Downstream Effects of Separation Assurance on Encounters between Unmanned and Manned Aircraft

David P. Thipphavong[1], Dr. Marcus A. Johnson[2], Mohamad S. Refai[3], and James W. Snow[4]
NASA Ames Research Center, Moffett Field, CA 94035

This paper documents a crucial piece of the ongoing effort to develop minimum operational performance standards for Unmanned Aircraft System (UAS) Detect-and-Avoid (DAA)—the estimation of the rate of encounters between UAS and manned aircraft operating under Visual Flight Rules (VFR). In fast-time simulations that included both simulated future UAS and actual present-day manned VFR aircraft, UAS encountered VFR aircraft once every 5.3 UAS flight hours. Modeled air traffic controller mitigations for conflicts between UAS and manned aircraft operating under Instrument Flight Rules only reduced the rate of encounters between UAS and VFR aircraft by 0.2% with no statistically significant or practical effect on encounter geometry characteristics. Analysis of the simulations without modeled air traffic controller mitigations showed that the highest rates of encounter and loss of well clear occurred at altitudes below 5000 feet. In addition, a surveillance range of 14.3 nautical miles was needed to detect all encounters between UAS and VFR aircraft. A surveillance range of 3.6 nautical miles was necessary to detect all losses of well clear. These results primarily inform the safety case and the surveillance requirements for UAS DAA systems.

Nomenclature

DMOD	=	distance modification
HMD	=	horizontal miss distance at closest point of approach (CPA)
HMD^*	=	horizontal miss distance at CPA threshold
d_h	=	current vertical separation

[1] Aerospace Engineer, Aviation Systems Division, Mail Stop-210-10, AIAA Member.
[2] Research Aerospace Engineer, Aviation Systems Division, Mail Stop-210-10, AIAA Member.
[3] Senior Engineer, Universities Space Research Association, Mail Stop 210-8.
[4] Software Engineer, Universities Space Research Association, Mail Stop 210-10.

d_h^* = current vertical separation threshold

d_x = horizontal separation in the x-dimension

d_y = horizontal separation in the y-dimension

r = slant range

r = slant range rate

r_{xy} = horizontal range

r_{xy} = horizontal range rate

t_{CPA} = time to horizontal CPA

v_{rx} = relative horizontal velocity in the x-dimension

v_{ry} = relative horizontal velocity in the y-dimension

τ_{mod} = horizontal modified tau

τ_{mod}^* = horizontal modified tau threshold

$\tau_{\mathrm{mod\_r}}$ = slant range modified tau

I. Introduction

THE RTCA Special Committee-228 (SC-228) is a consortium of government, industry, and academic institutions charged with developing Minimum Operational Performance Standards (MOPS) for Unmanned Aircraft Systems (UAS) that satisfy federal aviation regulations to remain well clear of other aircraft (14 CFR Part 91, §91.111 and §91.113) [1]. The Federal Aviation Administration (FAA) will utilize these MOPS to develop technical standards and regulations for detect-and-avoid (DAA) systems [2] and other equipment necessary for UAS to safely integrate into and routinely access the National Airspace System (NAS). This study uses fast-time simulation to estimate the rate of encounters and the rate of loss of DAA well clear (LoWC) [3] between UAS and manned aircraft operating under Visual Flight Rules (VFR) in U.S. domestic airspace as part of the effort by RTCA SC-228 to develop MOPS for UAS DAA systems.

Estimating the rates of encounter and LoWC required both actual present-day manned aircraft operations and simulated future UAS operations with realistic mission characteristics and aerodynamic performance. A recent study

[4] demonstrated that UAS are projected to fly in airspace regions where they could encounter (i.e., come into proximity with) manned aircraft such that the UAS DAA system and the UAS pilot might need to take action to preserve well clear separation. In addition to encounters, this study also analyzes the cases in which UAS and VFR aircraft experience a LoWC, an intermediate separation threshold between encounter and near mid-air collision, which is an event in which two aircraft are within 500 ft horizontally and 100 ft vertically [5].

The simulations conducted for this study capture to a greater extent than any study to date the complexities of the aircraft encounters and LoWC that could occur in the NAS with the introduction of UAS. A prior study analyzed the frequency and timeliness of different DAA alerting criteria for encounters between manned aircraft and nine types of simulated UAS as well as their geometric characteristics at initial LoWC [4]. Since then, nine additional UAS missions were developed based on literature review, subject-matter expert and stakeholder input, and socio-economic analysis [6]. In addition, the historical FAA and air defense radar data of manned aircraft used in the earlier study underwent additional processing using smoothing, filtering, and clustering algorithms [7] to make them more realistic. The current study utilizes the expanded UAS mission data set and the more realistic manned VFR aircraft data. In addition, while the prior study only analyzed situations in Class E airspace [4], the current study analyzes both encounters and LoWC across all airspace classes with one exception: Class A, which is outside of the scope of the RTCA SC-228 DAA MOPS [1].

One limitation of the prior study [4] and a more recent study on DAA alerting and guidance performance [8] is that they did not model air traffic control (ATC) mitigations for separation conflicts between UAS operating under Instrument Flight Rules (IFR) [9] and manned aircraft operating under IFR at the en route separation standard of 5 nmi horizontally and 1000 ft vertically.* It may be necessary to model manned IFR aircraft and ATC mitigations for conflicts between UAS and manned IFR aircraft because ATC mitigations issued to UAS may affect the frequency and type of encounters and LoWC that UAS have with VFR aircraft. As such, an original contribution of this paper is that it investigates the above limitation of prior studies by running and analyzing two sets of simulations for four days of simulated data in 2012. In the first set, simulated ATC mitigations are provided by a conflict prediction and resolution algorithm [10] that utilizes heuristics derived from ATC feedback in human-in-the-loop simulations [11]. In the second set, simulated ATC mitigations are not provided. The rates of encounter and LoWC between UAS and

*Small UAS are not covered under the FAA's UAS Integration Concept of Operations [9] and are not within the scope of the RTCA SC-228 MOPS [1]. Furthermore, small UAS do not require IFR operations. As such, this paper does not compute the encounter rate or the LoWC rate for small UAS.

manned VFR aircraft as well as their geometric characteristics are compared. (Note: For brevity, the phrase "ATC-like mitigations" will be used instead of "simulated ATC mitigations" in the remainder of the paper.)

The remainder of this paper is organized as follows. The next section provides additional background details on prior work by the UAS research community that paved the way for the current study, including the development of definitions for encounter and LoWC (Section II). The section after that discusses the methodology used in this study, including descriptions of the simulation platform, flight input data, and ATC-like mitigation algorithm (Section III). A set of fast-time simulations with ATC-like mitigations for separation conflicts between UAS and manned IFR aircraft and a set without ATC-like mitigations are then compared to analyze the downstream effects of ATC-like mitigations on the frequency and geometric characteristics of encounters and LoWC between UAS and VFR aircraft. Since the results indicate that ATC-like mitigations for separation conflicts between UAS and manned IFR aircraft do not substantially affect encounters and LoWC between UAS and VFR aircraft (Section IV.B), the remainder of the paper focuses on the simulations without ATC-like mitigations (Section IV.C). First, the locations of encounters and LoWC are analyzed to identify airspaces that are useful environments for conducting research on the selection of parameters for DAA systems. Then, the range and bearing of encounters and LoWC are analyzed to inform the RTCA SC-228 DAA MOPS on the minimum surveillance ranges needed for UAS on-board sensors to detect all encounters and LoWC. Lastly, the results of the research are summarized and their implications for future work are discussed (Section V).

II. Background

The second FAA-sponsored Sense-and-Avoid (SAA) Workshop [2] defined SAA as "the capability of a UAS to remain well clear from, and avoid collisions with, other airborne traffic." The self separation function is intended to be a means of compliance with the regulatory requirements (14 CFR Part 91, §91.111 and §91.113) to "see and avoid" and remain "well clear" of other aircraft. The UAS community has transitioned to using the term "detect and avoid" (DAA) rather than "sense and avoid" with no change in meaning. The rest of this paper uses DAA for consistency.

As part of the RTCA SC-228 effort to develop MOPS for DAA systems, this study analyzes both LoWC and encounters in simulation. The definitions of LoWC and encounter as well as related background information on these separation standards are provided next.

A. Loss of DAA Well Clear

The SAA workshop [2] defined "well clear" as the state of maintaining a safe distance from other aircraft that would not normally cause the initiation of a collision avoidance maneuver by the UAS or any other aircraft. A set of well clear definitions was proposed by a recent FAA report [2], a dedicated U.S. government workshop on well clear [3], and variations on methods utilized by TCAS II [5], [12]. The SAA Science and Research Panel—now known as the UAS Executive Committee (EXCOM) Science and Research Panel (SARP)—coordinated research efforts by the Massachusetts Institute of Technology Lincoln Laboratory, the U.S. Air Force Research Laboratory, and NASA to compare the performance of DAA alerting systems and their potential effect on the NAS when using these well clear definitions. Based on this work, a well clear definition was recommended to RTCA SC-228 and the FAA. After incorporating feedback from both organizations, a consensus on the definition of well clear for UAS was reached.

According to this definition, loss of DAA well clear (LoWC)—which is different than the subjective "well clear" in 14 CFR Part 91, §91.113—is an event in which a UAS is in close proximity with another aircraft such that the following three conditions are concurrently true [1]:

1. $d_h \le d_h^*$ where $d_h^* = 450$ ft
2. $HMD < HMD^*$ where $HMD^* = 4000$ ft
3. $\tau_{\mathrm{mod}} < \tau_{\mathrm{mod}}^*$ where $\tau_{\mathrm{mod}}^* = 35$ sec and $DMOD = 4000$ ft

Fig. 1 illustrates the variables and parameters used to define well clear for UAS: d_h (vertical distance), HMD (horizontal miss distance), and τ_{mod} (modified tau) and its complementary $DMOD$ (distance modification) threshold, each of which will be described in detail in this section. The asterisked variables are thresholds and the non-asterisked variables are measured or projected values. In Fig. 1a and Fig. 1b, the dashed objects are projections of the aircraft. This schematic illustrates an encounter between a UAS flying level heading due east and a manned aircraft flying level heading due west.

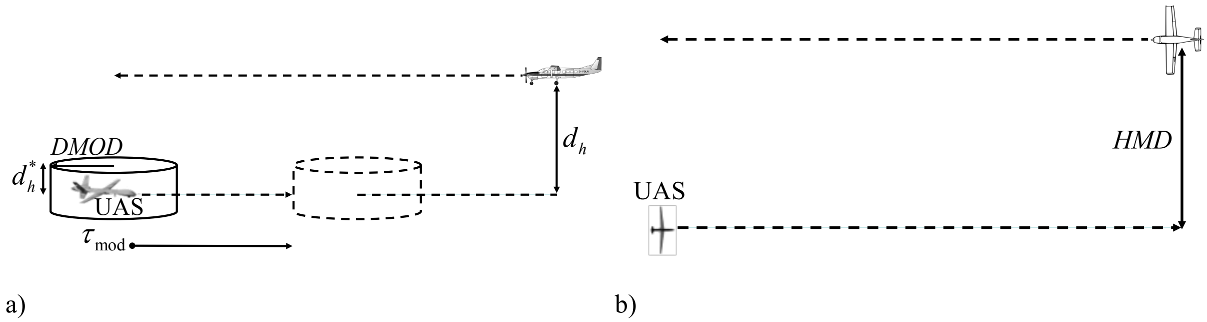


Fig. 1 Schematic of the types of variables and parameters used to define encounter and LoWC (not drawn to scale): a) side view, and b) top-down view.

The LoWC definition uses a spatial separation threshold in the vertical dimension known as d_h^* to which the current vertical separation between the two aircraft is compared:

$$d_h = |h_2 - h_1| \tag{1}$$

The LoWC definition also utilizes a spatial separation metric in the horizontal dimension known as horizontal miss distance (HMD), which is the projected separation in the horizontal dimension at the predicted closest point of approach (CPA) using linear extrapolation in the horizontal dimension:

$$HMD = \begin{cases} \sqrt{(d_x + v_{rx}t_{CPA})^2 + (d_y + v_{ry}t_{CPA})^2} & \text{for } t_{CPA} \geq 0 \\ -\infty & \text{for } t_{CPA} < 0 \end{cases}$$

where

$d_x = x_2 - x_1$ (horizontal separation in the x-dimension)

$d_y = y_2 - y_1$ (horizontal separation in the y-dimension)

$v_{rx} = x_2 - x_1$ (relative horizontal velocity in the x-dimension) (2)

$v_{ry} = y_2 - y_1$ (relative horizontal velocity in the y-dimension)

$$t_{CPA} = -\frac{d_x v_{rx} + d_y v_{ry}}{v_{rx}^2 + v_{ry}^2}$$

Note that v_{rx} and v_{ry} are negative when aircraft are converging

In the example illustrated in Fig. 1, the HMD is the cross-track distance between the UAS and the manned aircraft because the former is flying due east while the latter is flying due west.

The LoWC definition also uses a temporal separation metric known as "modified tau" or τ_{mod} that estimates the time to CPA between two aircraft. Modified tau is adopted from the collision detection logic of the Traffic Alert and Collision Avoidance System (TCAS) [5] that is on board manned aircraft.

Modified tau is based on the concept of "tau" (τ), which is calculated as the ratio of slant range (r) between aircraft to their slant range rate (r) and measured in seconds:

$$
\begin{aligned}
&\tau = -r / r \\
&\text{where} \\
&r = \sqrt{r_{xy}^2 + d_h^2} \\
&r_{xy} = \sqrt{d_x^2 + d_y^2} \\
&\text{Note that } r \text{ is negative when aircraft are converging} \\
&\text{Note that } \tau \text{ is positive when aircraft are converging}
\end{aligned}
\tag{3}
$$

As described in the TCAS II Manual [5], one issue with the tau metric is that the calculated tau can be large even when the physical separation between two aircraft is small if the rate of closure is low (e.g., two flights flying at approximately the same speed, on the same heading, and offset by a small distance). In such a situation, the calculated tau value does not assure adequate separation because a sudden trajectory change that increases the closure rate (e.g., a turn) may cause LoWC. To provide protection for these types of situations, a modified alerting threshold referred to as "modified tau" was developed for use in TCAS II. Modified tau utilizes a parameter known as "distance modification" ($DMOD$) to provide a minimum threat range boundary encircling the ownship aircraft that triggers an alert regardless of the calculated value of tau.

In TCAS II, modified tau ($\tau_{\text{mod\_r}}$) is calculated using slant range (r) and slant range rate (r). By comparison, during the second FAA-sponsored Sense-and-Avoid (SAA) Workshop [2], it was decided that modified tau (τ_{mod}) in the DAA well clear definition be calculated based on horizontal range (r_{xy}) and horizontal range rate (r_{xy}) and measured in seconds as follows:

$$
\tau_{\text{mod}} = \begin{cases} 0 & \text{when } r_{xy} \le DMOD \\ -\dfrac{(r_{xy}{}^{2} - DMOD^{2})}{r_{xy} r_{xy}} & \text{when } r_{xy} > DMOD \text{ and } r_{xy} < 0 \\ \text{inf} & \text{when } r_{xy} > DMOD \text{ and } r_{xy} > 0 \end{cases} \tag{4}
$$

where $DMOD$ is a constant, and

$$
r_{xy} = \frac{d_x \cdot v_{rx} + d_y \cdot v_{ry}}{r}
$$

B. Encounter

An encounter in this study is notionally determined by when and where a DAA system becomes responsible for mitigating a potential threat. Since manufacturers may have differing operational requirements, encounters may be defined in a different way for each DAA system. The RTCA SC-228 safety sub-group came to a consensus to utilize a definition of encounter that is comprised of both temporal and spatial parameters like the definition of well clear while using threshold values that were prior to or outside of the generic volume in which the DAA system becomes responsible for mitigating potential threats.

Encounters are events in which UAS are in proximity with another aircraft such that the following two conditions are true:

1. $d_h \le d_h^*$ where $d_h^* = 2000$ ft
2. $\tau_{\text{mod}} < \tau_{\text{mod}}^*$ where $\tau_{\text{mod}}^* = 100$ sec and $DMOD = 4000$ ft

Note that there will be more encounters than LoWC because the definition of encounter has higher thresholds and does not have an HMD condition compared to the definition of LoWC.

C. Summary of LoWC and Encounter Definitions

Table 1 summarizes the metrics used in the definitions of LoWC and encounter.

Table 1 Metrics used in definitions of LoWC and encounter

	d_h	HMD	τ_{mod}	$DMOD$
LoWC	✓	✓	✓	✓
Encounter	✓		✓	✓

Table 2 summarizes the parameter thresholds used in the definitions of LoWC and encounter.

Table 2 Parameter thresholds for LoWC and encounter

	d_h	HMD	τ_{mod}	$DMOD$
LoWC	450 ft	4000 ft	35 sec	4000 ft
Encounter	2000 ft	N/A	100 sec	4000 ft

III. Methodology

This section describes the two analyses performed to estimate the frequency of encounters and LoWC between UAS and VFR aircraft in NAS-wide simulations and analyze their geometric characteristics for the RTCA SC-228 DAA MOPS. The scope of this study on the interactions between simulated UAS tracks and recorded radar tracks for VFR aircraft operating lower than 18,000 ft mean sea level (MSL) (i.e., under Class A airspace), higher than 500 ft above ground level (AGL) to avoid radar return clutter, and within the continental United States (CONUS) is within the scope of the RTCA SC-228 DAA MOPS.

Analysis 1 compares the encounters and LoWC between UAS and VFR aircraft in two sets of NAS-wide fast-time simulations, one set with modeled ATC-like mitigations for separation conflicts between UAS and manned IFR aircraft and one set without modeled ATC-like mitigations. Since Analysis 1 shows that ATC-like mitigations for separation conflicts between UAS and manned IFR aircraft do not substantially affect encounters and LoWC between UAS and VFR aircraft, Analysis 2 focuses on the simulations without ATC-like mitigations to: 1) identify airspace regions that would be useful for conducting research on selecting parameters for DAA systems, and 2) inform the RTCA SC-228 DAA MOPS of the surveillance ranges needed to detect all encounters and LoWC.

In order to perform these analyses, a series of three different algorithms were applied to historical FAA and air defense radar measurements to pre-process and synthesize them into tracks (Section III.A): 1) minimum-spanning tree clustering [7], 2) Kalman filter-based track association with constant velocity propagation model, and 3) stitching. A fast-time simulation platform [13] known as the Airspace Concept Evaluation System (ACES) was then used to play back the processed VFR tracks while also simulating UAS flights (about 26,500 per day). Each simulated UAS flew one of 18 missions (Section III.B), which were developed by reviewing the literature, interviewing stakeholders and subject-matter experts, and performing socio-economic analysis [6]. The simulated UAS tracks and the VFR playback tracks were then compared to identify instances when encounter and LoWC occurred. This NAS-wide approach to studying interactions between UAS and VFR aircraft is complementary to the pairwise approach of other research efforts that utilized MIT-Lincoln Laboratory's uncorrelated encounter model [14] and correlated encounter model [15].

In the simulations with ATC-like mitigations, manned IFR flights were also simulated based on actual flight schedule and flight plan data (Section III.C). An ATC-like conflict detection and resolution algorithm [10] separated simulated UAS flights from simulated manned IFR flights (Section III.D). The algorithm utilizes heuristics derived from ATC feedback during human-in-the-loop simulations [11].

Table 3 summarizes the preceding description of the simulations that were run for this paper. The remainder of Section III contains additional details on each simulation component in Table 3 as well as the database of airspace boundaries that was utilized to investigate where encounters and LoWC occurred (Section III.E).

Table 3 Summary of simulation components

Simulation	ATC-like mitigation algorithm	VFR tracks (playback)	UAS missions (simulated)	Manned IFR flights (simulated)
Unmitigated		✓	✓	
ATC-mitigated	✓	✓	✓	✓

A. VFR Playback: 84th Radar Evaluation Squadron (RADES) Air Defense Radar Data

The 84th Radar Evaluation Squadron (RADES) at Hill Air Force Base, Utah provided historical FAA and air defense radar measurements. They collect data through the Eastern and Western Defense sectors and provide it to a variety of government entities. They maintain continuous real-time feeds from short-range radars in the interior of the CONUS and long-range air route surveillance radars that cover the perimeter. Four days of traffic data from four different months in 2012 were processed into tracks for use in the simulations conducted for this study: January 11, April 21, July 17, and October 6, 2012. These days were chosen because they did not have adverse meteorological conditions that might impact VFR traffic densities.

A series of algorithms was developed by NASA and its partners to mitigate many of the challenging characteristics in the raw radar data, such as: 1) inconsistent or absent Mode 3/A transponder identification, 2) multiple position reports for the same aircraft from different radar locations, 3) position reports without altitude measurements, 4) asynchronous position reports, and 5) missing position reports. The unique flight characteristics and data availability for cooperative VFR flights (Mode 3/A transponder code of 1200) and non-cooperative VFR flights (no Mode 3/A transponder code) necessitated the development of separate algorithms to process their raw radar measurements into 4-D tracks. (Flights with a Mode 3/A transponder code other than 1200 are treated as IFR flights; these tracks were not played back because IFR flights were modeled in the simulations with ATC-like mitigations based on flight plan information extracted from various NAS messages in ASDI data as described in Section III.C.)

1. Minimum-Spanning Tree Clustering Algorithm

To create tracks for cooperative VFR flights, NASA researchers developed a minimum-spanning tree clustering algorithm [7] for the radar measurements with a Mode 3/A transponder code of 1200. The clustering portion of this algorithm consists of two parts: 1) grouping together radar data that lie within time windows of two minutes in duration, and 2) comparing clusters across consecutive time windows. First, the algorithm gathered all radar measurements in the first two-minute time window of the data set and divided them into groups such that the sum of the distances between radar positions within each group and the distances between groups was minimized. The time window was then moved forward 10 seconds and the process was repeated for the rest of the data set. Second, the algorithm grouped the clusters in consecutive two-minute time windows such that the number of overlapping radar positions in each group of clusters was maximized. Lastly, a Kalman filter was used to smooth each group of radar data into trajectories.

2. Kalman Filter-Based Track Association Algorithm

Honeywell in collaboration with NASA developed a complementary algorithm to process “search only” radar measurements into non-cooperative VFR tracks. “Search only” refers to targets reported by primary radar based on electromagnetic wave reflections that were not reinforced with a beacon sensor report. This algorithm was a Kalman filter-based track association algorithm with constant velocity propagation model to identify and generate tracks from multiple returns. Since primary radar returns do not have altitude information, the algorithm assigned a single cruise altitude to each non-cooperative VFR aircraft trajectory (i.e., climbs and descents were not modeled). The algorithm did this by using a gamma distribution fitted to the altitude data (ft MSL) in the 3D Air Route Surveillance Radar-4 (ARSR-4) returns for non-cooperative VFR aircraft (shape, location, and scale parameters were approximately 3.174, -501.043, and 1593.602, respectively). ARSR-4 radars are used around the borders of the CONUS. This approach makes the assumption that the gamma distribution for altitude constructed from the ARSR-4 returns is representative of the altitude distribution across the entire CONUS.

3. Stitching Algorithm

The clustering and track association algorithms addressed several issues with the raw radar measurements (Table 4), but closer inspection of the VFR trajectories produced by these algorithms found unrealistically short flights caused by dropouts and missing returns in the raw radar measurements. Thus, NASA developed a stitching algorithm that: 1) grouped unrealistically short flight trajectories with other trajectories that were sufficiently close in both time and distance such that a VFR aircraft could realistically fly between them, and 2) merged them using linearly interpolation between the end of one flight trajectory and the start of the other.

Table 4 summarizes the algorithms discussed with regard to their purpose, issues addressed, and issues outstanding. On average, about 24,300 flight hours of VFR tracks were played back per simulation day in this study.

Table 4 Summary of algorithms to process radar data

Sub-section	Algorithm	Purpose	Issues addressed	Issues outstanding
1	Minimum-spanning tree clustering	Process radar data with Mode 3/A transponder code of 1200 into tracks	Inconsistent Mode 3/A transponder identification, multiple position reports for the same aircraft from different radar locations, and position reports without altitude measurements	Unrealistically short flights due to data dropouts and missing returns
2	Kalman filter-based track association	Process radar data without Mode 3/A transponder code into tracks	Same as above and also absent Mode 3/A transponder identification	Same as above
3	Stitching algorithm	Merge short trajectories with other trajectories generated by clustering and track association algorithms	Unrealistically short flight trajectories due to data dropouts and missing returns	Residual noise

B. UAS Missions

The FAA's UAS Integration Concept of Operations (FAA CONOPS) [9] requires UAS to operate under IFR and allows UAS to operate in airspace with manned aircraft. One key challenge for UAS integration into the NAS is that UAS operate and fly differently than most manned IFR aircraft. For instance, while manned IFR aircraft typically fly from origin to destination along fixed airways and jet routes, UAS are expected to fly mission-oriented flight plans that can include many turns and altitude changes within an area. Modeling of projected UAS operations is crucial for accurately estimating the safety provided by DAA systems for UAS operations in the NAS.

Intelligent Automation, Inc. (IAI) in collaboration with NASA developed the set of 18 UAS mission types used in this study [6] that includes nine new UAS missions in addition to the preliminary set of nine UAS missions created for a prior study on DAA alerting and LoWC [4]. These 18 UAS mission types (Table 5) were developed based on literature review and socio-economic analysis as well as interviews with stakeholders and subject-matter experts regarding:

- Flight profile (e.g., route, altitude, takeoff time, duration),
- Payload (sensors, equipment),

- Operational logistics (e.g., number of flights per day, time of day), and
- Aircraft type

Table 5 UAS mission types simulated

UAS mission type	Prior study [4]	Current study
Air quality monitoring	✓	✓
Cargo transport	✓	✓
Flood inundation mapping	✓	✓
Flood stream flow monitoring	✓	✓
Remotely piloted air taxi (Cirrus)	✓	✓
Remotely piloted air taxi (Mustang)	✓	✓
Strategic fire monitoring	✓	✓
Tactical fire monitoring	✓	✓
Weather data collection	✓	✓
Aerial imaging and mapping		✓
Airborne pathogen tracking		✓
Border patrol monitoring		✓
Law enforcement		✓
Maritime patrol monitoring		✓
Point source emission monitoring		✓
Spill monitoring		✓
Traffic monitoring		✓
Wildlife monitoring		✓

As indicated in [4], the characteristics of these missions are consistent with the missions outlined in the FAA CONOPS [9], RTCA DO-320 [16], and a recent Volpe Technical Report [17]. On average, about 26,500 UAS flights were modeled flying a total of about 55,000 hours per simulation day in this study. This is the level of UAS demand projected by socio-economic analysis for 25 years in the future. This projection is based on factors such as gross domestic product and population demographics [6]. The UAS aircraft performance models utilized in the current study were generated from industry data [18] and validated by IAI [6].

Fig. 2 illustrates a sample of the UAS missions simulated in this paper. For instance, the radiator-grid patterns in the western portion of the CONUS are strategic wildfire missions, each of which are 20 hours in duration and modeled as a General Atomics MQ-9 Reaper. In addition, many of the point-to-point trajectories in the eastern portion of the CONUS are remotely piloted air taxi missions that are between 20 and 45 minutes in duration and modeled as Cessna 510 Citation Mustang or Cirrus SR22 aircraft. (See [6] for additional details.)

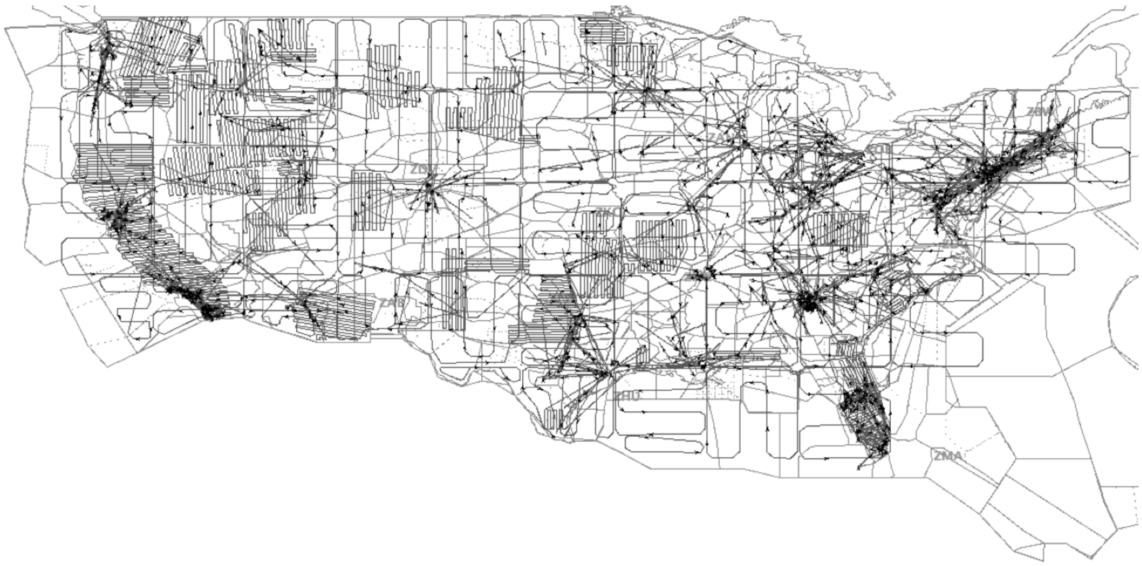


Fig. 2 Sample of simulated UAS missions.

C. IFR Flights: Airspace Situation Display to Industry (ASDI) Data

Manned IFR aircraft were modeled in the simulations with ATC-like mitigations based on the flight demand schedule and flight plan information extracted from various NAS messages in ASDI data. For instance, flight plan route, cruise altitude, and cruise true airspeed data were extracted from the ASDI FZ (Flight Plan Information) message. The last filed flight plan before takeoff for an aircraft was assumed to contain the desired route. On average, about 26,500 UAS flights were modeled flying a total of about 55,000 hours per simulation day in this study.

D. ATC-like Mitigation Model: Autoresolver

Simulated ATC mitigations in this study were provided by a conflict prediction and resolution algorithm known as Autoresolver [10] that utilizes heuristics derived from ATC feedback during human-in-the-loop simulations [11]. Autoresolver issued maneuvers to resolve two types of separation assurance conflicts at the current en route separation standard of 5 nmi horizontally and 1000 ft vertically: 1) predicted conflicts between manned IFR aircraft and UAS aircraft, and 2) predicted conflicts between two manned IFR aircraft. In this study, Autoresolver was configured such that conflict resolution maneuvers also maintained separation of at least 5 nmi horizontally or 1000 ft vertically with all other IFR flights—both manned and unmanned—as well as separation of at least 1.5 nmi horizontally or 500 ft vertically with all other VFR flights to avoid creating new conflicts, encounters, or LoWC. This was assumed to model how air traffic controllers maintain sufficient separation between all aircraft at all times. Encounters and LoWC between UAS and VFR aircraft still occurred in the simulations with ATC-like mitigations because VFR aircraft change their flight paths horizontally and vertically unpredictably on a regular basis.

E. Airspace Class Database

The National Geospatial-Intelligence Agency's Digital Aeronautical Flight Information File (DAFIF) was utilized to categorize encounters and LoWC by airspace class. It contains airspace boundaries defined in terms of latitudes, longitudes, and altitudes for Class B (upside-down wedding cake between the surface and 10,000 ft MSL around the busiest airports), Class C (upside-down wedding cake between the surface and 4000 ft MSL around medium-traffic airports), and Class D (cylinder between the surface and 2,500 ft MSL at smaller airports that have an operational control tower).

Most altitude boundaries in the DAFIF are defined in terms of MSL, but some are defined in terms of AGL. All AGL altitude boundaries were converted to MSL using the U.S. Geological Survey's National Elevation Data [19]-[20].

Encounters and LoWC not within a Class B, C, or D airspace boundary as defined in the DAFIF were categorized as occurring in Class A airspace if the altitude of the UAS was between altitude 18,000 ft and 60,000 ft MSL. Lastly, the rest of the encounters and LoWC were grouped into a "Class E/G" category due to the lack of airspace boundary data for Class E (all controlled airspace not Class A, B, C, or D) and G (uncontrolled airspace) in the DAFIF database.

IV. Results

The first part of this section compares the frequency and geometry of encounters and LoWC between UAS and VFR aircraft in two sets of simulations, one with ATC-like mitigations and the other without ATC-like mitigations. The purpose of this analysis is to assess the extent to which ATC-like mitigations for separation conflicts between UAS and manned IFR aircraft affect encounters and LoWC between UAS and VFR aircraft. Since the results of this analysis found that ATC-like mitigations do not have a substantial impact, the second part of this section focuses on the results of the simulations without ATC-like mitigations in greater detail with regard to: 1) airspaces that could serve as useful environments for conducting research on the selection of parameters for DAA systems, and 2) minimum surveillance ranges needed for UAS on-board sensors to detect encounters and LoWC.

A. Filters

Encounters and LoWC were filtered out of the analysis if the UAS or the VFR aircraft met at least one of the following conditions: 1) position was in class A airspace, 2) time in the ACES simulation was less than two minutes (i.e., pop-up), 3) altitude was less than 10,000 ft and airspeed was greater than 250 kts. The first filter was applied to be consistent with the scope of the RTCA SC-228 DAA MOPS. Typically, UAS will not use DAA systems while in Class A airspace since ATC will separate UAS from all IFR traffic. The second filter was utilized because pre-departure scheduling by ATC would have prevented these situations by ensuring sufficient separation with other aircraft. The third filter was employed because Federal Aviation Regulations do not permit flights below altitude 10,000 ft to fly faster than 250 kts [14 CFR, Part 91, §91.117(a)].

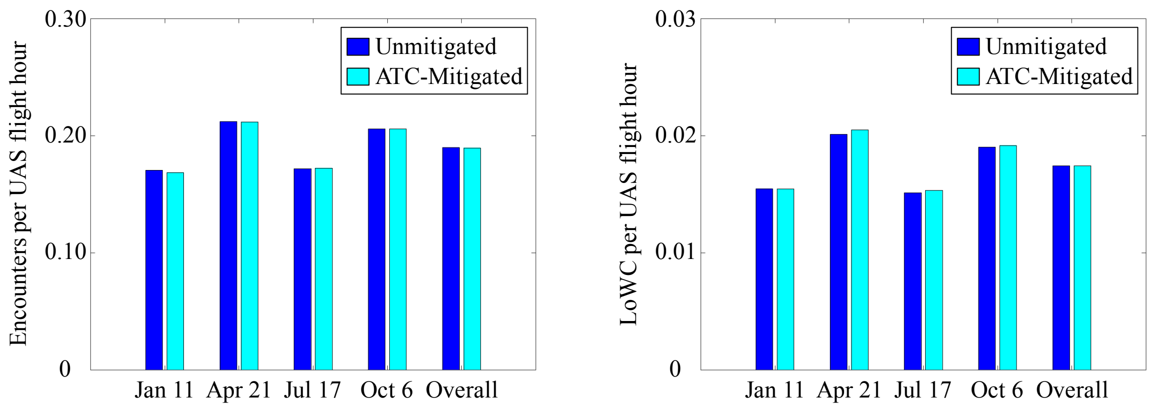
About half of the encounters and LoWC were filtered out of the analysis. Of these, more than 90% were filtered out because they were in class A airspace (filter 1) or they were pop-up events (filter 2) or both. On average, there were about 4900 encounters and 450 LoWC per simulation day in this study.

B. Analysis 1: Effect of ATC-like Mitigations on Encounters and LoWC between UAS and VFR Aircraft

1. Differences in Rates of Encounter and LoWC

Fig. 3a is a plot of the rate of encounters between UAS and VFR aircraft in the simulations without ATC-like mitigations provided by Autoresolver (blue bars) and the simulations with ATC-like mitigations (cyan bars). Fig. 3b is the corresponding plot for LoWC. The rates of encounter and LoWC were calculated by dividing the number of encounter and LoWC boundary crossings, respectively, by the total UAS flight time. Note that the scales of the two charts differ by one order of magnitude.

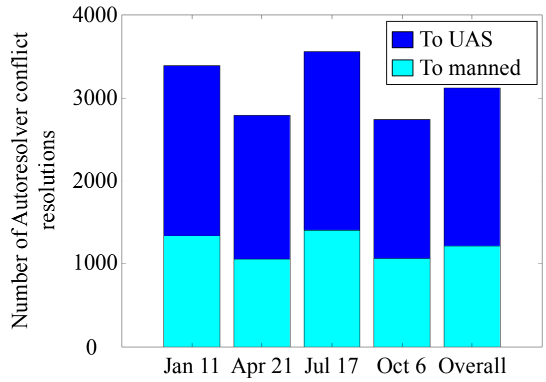
The two plots illustrate that the maneuvers issued by Autoresolver to resolve conflicts between UAS and manned IFR aircraft did not affect the rates of encounter or the rates of LoWC between UAS and VFR aircraft. This result was observed consistently across all four simulation days. As seen in the rightmost set of bars in Fig. 3a, the overall rate of encounters in the simulations with ATC-like mitigations was only 0.2% lower than in the simulations without ATC-like mitigations; both were about 0.19 encounters per UAS flight hour. Furthermore, as seen in the rightmost set of bars in Fig. 3b, the overall rate of LoWC in the two sets of simulations was essentially equal; both were about 0.018 LoWC per UAS flight hour. The results of these simulations indicate that ATC-like mitigations for separation conflicts between UAS and manned IFR aircraft did not affect encounter and LoWC rates between UAS and VFR aircraft.



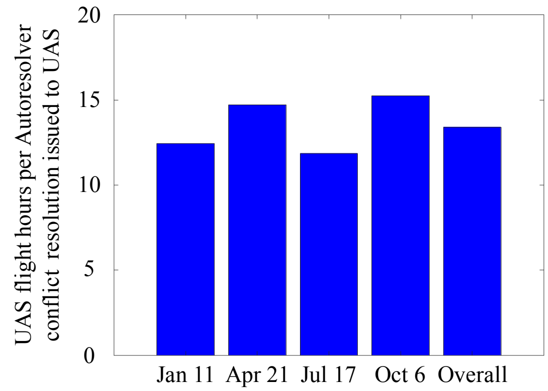
a) b)

Fig. 3 Comparison of rates of a) encounter and b) LoWC between UAS and VFR aircraft by day in simulations without ATC-like mitigations (blue bars) and with ATC-like mitigations (cyan bars).

The rates of encounter and LoWC between UAS and VFR aircraft in the simulations with ATC-like mitigations and the simulations without ATC-like mitigations were essentially the same even though an average of 3100 conflict resolution maneuvers were issued per day of the ATC-mitigated simulations for conflicts between UAS and manned IFR aircraft—61% of which were sent to UAS (Fig. 4a). Overall, Autoresolver issued one resolution to a UAS every 13.4 UAS flight hours (Fig. 4b) for predicted conflicts with manned IFR aircraft.



a)



b)

Fig. 4 a) Number of Autoresolver conflict resolutions issued by day, and b) inverted rate of Autoresolver conflict resolutions issued to UAS by day.

The rates of encounter and LoWC between UAS and VFR aircraft being nearly equal was not necessarily expected because Autoresolver is intended to model how air traffic controllers maintain separation between all aircraft at all times. More specifically, the conflict resolution maneuvers issued by Autoresolver to UAS in the ATC-mitigated simulations to maintain the en route separation standard of 5 nmi horizontally and 1000 ft vertically between UAS and IFR aircraft also preserved separation of at least 1.5 nmi horizontally or 500 ft vertically between UAS and VFR aircraft to avoid creating new encounters and LoWC.

The primary reason for the negligible differences in the rates of encounter and LoWC between the simulations with ATC-like mitigations and the simulations without ATC-like mitigations is that VFR aircraft were usually not in the vicinity of separation conflicts between UAS and manned IFR aircraft. Fig. 5a is a histogram of the horizontal distance between the UAS and the nearest VFR aircraft at the time Autoresolver issued a resolution maneuver to the UAS for conflicts with manned IFR aircraft. It illustrates how conflict resolution maneuvers issued by Autoresolver to UAS typically did not affect potential encounters and LoWC between the UAS and VFR aircraft because they usually were not in the general vicinity of each other. Fig. 5b is the corresponding histogram of the vertical separation between these UAS and VFR aircraft. Overall, only 863 UAS were separated from the nearest VFR aircraft by less than 10 nmi (i.e., the horizontal range needed to detect 99% of encounters as seen in Section IV.C.5) and 2000 ft (i.e., the vertical separation threshold in the encounter definition). Furthermore, even when VFR aircraft were in the vicinity of UAS, it would not necessarily be the case that UAS would be maneuvered in a way that would affect encounters or LoWC with VFR aircraft downstream.

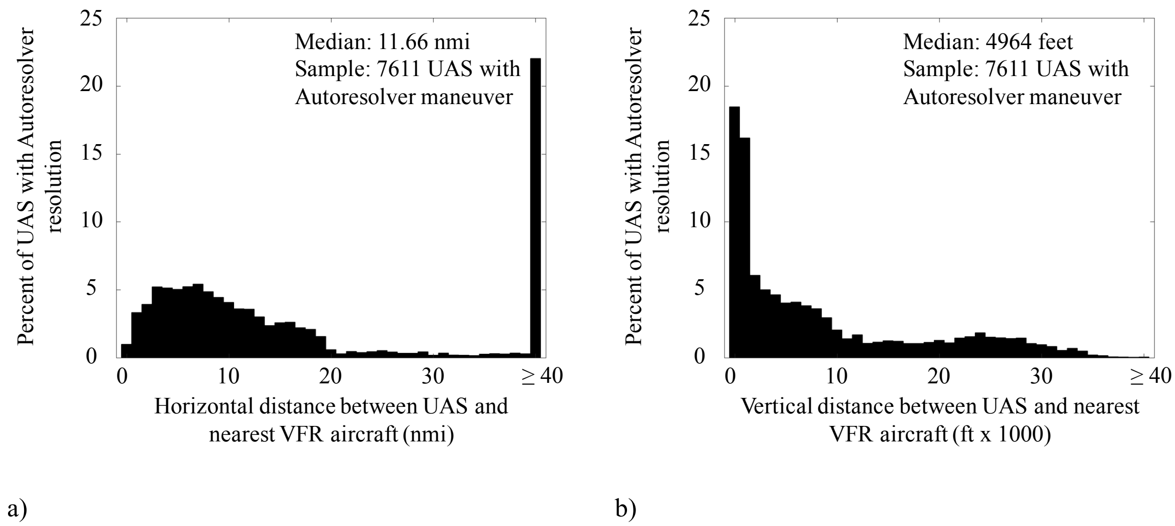


Fig. 5 a) Horizontal distance, and b) vertical distance between UAS and nearest VFR aircraft at time of Autoresolver resolution.

In summary, the analyses in this section demonstrate that ATC-like resolutions issued to UAS for conflicts with manned IFR aircraft had essentially no effect on the rates of encounter and LoWC between UAS and VFR aircraft.

2. Differences in Geometric Characteristics of Encounters and LoWC

The prior analysis demonstrates that ATC-like mitigations provided by Autoresolver for conflicts between UAS and manned IFR aircraft did not affect the rate of encounters or the rate of LoWC between UAS and VFR aircraft. This section explores the extent to which ATC-like mitigations affected the geometric characteristics of those encounters and LoWC. In total, nineteen geometric characteristics at the time of encounter and LoWC were analyzed: seven absolute geometric characteristics each for the UAS and VFR aircraft and five relative geometric characteristics (Tables 6 and 7).

The two-sample Kolmogorov-Smirnov (KS2) test was used to identify which geometric characteristics (if any) were affected by ATC-like mitigations. The KS2 test is a nonparametric hypothesis test that estimates the probability that two data sets come from the same underlying distribution. A small p-value (e.g., less than or equal to 0.05) would indicate that ATC-like mitigations have a statistically significant effect on the geometric characteristic analyzed. These cases require additional investigation to determine whether or not there were any practical differences.

Table 6 contains the p-values of the KS2 test for the nineteen geometric characteristics evaluated at the time of encounter. Eighteen of them were not statistically different at the 10% level or less for any of the four simulation days. Only modified tau was statistically different at the 5% significance level for one simulation day (October 6) and at the 10% significance level for two other simulation days (January 11 and April 21). To investigate the extent to which this statistical difference was practically different, modified tau is plotted in Fig. 6 for the encounters between UAS and VFR aircraft in the October 6 simulation without ATC-like mitigations (blue bars) and in the October 6 simulation with ATC-like mitigations (cyan bars). On this chart, the leftmost group of bars is the percent of encounters between UAS and VFR in which modified tau ranged from 0 sec up to but not including 10 sec, for example.

Fig. 6 illustrates that there were no practical differences between the modified tau distributions in the October 6 simulations. The combination of this result and the KS2 test results indicate that ATC-like mitigations for separation conflicts between UAS and manned IFR aircraft did not significantly affect the geometric characteristics of encounters between UAS and VFR aircraft in the simulations conducted in this study.

Table 7 contains the p-values of the KS2 test applied to the same set of nineteen geometric characteristics at the initial time of LoWC. None of them were even close to being statistically different, which indicates that ATC-like mitigations for separation conflicts between UAS and manned IFR aircraft did not significantly affect the geometric characteristics of LoWC between UAS and VFR aircraft in the simulations conducted in this study.

In summary, the results presented in this section demonstrate that Autoresolver resolutions issued to UAS for conflicts with manned IFR aircraft had almost no effect on the geometry characteristics of encounters and LoWC between UAS and VFR aircraft. Thus, the rest of this paper will focus on analyzing encounters and LoWC between UAS and VFR aircraft in the simulations without ATC-like mitigations for conflicts between UAS and manned IFR aircraft.

Table 6 Two-sample Kolmogorov-Smirnov test p-values for encounters

[Significance Level: (*) 10%, (**) 5%]

Geometric Characteristic	Aircraft	Jan 11	Apr 21	Jul 17	Oct 6
Latitude	UAS	1.000	1.000	1.000	1.000
	VFR	1.000	1.000	1.000	1.000
Longitude	UAS	1.000	1.000	1.000	1.000
	VFR	1.000	1.000	1.000	1.000
Altitude (AGL)	UAS	1.000	0.987	0.998	0.926
	VFR	0.998	1.000	1.000	0.963
Altitude (MSL)	UAS	1.000	0.970	0.955	0.973
	VFR	0.998	1.000	1.000	0.963
Heading	UAS	1.000	1.000	0.998	1.000
	VFR	0.398	0.452	0.838	0.732
Airspeed	UAS	0.664	0.171	0.280	0.208
	VFR	1.000	0.985	0.998	1.000
Vertical speed	UAS	0.948	0.937	1.000	0.944
	VFR	0.903	0.999	0.989	0.997
Modified tau	Both	0.083 (*)	0.070 (*)	0.213	0.022 (**)
Horizontal separation	Both	0.889	0.998	0.995	0.998
Vertical separation	Both	1.000	1.000	1.000	1.000
Horizontal closure rate	Both	0.987	1.000	0.935	1.000
Vertical closure rate	Both	0.995	0.986	0.997	1.000

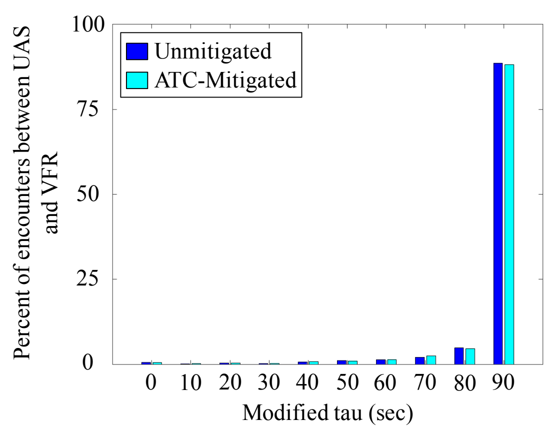


Fig. 6 Comparison of modified tau for encounters in the October 6, 2012 simulation without ATC-like mitigations (blue bars) and in the October 6, 2012 simulations with ATC-like mitigations (cyan bars).

Table 7 Two-sample Kolmogorov-Smirnov test p-values for LoWC

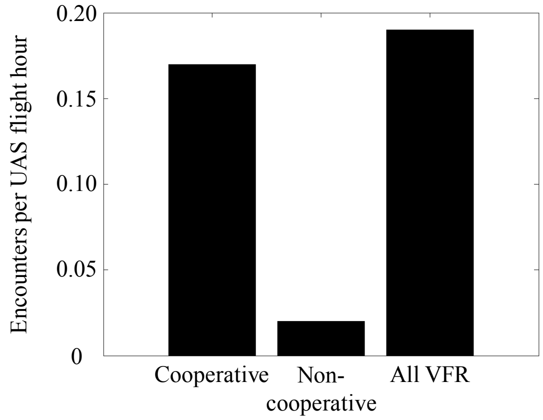
[Significance Level: (*) 10%, (**) 5%]

Geometric Characteristic	Aircraft	Jan 11	Apr 21	Jul 17	Oct 6
Latitude	UAS	1.000	1.000	1.000	1.000
	VFR	1.000	1.000	1.000	1.000
Longitude	UAS	1.000	1.000	1.000	1.000
	VFR	1.000	1.000	1.000	1.000
Altitude (AGL)	UAS	1.000	1.000	1.000	1.000
	VFR	1.000	1.000	1.000	1.000
Altitude (MSL)	UAS	1.000	1.000	0.996	1.000
	VFR	1.000	1.000	1.000	1.000
Heading	UAS	0.999	0.999	1.000	1.000
	VFR	1.000	1.000	1.000	1.000
Airspeed	UAS	1.000	1.000	0.999	1.000
	VFR	1.000	1.000	0.981	1.000
Vertical speed	UAS	0.990	0.990	0.993	0.996
	VFR	0.996	0.996	1.000	1.000
Modified tau	Both	0.946	0.946	0.995	0.999
Horizontal separation	Both	0.952	0.952	0.943	1.000
Vertical separation	Both	1.000	1.000	1.000	1.000
Horizontal closure rate	Both	0.998	0.998	0.991	1.000
Vertical closure rate	Both	0.999	0.999	1.000	1.000

C. Analysis 2: Informing the Development of Requirements in the RTCA SC-228 DAA MOPS

1. Rates of Encounter and LoWC by VFR Type

Fig. 7a is a plot of the rates of encounter between UAS and VFR aircraft in the four simulation days without ATC-like mitigations. Overall, there were about 0.17 encounters between UAS and cooperative VFR aircraft per UAS flight hour, which equates to about one encounter every 5.9 UAS flight hours. In addition, encounters between UAS and non-cooperative VFR aircraft occurred at a rate of about one every 49.7 UAS flight hours. Overall, UAS encountered VFR aircraft about once every 5.3 UAS flight hours. As illustrated in Fig. 7b, the overall rate of LoWC between UAS and VFR aircraft was about one order of magnitude lower at one every 57.3 UAS flight hours.



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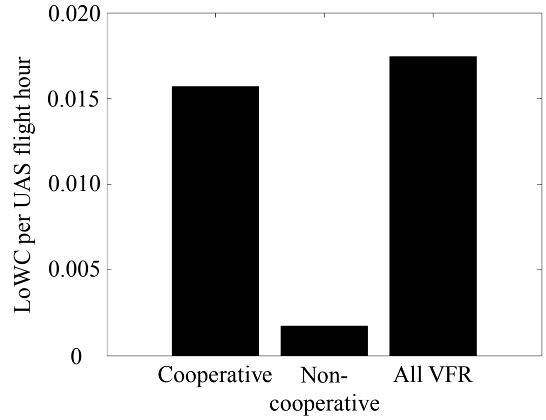
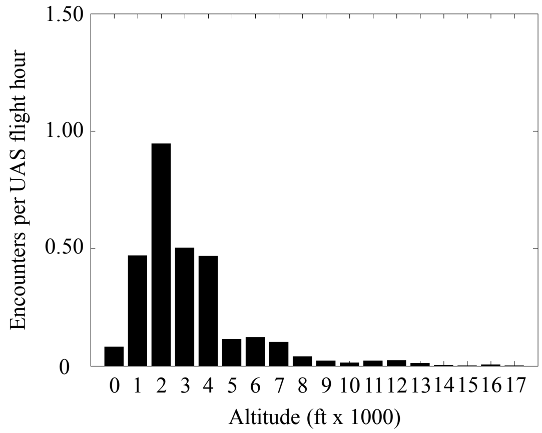


b)

Fig. 7 a) Encounters, b) LoWC per UAS flight hour between UAS and VFR aircraft by VFR type.

2. Rates of Encounter and LoWC by Altitude Band

Fig. 8a and Fig. 8b illustrate the rates of encounter and LoWC, respectively, between UAS and VFR aircraft by altitude bands of 1000 ft (e.g., the leftmost bar of Fig. 8a is the encounter rate in the altitude band from 0 ft up to but not including 1000 ft). Encounter and LoWC rates were both highest at altitudes below 5000 ft. This result indicates that altitudes below 5000 ft are a useful environment for conducting research on the selection of parameters for DAA systems. This result was driven by where VFR flights currently operate as recorded in the RADES radar data (Section III.A) and where UAS missions are projected to be (Section III.B).



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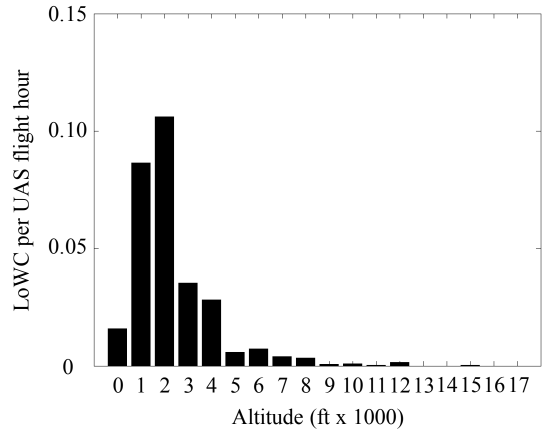


b)

Fig. 8 a) Encounters, b) LoWC per UAS flight hour between UAS and VFR aircraft by altitude band.

3. Distribution of Encounters and LoWC by VFR Type

Fig. 9 is a plot of the number of encounters and LoWC during the four unmitigated simulation days by type of VFR aircraft. The rightmost bar is the overall number of encounters between UAS and VFR aircraft. The blue part of this bar represents the encounters that did become LoWC while the cyan part represents the encounters that did not become LoWC. During the four days of unmitigated simulations, there were a total of 19,494 encounters between UAS and VFR aircraft, of which 9.2% also became LoWC.

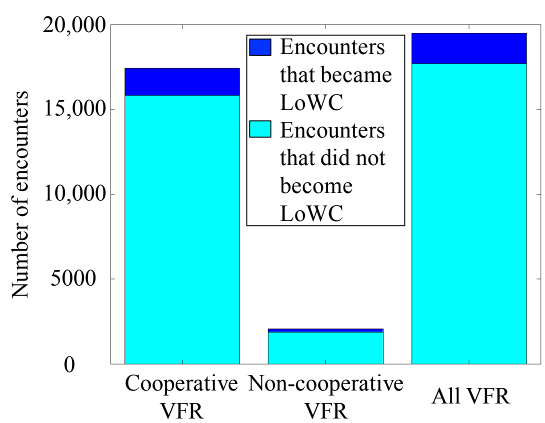
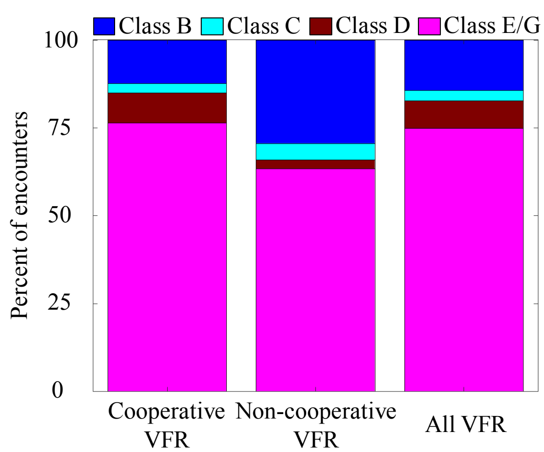


Fig. 9 Number of encounters and LoWC by VFR type.

4. Distribution of Encounters and LoWC by Airspace Class and VFR Type

Fig. 10a and Fig. 10b illustrate the proportion of encounters and LoWC, respectively, between UAS and VFR aircraft that occurred in each class of airspace during the four unmitigated simulation days. It is possible for these safety-critical events to occur between UAS and non-cooperative VFR aircraft in these airspaces since the latter can be exempted from the transponder requirement (e.g., if the aircraft does not have a certified engine-driven electrical system).

The magenta portions of each bar indicate that most encounters and LoWC occurred in Class E/G airspace as expected based on where UAS missions are projected to be (Section III.B). However, there were differences in the proportions of encounters and LoWC that occur in Class B, C, and D airspaces, respectively. For instance, there were more encounters between UAS and VFR aircraft in Class B airspace (blue portion of the rightmost bar in Fig. 10a) than in either Class C or Class D. By comparison, there were more LoWC in Class D airspace (maroon portion of the rightmost bar in Fig. 10b) than in either Class B or Class C. Combined, these results indicate that encounters in Class D airspace were more likely to become LoWC than encounters in Class B airspace in this study.



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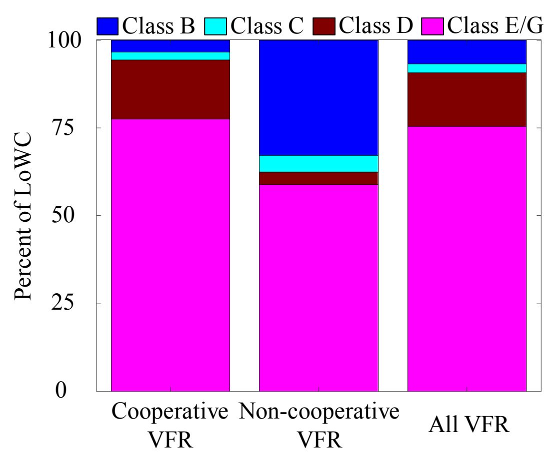


b)

Fig. 10 Percent of a) encounters, b) LoWC between UAS and VFR aircraft by airspace class and VFR type.

Fig. 11 plots the percentage of encounters between UAS and VFR aircraft that became LoWC by airspace class in the simulations without ATC-like mitigations. The percentage was lowest in Class B airspace (blue bar) at about

4.3% (130 out of 2998). By comparison, it was highest in Class D airspace (maroon bar) at about 15.3% (288 out of 1880). That is, encounters in Class D airspace became LoWC about three-and-a-half times as often as encounters in Class B airspace. These results indicate that Class D airspace is a useful environment for conducting research on the selection of parameters for DAA systems.

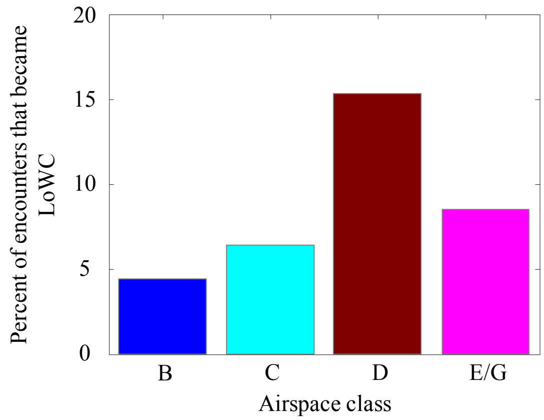


Fig. 11 Percentage of encounters that became LoWC by airspace class.

5. Range and Relative Heading at Initial Time of Encounter and LoWC

Besides researching the safety aspect of integrating UAS into the NAS, RTCA SC-228 is also defining MOPS requirements for the surveillance aspect of DAA systems. As part of this work, this section investigates the range needed to detect all instances of encounters and LoWC in the simulations without ATC-like mitigations. Fig. 12a is a histogram of the range between UAS and VFR aircraft at the initial time of encounter in these simulations. It shows that a minimum surveillance range of 14.32 nmi was needed to detect all encounters between UAS and VFR aircraft in this data set. Fig. 12b is a histogram of the range between UAS and non-cooperative VFR aircraft at the initial time of encounter. It indicates that radar systems on board UAS needed a minimum surveillance range of 13.59 nmi to detect all encounters involving non-cooperative VFR aircraft in this data set.

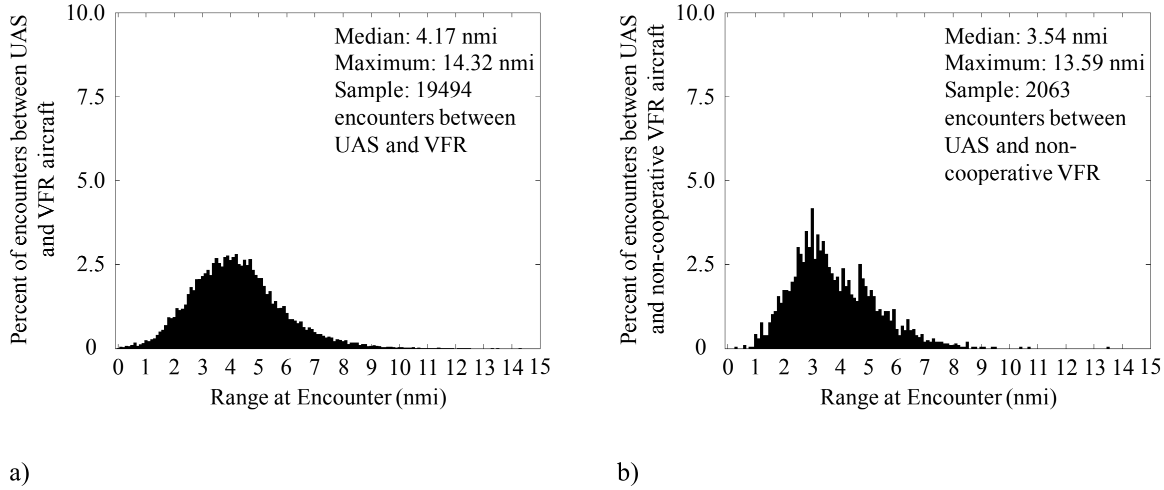
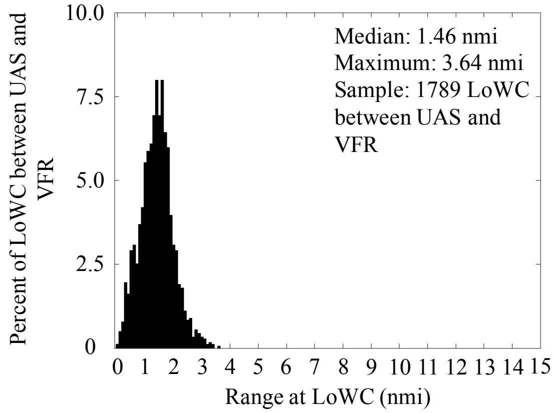


Fig. 12 Range at initial time of encounter between UAS and: a) all VFR aircraft, b) non-cooperative VFR aircraft.

Fig. 13a is the corresponding histogram of the range between UAS and VFR aircraft at the initial time of LoWC in the simulations without ATC-like mitigations. It shows that a minimum surveillance range of 3.64 nmi was required to detect all LoWC in these simulations. Fig. 13b is a histogram of the range between UAS and non-cooperative VFR aircraft at the initial time of LoWC. It indicates that radar systems on board UAS needed a minimum surveillance range of 2.49 nmi to detect all LoWC involving non-cooperative VFR aircraft in this data set. Larger surveillance ranges than these minimums are needed to account for the time required for the DAA tracking, alerting, and guidance processes as well as coordination with ATC and uncertainty (e.g., unexpected maneuvers by VFR aircraft).



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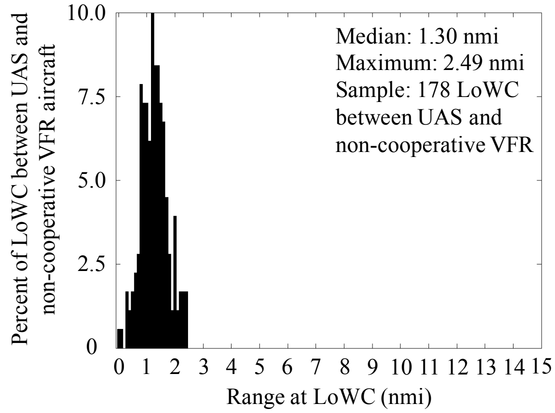

b)

Fig. 13 Range at initial time of LoWC between UAS and: a) all VFR aircraft, b) non-cooperative VFR aircraft.

Fig. 14a and Fig. 14b are plots of the range (nmi) and bearing (15-degree bins) between UAS (ownship shown flying due east) and VFR aircraft at the initial time of encounter and LoWC, respectively. They illustrate the contours within which 99% (blue), 90% (cyan), 80% (maroon), and 60% (magenta) of the data were located. For instance, the blue contour in Fig. 14a shows the distances needed to detect 99% of encounters between UAS and VFR aircraft that were located in front (0°), in back (180°), on the right (90°), and on the left (270°) of the UAS. As expected, the shapes of the contours indicate that UAS entered into both encounter and LoWC at much further ranges with VFR aircraft that were located in front of the UAS as indicated by the portion of the contours around 0° (e.g., due to head-on cases) compared to VFR aircraft that were located on the sides or behind the UAS.

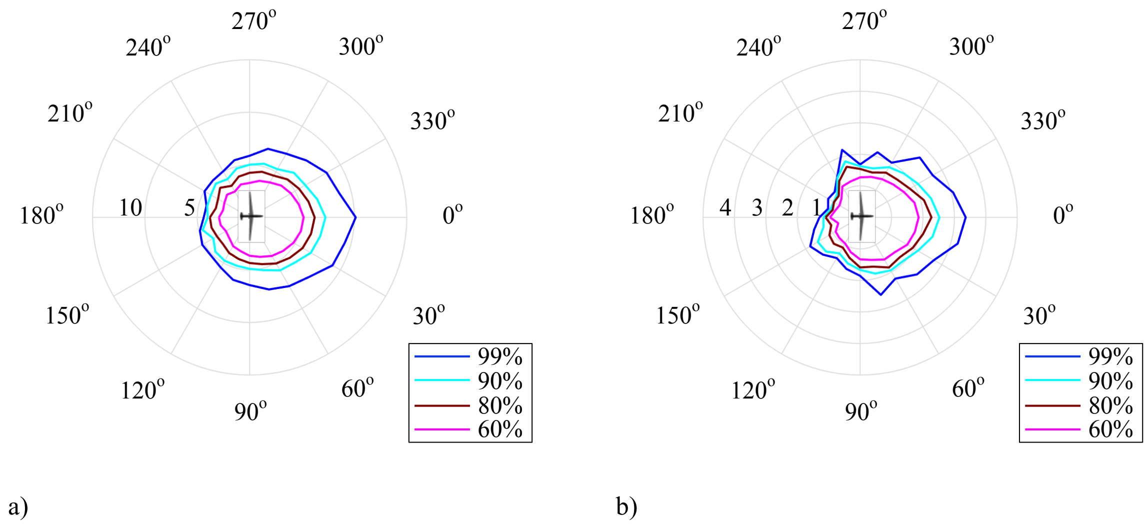

Fig. 14 Range (nmi)-bearing plots between UAS ownship and VFR in: a) encounters, b) LoWC.

V. Conclusion

RTCA SC-228 is developing minimum operational standards for DAA systems that will enable UAS to fulfill the see-and-avoid requirement to preserve well clear separation from other aircraft—both manned and unmanned. As part of that effort, this study measured the rates of encounter and LoWC between UAS and VFR aircraft in NAS-wide simulations for four days in 2012. Running additional days of simulation in follow-up work would improve the statistical accuracy of these rate estimates and expand the set of safety-critical interactions that would be available for follow-up studies to inform the alerting, guidance, surveillance, and other aspects of the MOPS for UAS DAA systems.

Besides the rates of encounter and LoWC between UAS and VFR aircraft that were estimated, one of the main takeaway results from this study is that ATC-like mitigations for conflicts between UAS and manned IFR aircraft did not substantially affect the rates of encounter and LoWC between UAS and VFR aircraft or the geometric characteristics of these safety-critical events. Although the Autoresolver algorithm that provided ATC-like mitigations in this study utilized heuristics derived from ATC feedback in human-in-the-loop simulation, it is important to verify the results of this study with other separation assurance conflict resolution algorithms in follow-up work.

Furthermore, even though ATC-like mitigations for conflicts between UAS and manned IFR aircraft did not substantially affect the interactions between UAS and VFR aircraft, it does not necessarily ensure that the conflict resolutions issued by ATC will be compatible with the guidance provided by UAS DAA systems. As such, it is also important to conduct follow-up research to develop methods that ensure interoperability between separation assurance conflict resolutions sent by ATC, guidance provided by DAA systems on board UAS, and resolution advisories issued by TCAS systems on board manned and unmanned aircraft.

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