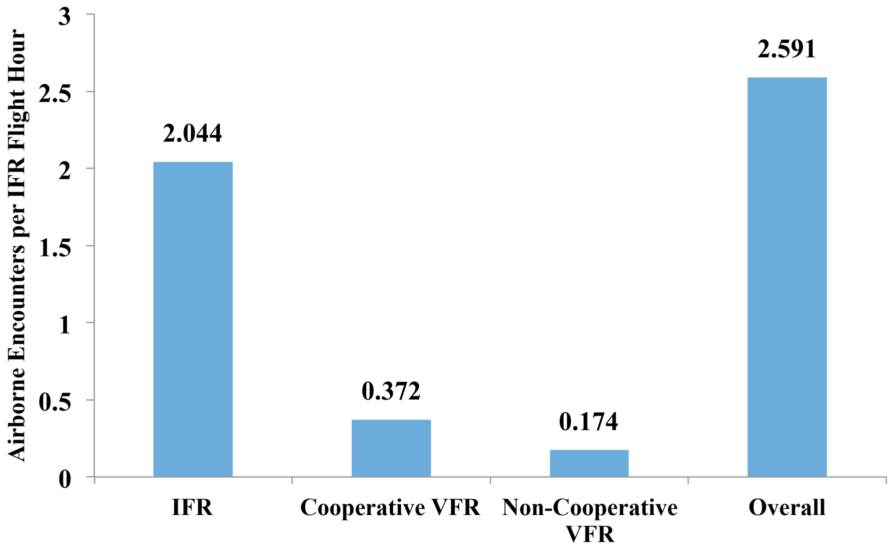

Figure 1: Encounters per IFR flight hour between IFR aircraft and: 1) other IFR aircraft, 2) aircraft operating under VFR squawking Mode 3/A transponder code of 1200 (cooperative VFR), and 3) aircraft operating under VFR with no transponder (non-cooperative VFR).

A.4.2 Analysis 2

Similar to Analysis 1, the investigation of UAS-VFR encounter rates and relative state data in Analysis 2 is focused on airborne encounters that occur at or below FL180, above 500 ft AGL, and within the CONUS. In addition, encounters where at least one flight is in the ACES simulation for less than 2 minutes are filtered out, and the calculation of UAS flight times begins 2 minutes after departure and ends at arrival or the time of the last VFR flight track (whichever came first). As in Analysis 1, the aggregate data for UAS-VFR unmitigated encounter rates are reported for 21 days of historical data from four months (January, April, July, and October) in 2012.

Figure 2 plots the aggregate rate of airborne encounters between a simulated UAS aircraft and an aircraft operating under VFR squawking 1200 transponder code (cooperative VFR) and between a simulated UAS aircraft and an aircraft operating under VFR with no transponder (non-cooperative VFR). Nearly 90% of UAS-VFR encounters were UAS-cooperative VFR encounters. An airborne encounter between a UAS and a cooperative VFR aircraft occurred about once every 5.0 hours. Likewise, an encounter between a UAS and a non-cooperative VFR aircraft occurred approximately once every 39.4 hours.

The relative comparison between these encounter rates is expected due to the lack of altitude information in the non-cooperative VFR radar data (see A.3.3.1), which constrained them to be assigned a single cruise altitude in the ACES simulations. As a result, potential encounters that could have occurred due to climbs and descents are not represented. Overall, a UAS is expected to encounter a VFR aircraft about once every 4.4 hours.

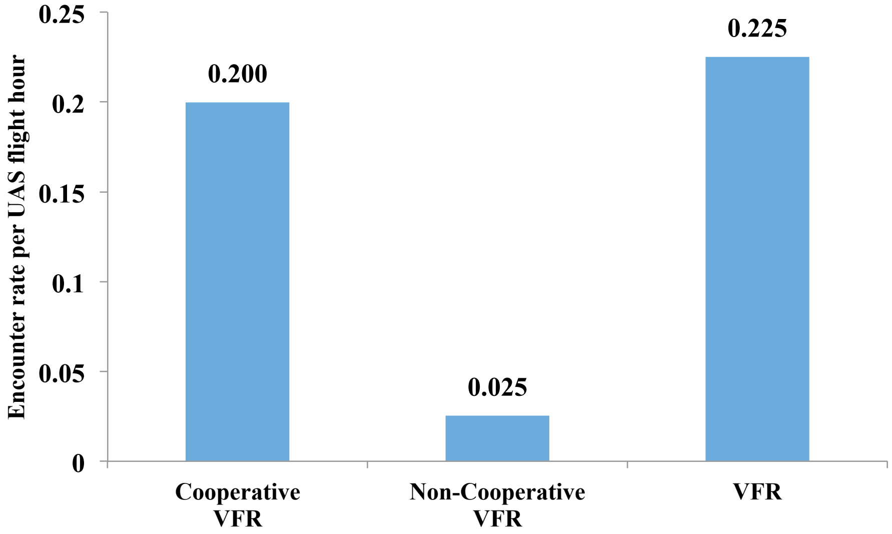

Figure 2: Encounters per UAS flight hour between UAS and VFR aircraft.

A.4.3 Analysis 3

A separate set of ACES simulations was run to investigate the potential caveat that the unmitigated UAS-VFR encounter rates and relative state data may be affected by conflict resolution maneuvers issued to UAS for separation with manned IFR flights. Four of the days in Analysis 2 (January 11, April 21, July 17, and October 6, 2012) were run with ATC-like mitigation provided by a conflict detection and resolution algorithm named Autoresolver that models ATC preferences regarding which aircraft in a conflict to maneuver based on controller feedback in HITL simulations (see A.3.4 for additional details).

The ATC-like mitigations issued by Autoresolver (about 3000 per simulation for UAS-manned IFR conflicts, 60% of which went to UAS) were infrequent (about one Autoresolver mitigation to UAS per 13.75 UAS flight hours) and did not substantially affect UAS-VFR encounter rates. As illustrated in Figure 3, the biggest difference in any of the four days relative to the unmitigated runs is less than 1.5%. Overall, the UAS-VFR encounter rates are only about 1% higher in the mitigated runs compared to the unmitigated runs. This can be attributed to the randomness of unexpected accelerations by VFR flights (i.e., playback tracks) in the vicinity of UAS-manned IFR conflicts and resolution maneuvers.

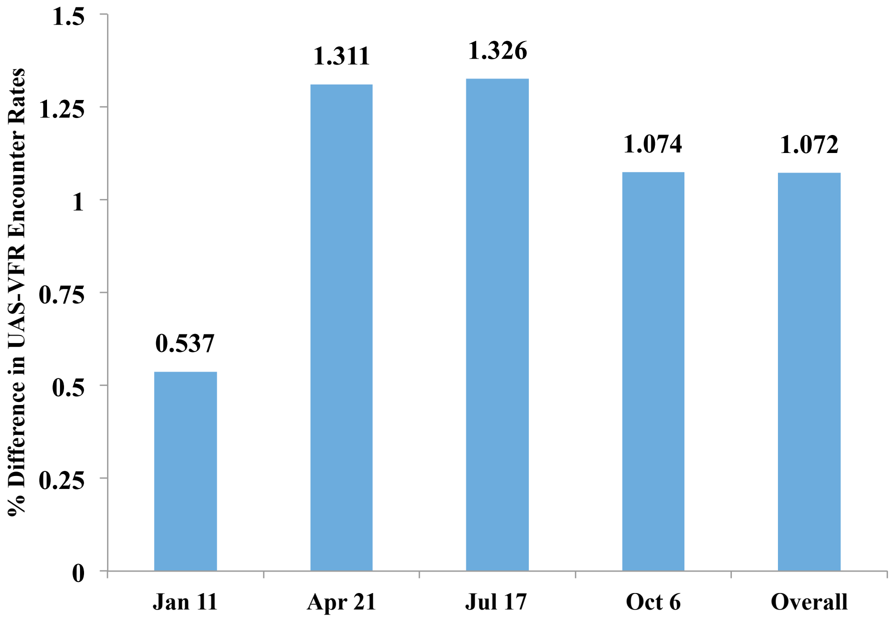

Figure 3: Difference in UAS-VFR encounter rate with mitigation relative to without mitigation.

With regard to the relative state data of UAS-VFR encounters in the mitigated and unmitigated runs, the two-sample Kolmogorov-Smirnov (KS2) test was used to identify whether modified tau and the following data for the UAS and VFR had different distributions: 1) latitude, 2) longitude, 3) altitude (AGL), 4) altitude (mean sea level, or MSL), 5) heading, 6) turn rate, 7) airspeed, 8) vertical speed, and 9) acceleration. The distributions of the following relative state data were different at the 5% significance level:

- Modified tau
- UAS airspeed
- VFR airspeed
- VFR turn rate
- UAS acceleration
- VFR acceleration

Plots of the cumulative distribution functions (CDFs) of these data from the mitigated and unmitigated runs were then generated to determine which relative state data were substantially different for practical purposes. Each of the six relative state data flagged by the KS2 test had mitigated and unmitigated CDFs with substantial overlap (for example, see Figure 4 of the CDFs of modified tau data). This indicates that ATC-like mitigations issued by Autoresolver for UAS-manned IFR conflicts did not substantially affect the relative state data of UAS-VFR encounters at an aggregate level.

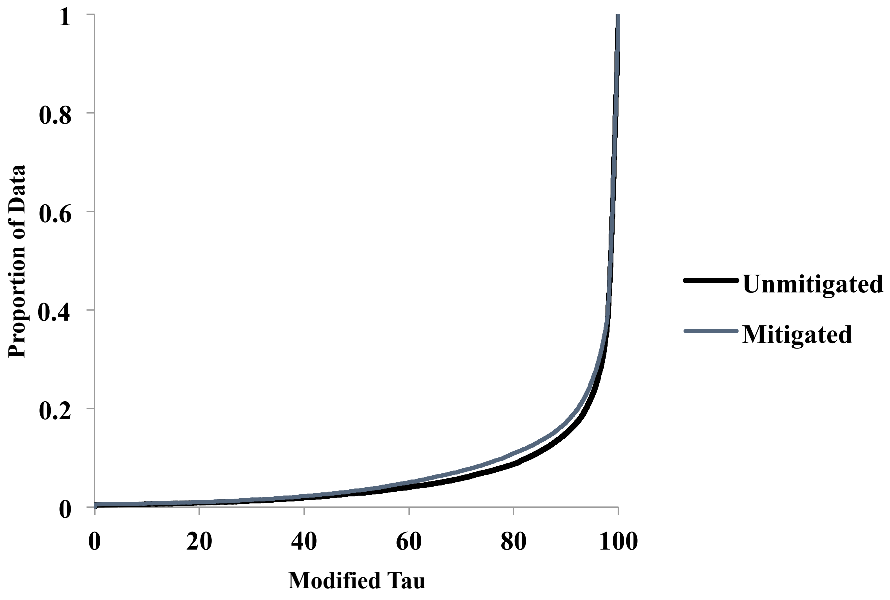

Figure 4: CDFs of modified tau for UAS-VFR encounters in unmitigated and mitigated simulations.

The 1% difference in UAS-VFR encounter rates (see Figure 3) and the similarities in the relative state data (see Figure 4) indicate that ATC-like mitigations for UAS-manned IFR conflicts do not affect UAS-VFR encounters at an aggregate level. Thus, the results of Analysis 2 can be used in the calculation of the required risk ratio of the DAA system.

A.5 Conclusion

Two analyses were conducted to estimate the frequency of unmitigated encounters: 1) historical air defense radar data of aircraft operating under IFR and VFR were synthesized and processed into tracks that were analyzed to compute aggregate rates of airborne encounters between aircraft operating under Instrument Flight Rules (IFR) and other aircraft operating under IFR as well as those operating under Visual Flight Rules (VFR), and 2) eighteen UAS missions consisting of approximately 20,000 flights were also simulated against the historical VFR aircraft traffic using a NAS-wide fast-time simulation platform to compute the aggregate rates of airborne encounters between UAS and VFR aircraft. In both cases, twenty-one days total from a cross section of four months in 2012 were used. In addition, for the UAS-VFR analysis, an assumption regarding the influence of ATC mitigation for UAS-IFR conflicts on UAS-VFR interactions was also verified by using a model of ATC-like mitigation to simulate UAS missions being separated from aircraft operating under IFR.

Analysis 1 computed frequency of encounters between aircraft operating under IFR and other aircraft. It was concluded that an IFR flight would encounter another aircraft every 0.4 hours on average, however only encounter a cooperative VFR aircraft every 2.7 hours and a non-cooperative VFR aircraft every 5.7 hours. The differences in closure rates, airspace structure, geographic operational areas, and frequency and duration of aircraft operating under different flight rules are reflected in their relative encounter rates.

Analysis 2 computed the frequency of encounters between simulated UAS aircraft and aircraft operating under VFR. It was concluded that a UAS would encounter a VFR aircraft about once every 4.4 hours on average. Nearly 90% of the time the VFR aircraft involved in the encounter was squawking Mode 3/A transponder code of 1200 (i.e., cooperative VFR).

A potential caveat that the unmitigated UAS-VFR encounter rates and relative state data in Analysis 2 could be affected by conflict resolution maneuvers issued to UAS for separation with manned IFR flights was also investigated in Analysis 3 through simulations with an ATC-like mitigation model. The difference in encounter rates between the mitigated and unmitigated simulations was 1%, and statistical tests and CDF plots of the relative state data did not find substantial differences. In combination, these results indicate that ATC-like mitigations for UAS-manned IFR conflicts do not affect UAS-VFR encounters at an aggregate level, and the results of Analysis 2 can be used in the calculation of the required risk ratio for DAA systems.

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