Analysis of Conflicts among Urban Air Mobility Aircraft and with Traditional Aircraft

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***Abstract*—This paper provides an initial analysis of conflicts among Urban Air Mobility aircraft and with traditional aircraft based on fast-time simulations of 20 full-day scenarios. Several sets of separation minima with added performance-based separation are applied, and the resulting separation conflicts are classified. Safety metrics relevant to separation standards are evaluated. The results shed light on future performance-based separation standards and safety metrics for separation standards involving Urban Air Mobility aircraft.**

***Keywords*—urban air mobility, separation standards, conflict detection, safety metric, performance-based separation**

I. Introduction

Urban Air Mobility (UAM) is an emerging concept that uses electric Vertical Take-Off and Landing (eVTOL) aircraft for transporting people and goods around metropolitan areas [1]. UAM aircraft would conduct frequent short-distance flights carrying two to six passengers in low-altitude airspace as a practical and cost-effective mobility alternative for the general public as cities grow [2,3].

To integrate UAM operations into the National Airspace System, it is important to study the safety of UAM operations and UAM interactions with traditional aircraft operating under Instrument Flight Rules (IFR) or Visual Flight Rules (VFR). Eventually separation standards for UAM aircraft and for UAM versus traditional aircraft can be established.

While traditional separation standards for IFR and VFR flights were developed empirically, based on experience and judgement of operations experts, recent Detect-And-Avoid (DAA) Well Clear (DWC) separation standards for Unmanned Aircraft System (UAS) have been based on research efforts that evaluate many operational suitability metrics such as crosstrack deviation and mitigated risk ratio [4,5]. Without historical UAM traffic data, simulated scenarios of the envisioned traffic density must be used to evaluate suitable metrics for UAM.

As a first step, this paper focuses on evaluating conflicts among UAM aircraft and with traditional aircraft to understand appropriate safety metrics for separation standards. Fast-time simulations are done with 20 air traffic scenarios in Dallas Forth-Worth (DFW) Terminal Radar Approach Control (TRACON) airspace. The UAM traffic density is at the scale of UAM Maturity Level (UML) 4, which represents more than 100 simultaneous UAM operations in a metropolitan area [2]. A few safety metrics for several sets of separation minima are studied. The main contributions of this paper are that it helps to understand various conflicts among UAM aircraft and with traditional aircraft; it demonstrates an approach to UAM performance-based separation; it provides an evaluation of collision risks involving UAM aircraft; and it provides a study on a new metric of time available before maneuvering to avoid loss of separation for evaluating separation minima.

The rest of this paper is organized as follows. Sec. II describes the scenarios in detail. Sec. III explains the approach. Sec. IV presents the results and discussions. Sec. V summarizes the conclusions and future work.

II. Traffic Scenarios

The traffic scenarios for DFW TRACON (D10) in this study are obtained by merging UAM scenarios at UML-4 scale, confined by proper airspace constraints and route structure, with real-world scenarios of traditional air traffic. The scenarios are the input to a fast-time simulation program.

A. UAM Traffic Scenario

The UAM scenarios have high fidelity since they contain UAM trajectories that take into account DFW demand estimates, airspace constraints, and UAM route structure. The trajectories only provide updates on current aircraft states in the fast-time simulation of the scenarios. No future states are used for conflict detection and resolution.

Demand estimates for UAM flights in the DFW region were developed by the Virginia Tech Air Transportation Systems Laboratory for NASA using a mode-choice model for commuter trips [6]. They are based on an economic assessment of the demand for UAM in the region using cost assumptions appropriate for technological advances 15 to 20 years hence.

In order to procedurally deconflict UAM flights from IFR traffic, NASA designed a set of airspace constraints and UAM routes, as depicted in Fig. 1. The Class B airspace extends to the ground around DFW and Dallas Love Field (DAL) airports. To minimize interaction between UAM operations and Air Traffic Control (ATC), it is required for UAM flights to avoid the Class B airspace. NASA designed a UAM route network for the DFW area that contains narrow paths or corridors through the Class B airspace. The UAM routes are designed to avoid wake turbulence due to the South-Flow IFR traffic at

DFW. A formal route structure is not required in Class E/G airspace, where flights can fly direct paths between their departure and arrival vertiports. Parallel routes have been chosen with a centerline separation of mostly 1500 ft. This is inspired by the primary route width [7] of 0.2 nmi plus a 300-ft buffer for Required Navigation Performance (RNP) 0.1. This does not assure that, without additional separation requirements, aircraft with RNP 0.1 is safe enough to operate on such parallel routes though. A much safer route separation would be twice the containment limit [8] of a route; that is, 4 x RNP value = 0.4 nmi for RNP 0.1. This 2400-ft route separation could limit the UAM capacity. Fig. 1 shows the airspace constraints, vertiports, and route structure. The airspace constraints are shown in yellow. The small green squares represent vertiports. The route structure is indicated by the cyan lines and is defined by the intersections labeled in magenta. A more recent enhanced design can be found in [9].

Fig. 1. Airspace constraints, vertiports, and route structure at DFW.

UAM trajectories are produced in the Advanced Trajectory Services – Toolkit for Integrated Ground and Air Research (ATS-TIGAR) [10,11]. The UAM flights are distributed across vertiports using a demand set for origin and destination passenger trips. An aircraft is selected by a fleet management based on earliest available time from a nearby vertiport when creating clearing or repositioning flights. A clearing flight is one that is being removed from a vertiport full of parked aircraft so that space become available for a landing flight. A repositioning flight is one that is being moved to the origin vertiport that is not available at the time the trip is planned. The flight routing logic uses a search algorithm that selects routes based on shortest path through the route network. A total of 50 vertiports are used. The number of possible routes in the network is equal to the possible origin-destination vertiport pairs. The vertiport scheduling ensures that no two vehicles occupy the same resource during the same time window, so no overlapping reservations are permitted on the vertiport scheduling timelines. The fleet management ensures that no fleet vehicle could support multiple operations at once, and that there is continuity of operations from vertiport to vertiport for any fleet aircraft.

Two UAM scenarios are generated and used in this analysis. Each is 24 hours long, one with and the other without Pre-departure Conflict Detection and Resolution (PCDR). PCDR includes predeparture delays and lateral, speed, and altitude maneuvers that deviate the aircraft from the nominal flight plans to avoid conflicts based on the horizontal and vertical separation minima of 1200 ft and 500 ft, respectively. The 1200-ft horizontal minimum is inspired by the primary route width of 0.2 nmi for RNP 0.1. Note that this could be violated for two UAM flights on parallel routes with the 1500-ft centerline separation when deviations from the centerline are still within the primary route width. The flight identifiers in the scenarios differ as they are not directly related except that the same demand set is used. The scenario without PCDR contains 9973 flights and the one with PCDR contains 10115 flights. The numbers are different because the UAM trajectories are different. The deconfliction is not done near the vertiports because the horizontal separation minimum there would be much smaller than 1200 ft. The trajectories are represented as discretized positions at one-second intervals. PCDR is expected to reduce the number of conflicts observed for that scenario. Another difference between the two scenarios is that the UAM state updates for the scenario without PCDR adhere more closely to the original flight plans than those for the scenario with PCDR, which deviate more frequently from the flight plans. Typical flow rates for both arrival and departure at a vertiport is between 30 and 50 per hour with one busy vertiport modeled with a high flow rate of 80-112 departures and arrivals per hour for two periods of 4 to 5 peak hours.

B. Traditional IFR/VFR Traffic Scenario

Twenty input scenarios were generated by merging 10 “traditional traffic” scenarios of recorded real-world IFR and VFR operations within D10 with the two UAM scenarios. Ten typical days (i.e. pre-pandemic) from June through August of 2019 were selected; five with DFW in a South-Flow (SF) configuration, three with DFW in a North-Flow (NF) configuraton, and two with DFW switching between NF and SF configurations. Typically, less than 15% are NF days at DFW. The real-world air traffic data including the flight plans were obtained from the NASA Sherlock Data warehouse [12]. UAM traffic was added to each of the 10 selected traditional traffic scenarios starting at midnight DFW local time. The recorded real-world traffic included IFR, VFR, and unassociated (UNA) flights.

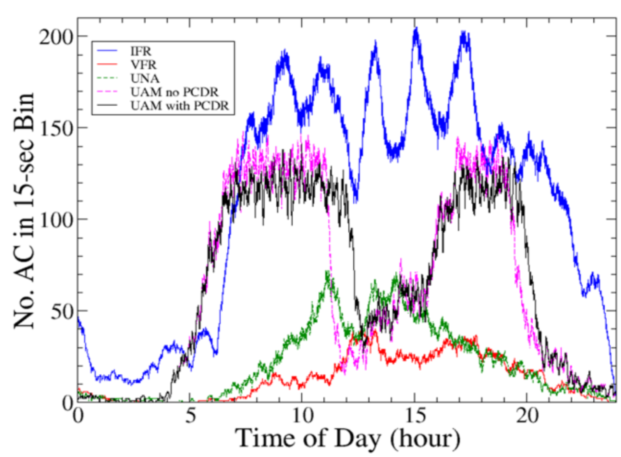

Fig. 2. Simutaneous operations for recorded real-world air traffic at D10 on June 21, 2019 and the UAM scenarios with and without PCDR.

The number of simultaneous operations for different types of flights displays similar patterns of peaks during the day for different days. The more overlap among the peaks, the more likely the aircraft may be in conflict. Fig. 2 shows the number of simultaneous operations per 15-second bin for one of the selected days with different types of flights separated. The UAM flights show two daily demand peaks, which overlap well with different types of real-world flights and thus should yield representative conflicts between UAM and traditional flights. The UAM flights with and without PCDR are shown in the same figure for comparison, but they do not fly simultaneously in the same scenario. PCDR induces delays that slightly flatten and broaden the demand peaks without changing the general demand profile.

III. APPROACH

Conflicts among UAM aircraft and with traditional aircraft are first generated from playing back each of the input scenarios in a fast-time simulation environment while using only the flight plans and current states of the flights but not information on future states. Selected sets of separation minima are used. A conflict is defined as a projected loss of separation (LOS) with another aircraft. The generated conflicts are then classified based on the LOS locations on the flight-plan routes. Several safety metrics for the conflicts are then evaluated.

A. Separation Minima

The separation minima between two IFR flights or an IFR and a VFR flight in Class B airspace are specified in FAA Order JO 7110.65Z [13]. If UAM flights were considered VFR in Class B airspace, the required separation minima with traditional IFR/VFR aircraft that weigh greater than 19000 lb and turbojets needs to be 1.5 nmi horizontally and 500 ft vertically. There is no required minimum among VFR flights.

To simulate the scenarios and analyze the conflicts, we choose four sets of separation minima for two UAM aircraft with the horizontal/vertical separation minima of 500 ft/100 ft, 1200 ft/500 ft, 1800 ft/500 ft, and 2200 ft/450 ft. The last set corresponds to the UAS DWC criteria. A loss of separation occurs when both the horizontal and vertical separations are violated. The choices are not intended to cover the spectrum of possible minima for an eventual UAM separation standard. Instead, they are chosen to foster an understanding of UAM conflicts. They are near the horizontal separation of 1200 ft that the PCDR uses for conflict detection and resolution. Four sets of separation minima between UAM and traditional IFR/VFR flights are also chosen, which are horizontal/vertical separation minima of 500 ft/100 ft, 0.6 nmi/500 ft, 1 nmi/500 ft, and 1.5 nmi/500 ft. Wake turbulence requirements [13] with UAM aircraft categorized in the "small" weight class, are also imposed. The 500 ft/100 ft separation minima are for Near Mid-Air Collisions (NMACs).

Performance-based separation (PBS) will be discussed and applied to aircraft on parallel routes or near origin and destination vertiports. Also, aircraft on diverging courses [13] are not eligible to be considered as being in conflict.

B. Methods

Each of the 20 scenarios of UAM and traditional flights is played back with a fast-time simulation program called Terminal Tactical Separation Assured Flight Environment (T-TSAFE) [14,15]. T-TSAFE models the actions of an air traffic controller in that it may detect tactical conflicts and prescribe resolution maneuvers with a look-ahead time of approximately two minutes. (Note: For the purposes of this study, only conflict detection was needed; conflict resolution was inhibited.) At each track update, T-TSAFE is given the current states of all active aircraft and their available flight plans. It is not provided any future states; instead, it infers the future states within the look-ahead time based on available flight intent information. In other words, T-TSAFE makes a trajectory prediction for a period equal to the look-ahead time. The predictions are based on a single deterministic trajectory built upon the available flight intent information and current states of the aircraft, including the conformance of the states with the flight intent routes. The conflict detections are based on the precise separation minima with no additional buffers. Thus, uncertainties in the states and in the flight intent information, current deviations from the intent routes, and the separation minima all affect the detection.

Flight intent information for the UAM flights includes the flight plans, which are the origin-destination (OD) routes uniquely selected from the route structure and are part of the adaptation files for T-TSAFE. Flight intent information for the real-world air traffic is within the traffic data in the scenarios with waypoints and detailed nominal interior routes of IFR flights from the DFW adaptation [14,15]. As mentioned earlier, the UAM tracks without PCDR follow the OD routes closely by construction. However, the deviations of the tracks with PCDR from the intended OD routes introduce uncertainties in T-TSAFE trajectory predictions and conflict detection.

The conflicts are classified by phase of flight, origin and destination vertiports, and departure or arrival airports for IFR flights, and are analyzed with the safety metrics discussed in the next section.

C. Conflict Classification

1) UAM Flight Phases

The phases of flight for UAM aircraft are defined in terms of the OD routes for conflict classifications. A UAM OD route consists of a set of waypoints that may have speed and altitude restrictions except for one or more waypoints close to the origin and destination vertiports. The speed restrictions in the scenarios typically equal the cruise speed of 130 knots and the altitude restrictions equal the cruise altitude of 1100 ft or 1600 ft. The waypoint names without speed and altitude restrictions begin with letter "Z", which is followed by numbers. Table 1 shows a flight plan with waypoints separated by double dots. The flight phases are departure, enroute, and arrival. The departure phase is defined by the route segments from the origin vertiport to the first (non-Z) waypoint. The enroute phase is defined by the route segments from the first non-Z waypoint to the last non-Z waypoint before the arrival vertiport. The arrival phase is defined by the route segments from the last non-Z waypoint to the destination vertiport.

TABLE I. AN EXAMPLE FLIGHT PLAN AND THE PHASES OF FLIGHT

Name	Route String
OD Route	"DF14..Z302..CW16..CW08..CW09..BW03..CW10..BW04..CW11..CW12..BW13..Z284..DF4"
Departure Phase	"DF14..Z302..CW16"
Enroute Phase	"CW16..CW08..CW09..BW03..CW10..BW04..CW11..CW12..BW13"
Arrival Phase	"BW13..Z284..DF4"

TABLE II. CLASSIFICATION OF UAM-UAM CONFLICTS

Class	Setup of Aircraft Pair at LOS
DDSV	Departure vs Departure of Same origin Vertiport
DDDV	Departure vs Departure of Different origin Vertiport
DASV	Departure vs Arrival of Same origin and destination Vertiport
DADV	Departure vs Arrival of Different origin and destination Vertiport
DE	Departure vs Enroute
AASV	Arrival vs Arrival of Same origin Vertiport
AADV	Arrival vs Arrival of Different arrival Vertiport
AE	Arrival vs Enroute
CEE	Corridor-track Enroute vs Enroute for parallel routes with both aircraft being in conformance
NCEE	Non-CEE: Enroute vs Enroute with same route, or non-parallel routes, or parallel routes with one or both aircraft being out of conformance

2) UAM-UAM conflicts

To analyze the conflicts between a pair of UAM flights for various separation minima for different scenarios, we first group them by class. The UAM-UAM conflicts are classified based on the three flight phases of UAM flights at the location of projected first LOS. The classes are defined in Table II.

Note that the CEE and NCEE conflicts are distinguished so as to apply performance-based separation on them as they may occur in future UAM corridor tracks. The conformance in the CEE and NCEE definitions means the aircraft are within the primary route width of 0.1 nmi RNP value. As mentioned in Sec. II.A, the UAM route structure as modeled for this study contains routes that are parallel and are separated by 1500 ft, which may not be adequate for independent parallel conformed flights. A more adequate separation of 2400 ft might be desired, but that could limit the airspace capacity too much. For the purpose of demonstrating PBS, the horizontal/vertical separation minima of 1200 ft/500 ft will be used for CEE encounters even when general separation minima are higher. This is similar to IFR dependent final approaches along parallel localizers [13]. Reduced separation for the encounters with same departure and/or arrival vertiports should be applied as well since expected procedural separations near a vertiport are implied but not enforced in the UAM scenarios.

3) UAM–Non-UAM Conflicts

Conflicts between UAM and traditional flights of various types are similarly classified according to the UAM flight phases and the flight types of IFR, VFR, helicopter, and unassociated (UNA). UNA flights do not have flight plans associated with them and cannot be identified with call signs. The helicopter (HELO) type is separated out of the VFR type because of their similarity to UAM flights and (as will be presented in Sec. IV) the large number of LOSs involving them. For IFR flights to and from major airports we further separate them into departure and arrival flights. Major airports for D10 are DFW and DAL. The relatively small number of flights and less available flight intent information for the remaining 29 small non-major airports at D10 justify their being categorized together separately from those at DFW and DAL. Table III shows the classes for the conflicts between UAM and non-UAM flights.

TABLE III. CLASSIFICATION OF UAM–NON-UAM CONFLICTS

Class	Setup of Aircraft Pair at LOS
DU	Departure UAM vs UNA
AU	Arrival UAM vs UNA
EU	Enroute UAM vs UNA
DH	Departure UAM vs HELO
AH	Arrival UAM vs HELO
EH	Enroute UAM vs HELO
DV	Departure UAM vs VFR
AV	Arrival UAM vs VFR
EV	Enroute UAM vs VFR
DMD	Departure UAM vs Major-airport IFR Departure
AMD	Arrival UAM vs Major-airport IFR Departure
EMD	Enroute UAM vs Major-airport IFR Departure
DMA	Departure UAM vs Major-airport IFR Arrival
AMA	Arrival UAM vs Major-airport IFR Arrival
EMA	Enroute UAM vs Major-airport IFR Arrival
DNM	Departure UAM vs Non-major-airport IFR
ANM	Arrival UAM vs Non-major-airport IFR
ENM	Enroute UAM vs Non-major-airport IFR

D. Safety Metrics

The number and nature of different classes of conflicts in the scenarios for the selected sets of separation minima are studied to assess the collision risks and average time available before maneuvering to avoid the loss of separation. The relevant metrics are described next.

1) Number of LOSs

The number of LOSs of different classes among UAM and with traditional real-world aircraft are counted and the nature of the conflicts are examined so that PBS can be applied. When the number of LOSs is on the order of hundreds or thousands, the tactical separation management function is unlikely to safely maneuver and maintain separation of the flights.

2) Number of NMACs

The number of NMACs of different classes among UAM and with traditional real-world aircraft is counted for collision-risk calculations. A number in the hundreds or thousands may suggest an improper scenario.

3) Number of Wake LOSs

The number of wake turbulence LOSs between a UAM flight and a non-UAM real-world flight are counted separately as well. Any wake turbulence LOS will require proper attention as it suggests that some procedural separation is required.

4) Collision Risk

The collision risk is defined as the conditional probability of an NMAC among the losses of separation for a set of separation minima:

$$P(\text{NMAC}|\text{LOS}) = \text{No. of NMACs / No. of LOSs}$$

As a reference, the unmitigated collision risk was estimated to be 2.2% for the UAS DWC separation standard of horizontal 2200 ft and vertical 450 ft [16].

5) Time Available before Maneuvering

The average time available before maneuvering tactically to avoid a LOS is defined as the average time from the moment of first detection of a conflict to the first actual LOS for a look-ahead time of one minute. The larger the time available before maneuvering, the better the chance to avoid the LOS.

IV. Results and Discussions

The various conflicts among UAM and with traditional aircraft are analyzed and the safety metrics evaluated for the selected sets of separation minima. The results are discussed in the following subsections.

A. NMACs Analysis

An analysis of near-mid-air collisions was conducted for the case where the separation minima were 500 ft horizontally and 100 ft vertically.

Fig. 3 shows the number of UAM-UAM NMACs based just on the 500 ft/100 ft separation minima for the scenarios with and without PCDR, categorized by flight phase. As can be seen, the number of same-vertiport (i.e. DDSV + DASV + AASV) NMACs for the scenario without PCDR is large. This is expected since procedural separation may allow the aircraft to be as close as 200 ft even for today's helicopters [13] and no separation requirements in the vertiport area are enforced in the scenarios.

Note that the PCDR does not change the number of DDSV NMACs since it was not imposed on those departure-departure UAM pairs from the same vertiport. The PCDR does appear to have had an effect on arrivals to a vertiport. The number of DASV and AASV NMACs was lower with PCDR than without PCDR, even though arrivals were not deconflicted from departures or arrivals.

When finer routes around the vertiports are considered in the route design [9] and departure and arrival procedures are enforced, smaller performance-based separation may be applied. Thus, those same-vertiport NMACs should not be considered as collisions when PBS is applied. Thus, they will be grouped as invalid and not counted in the collision-risk calculations. Note that the total number of NMACs without PCDR is 1799 after excluding same-vertiport NMACs. This suggests that strategic separation management is necessary. The number of NMACS with PCDR reduced to just 4 after excluding same-vertiport NMACs. The PCDR strategically separates the aircraft and thus reduces the NMAC collision risk. One should note though that the UAM aircraft have been assumed to fly PCDR UAM trajectories perfectly without any uncertainties. The number of NMACs of the CEE type is zero, resulting from the fact that the 1500-ft separation between parallel tracks is much larger than the 500-ft horizontal separation minimum.

Fig. 4 shows the number of UAM–non-UAM NMACs for the 10 days of typical real-world air traffic with or without PCDR for the UAM flights. The runway configurations of North Flow, South Flow, or Mixed Flow (MF) are also indicated with MF meaning a switch between NF and SF occurred. NF was in use for about three hours on Aug. 28 and only one hour on Aug. 15. The average number of NMACs is 5.2 per day for SF and 7 per day for NF and MF. The number is not affected much by the PCDR of the UAM flights. The NMACs occur mostly between a UAM and an unassociated or a helicopter flight including some rare situations. For example, a single helicopter flight was involved in NMACs with eight different UAM flights on June 10 while the helicopter was in a holding pattern that overlaps with the routes of the UAM flights at different times. Thus, the number of UAM–non-UAM NMACs is small given that the tracks were merged without any separation procedure or maneuvering between the UAM and VFR, UNA, or HELO flights.

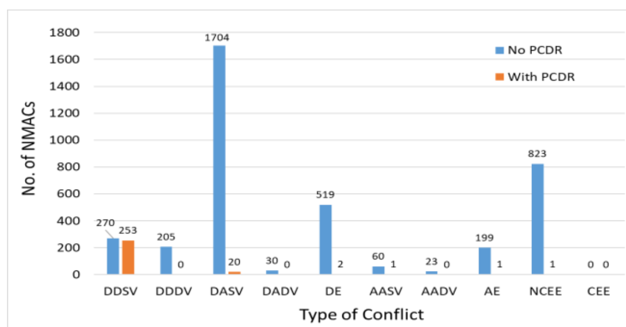

Fig. 3. Number of UAM-UAM NMACs by flight phase with and without PCDR

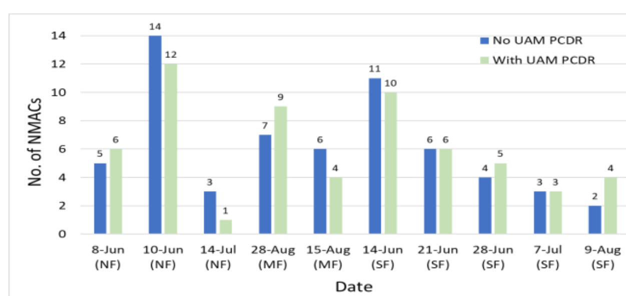

Fig. 4. Number of NMACs between UAM and non-UAM flights with and without UAM PCDR for 10 days of real-world air traffic.

B. Wake-LOS Analysis

The number of wake turbulence LOSs among UAM and IFR flights is shown for the scenarios with and without PCDR for the 10 days of typical real-world air traffic in Fig. 5. As can be seen, without PCDR, no wake turbulence LOS for the SF real-world traffic appears. This agrees with the UAM route structure design, in which the South-Flow IFR arrival routes have already been taken into account to avoid potential wake turbulence conflicts. Two wake turbulence LOSs appear with UAM PCDR. The reason for those two LOSs is that the UAM flights climbed up to 2500 ft, above the restrictions of 1100 ft or 1600 ft imposed by the route structure design. These were repositioning flights which fly directly between the origin and destination vertiports, not following the route network. Fig. 6 shows the ground tracks, with an insert of the altitude profiles, of the repositioning UAM flight behind the heavy IFR flight AAL239. The UAM levels at 2500 ft and it loses 5 nmi separation with flight AAL239, which is a heavy DFW arrival to runway 18R. The UAM flight is assumed to be in the "small" weight class. The stars are one minute apart leading to the indicated circles, which represents the first LOS. The circles are of a diameter of 5 nmi. The arrows indicate the directions of flight while the squares represent waypoints in the flight plans.

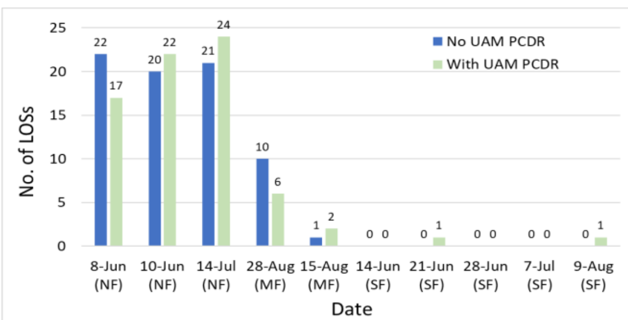

Fig. 5. Number of wake turbulence LOSs with and without UAM PCDR for 10 days of real-world air traffic

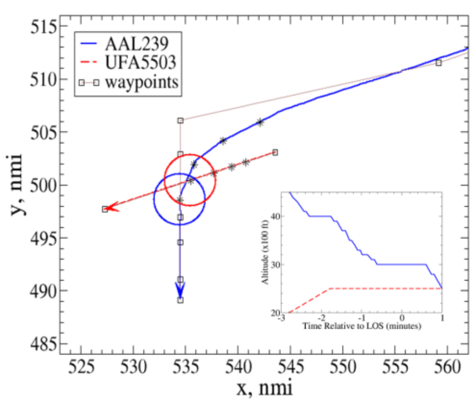

Fig. 6. Ground tracks with altitude-profile insert for a repositioning UAM flight and a heavy IFR flight in wake LOS

As is seen in Fig. 5, the number of wake LOSs for the North-Flow traffic is relatively large, suggesting that different UAM routes must be designed for different flows. While NF has not been considered in the route structure design, it is interesting to see how the wake LOSs occur. Fig. 7 shows the ground tracks, with an insert of the altitude profiles, of an example wake LOS involving NF traffic. The UAM flight is behind flight AAL1164 which is B752. The circles are of a diameter of 4 nmi. The stars are one minute apart leading to the indicated LOS. Note that the UAM route crosses under the nominal interior route of the IFR.

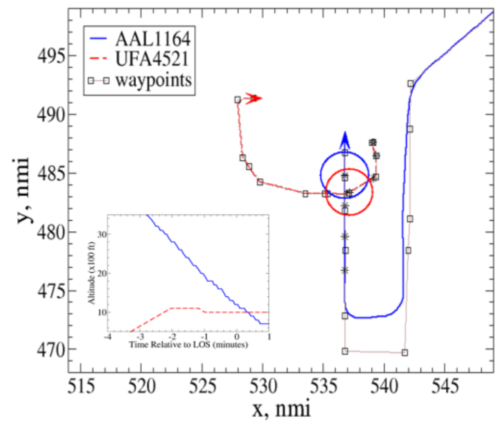

Fig. 7. Ground tracks with altitude-profile insert for a repositioning UAM flight and a B752 North-Flow IFR flight in wake LOS.

C. General LOS Analysis

1) UAM–UAM

The charts for the number of UAM-UAM losses of separation at different phases for three sets of separation minima with and without PCDR, without performance-based separation being applied yet, are shown in Figs. 8-10. The consequences of applying PBS are discussed in the following.

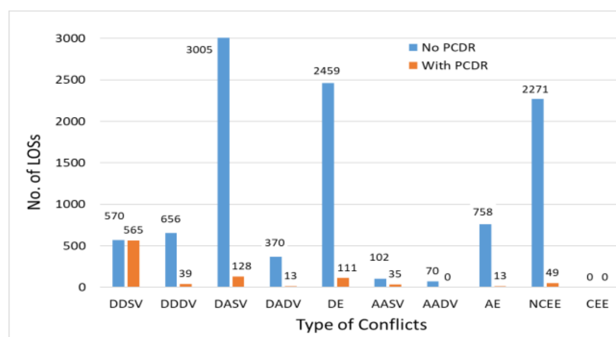

Fig. 8. UAM-UAM LOSs with and without PCDR for 1200 ft/500 ft.

Fig. 8 shows that the total numbers of same-vertiport LOSs, which includes DDSV, DASV, and AASV, for the 1200 ft/500ft separation minima are 728 and 3677, respectively, with and without PCDR. Although these values are large, as in Sec. IV.A, they may not be LOSs when departure and arrival procedures and PBS are considered. Thus, they are categorized as "invalid LOSs" and will be excluded in the safety-metric calculations in Secs. IV.D and IV.E. The number of CEE LOSs with and without PCDR is zero because the centerlines of the parallel routes are 1500-ft apart while the track positions have little deviations from the centerlines. The total number of LOSs other than same-vertiport and CEE LOSs, with and without PCDR are 225 and 6584, respectively. The latter number is likely too large to be resolved with tactical maneuvers.

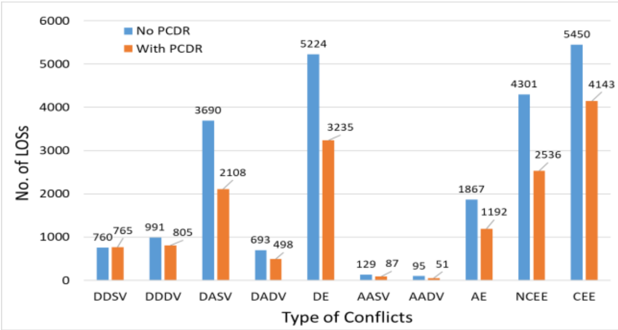

Fig. 9. UAM-UAM LOSs with and without PCDR for 1800 ft/500 ft.

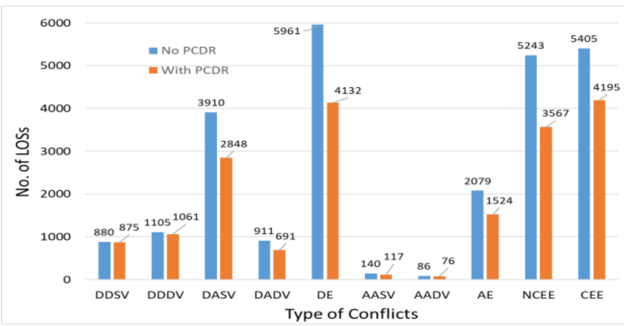

Fig. 10. UAM-UAM LOSs with and without PCDR for 2200 ft/450 ft

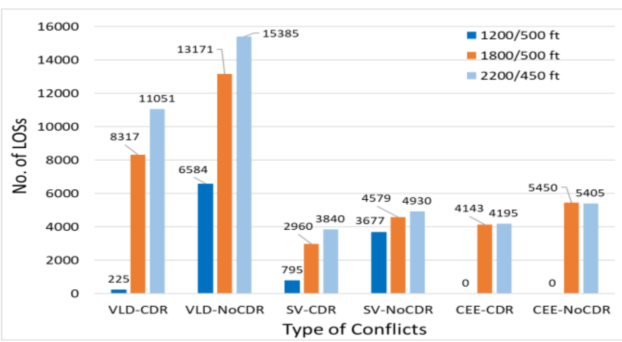

Fig. 11. Valid and invalid same-vertiport and CEE UAM-UAM LOSs with and without PCDR.

The number of LOSs increases quickly as the horizontal separation minimum increases from 1200 ft to 1800 ft and 2200 ft as can be seen in Figs 8-10. The number of LOSs reaches a few thousand even when there is PCDR because the PCDR uses 1200 ft/500 ft separation minima while the higher minima should have been used. The number of CEE LOSs reaches the thousands as well since the horizontal separation minima are larger than the 1500-ft separation of parallel routes. However, as explained in Sec. II.C.2, when the aircraft are conformed within the primary route width, PBS of 1200 ft/500 ft minima can be applied. Thus, the CEE LOSs for the horizontal separation minima of 1800 ft and 2200 ft are not LOSs when PBS is added to the separation requirement. That is, one should group the CEE LOSs in the invalid category as well. Fig. 11 shows the number of LOSs for the three sets of separation minima in terms of total valid LOSs with PCDR (VLD-CDR) and without PCDR (VLD-NoCDR) and invalid LOSs separated into same-vertiport LOSs, with PCDR (SV-CDR) and without PCDR (SV-NoCDR), and CEE LOSs, with PCDR (CEE-CDR) and without PCDR (CEE-NoCDR). Here valid LOSs include DDDV, DADV, DE, AADV, and AE. Note that the number of CEE LOSs for the 1800 ft and 2200 ft minima does not vary much as expected.

Fig. 12 illustrates a CEE LOS for the separation minima of 1800/500 ft. The symbology is the same as described previously. The stars are one minute apart leading to the circles, which represent the first LOS. The diameters of the circles are 1800 ft. Since the parallel routes are separated by 1500 ft, there would be no CEE LOSs as long as a horizontal separation minimum of 1200 ft is applied and track fluctuations around the routes are small in magnitude. This is not the case for horizontal separation minima of 1800 ft nor 2200 ft.

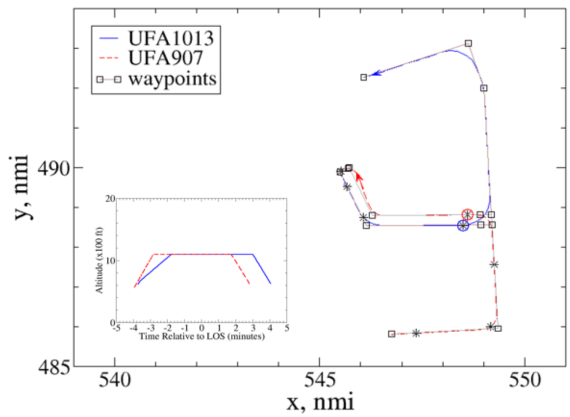

Fig. 12. Ground track with altitude-profile insert for a pair of UAM flights in an example CEE LOS.

Note that we specifically isolate and count the invalid same-vertiport and CEE LOSs instead of simply drop them as one would in an operational conflict detection system. This is because the approach to analyze conflicts and apply PBS is new. It may be even more suitable with the recently enhanced design of the DFW UAM route structure with refine details in the vicinity of vertiports [9] as they are closer to RNP routes. Study of the CEE and NCEE conflicts in a PBS paradigm, where the separation minima are a function of the degree of aircraft conformance to the routes, may help determine safe separation distances for parallel routes. In particular, it may help determine whether it is safe enough to separate routes by less than twice the containment limit [8] of 4 x RNP value.

2) UAM–non-UAM

The number of UAM–non-UAM losses of separation of different classes is compared for three sets of separation minima with and without PCDR of the UAM flights and with 10 different days of recorded real-world traffic of North and South Flows at DFW D10.

Figs. 13-15 show the number of various types of LOSs of UAM–non-UAM pairs for one South-Flow day with and without UAM PCDR and for horizontal/vertical separation minima of 1.5 nmi/500 ft, 1 nmi/500 ft, and 0.6 nmi/500 ft, with and without diverging courses as non-conflicts. The diverging courses here required a minimum horizontal separation of 0.8 nmi in addition to the definitions in FAA Order JO 1710.65Z [13]. Thus, no diverging courses are considered for the case of 0.6-nmi minimum separation.

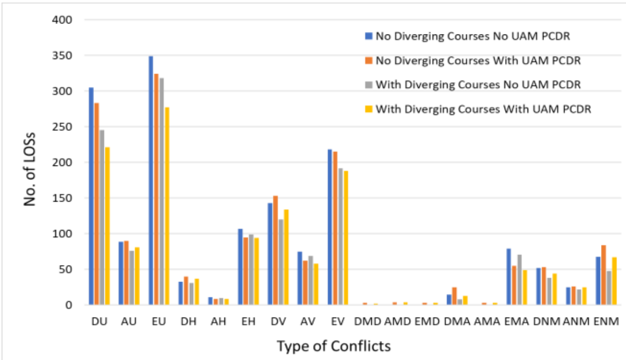

Fig. 13. UAM–non-UAM LOSs with 1.5 nmi/500 ft separation minima for the day of June 21, 2019 (South Flow).

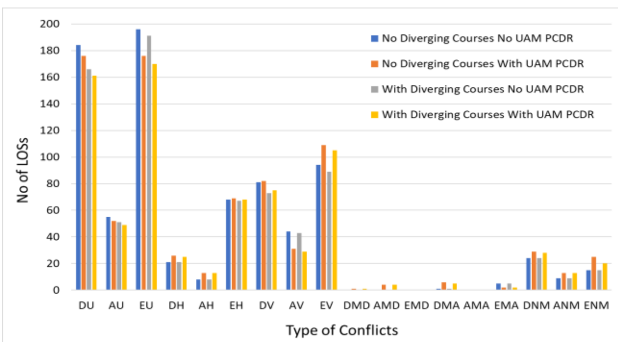

Fig. 14. UAM–non-UAM LOSs with 1 nmi/500 ft separation minima for the day of June 21, 2019 (South Flow).

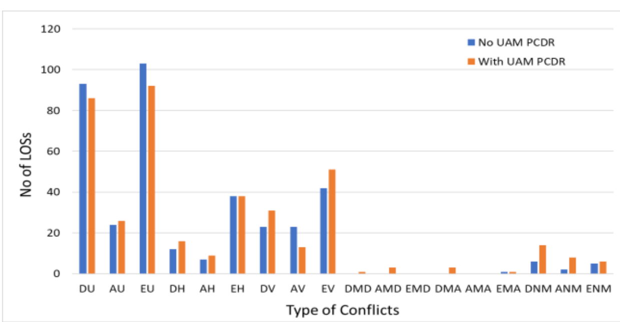

Fig. 15. UAM–non-UAM LOSs with 0.6 nmi/500 ft separation minima for the day of June 21, 2019 (South Flow).

As can be seen, the number of LOSs between a UAM and a VFR or HELO or UNA is large as compared to that of UAM with IFR of major or non-major airports. This is because the UAM routes have been designed to avoid wake turbulence conflicts with SF IFR flights at DFW without consideration of conflicts with other flights. The number of LOSs is consistently less when diverging courses as non-conflict is applied. UAM PCDR does not appear to have a consistent effect. The number of LOSs is 50% less when the separation minimum decreases from 1.5 to 1 nmi and is an additional 50% less when the separation minimum is reduced to 0.6 nmi.

Fig. 16 shows the number of various types of LOSs of UAM--non-UAM pairs for one North-Flow day with and without UAM PCDR and for the horizontal/vertical separation minima of 1.5 nmi/500 ft with and without consideration of diverging courses.

As can be seen in Fig. 16, same as in the South-Flow case, the number of LOSs between a UAM and a VFR or HELO or UNA is large. However, the number of LOSs of UAM with IFR aircraft of major airports is much larger than any typical South-Flow day. This is because the UAM routes were designed without considering IFR flights in North Flow at DFW. While the number of LOSs of different types is consistently less when diverging courses are considered (as was also observed in the South-Flow case), the effect of diverging courses is much larger for the North-Flow IFR flights at major airports. The PCDR of UAM flights again does not show a consistent effect.

Similar results for North-Flow days are observed for the horizontal/vertical separation minima of 1 nmi/500 ft, and 0.6 nmi/500 ft. In particular, the number of LOSs again generally is 50% less when the separation minimum is reduced to 1 nmi and it is an additional 50% less when the separation minimum is reduced to 0.6 nmi. The majority of LOSs involve VFR, HELO, and UNA flights as well. Thus, some procedural UAM separation from VFR/HELO/UNA flights may be needed.

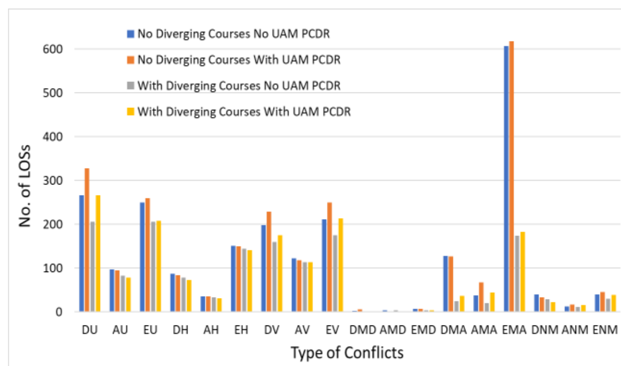

Fig. 16. UAM–non-UAM LOSs with 1.5 nmi/500 ft separation minima for the day of June 8, 2019 (North Flow).

D. *Collision-Risk Analysis*

Collision risks are estimated for different sets of separation minima in the scenarios using the valid NMACs and LOSs assuming the performance-based separation is applied. The scenario without UAM PCDR provides an instance, highly unrealistic though, of unmitigated NMACs while the one with PCDR has the NMACs mitigated by resolving conflicts with predeparture delays and lateral, speed, and altitude maneuvers to avoid conflicts based on the 1200 ft/500 ft separation minima.

Unmitigated NMAC collision risk has been used as a safety metric to evaluate DAA Well-Clear definitions needed for DAA systems for UAS operations. Earlier study recommended a value of unmitigated collision risk of 5% for consideration of a DWC [4]. To help establish DWC separation standards for UAS [5], a few DWC candidates were evaluated using an initial target collision risk of 1.5%. The final DWC standard was 2200 ft horizontally and 450 ft vertically. The unmitigated collision risk for this standard was estimated to be 2.2% [16].

Table IV shows the collision risks among UAM flights for the three sets of separation minima without PCDR. Table V shows the same for the cases with PCDR. As can be seen, the collision risks without PCDR for all three sets of separation minima are larger than 12%, much larger than the acceptable UAS collision risk of 2.2%. This is not unexpected as the scenario without PCDR is highly unrealistic in that the UAM aircraft may fly into one another in a route intersection or in opposite course along the same route segment. The collision risk with PCDR is 1.8% for the 1200 ft/500 ft minima, which yields a risk ratio (i.e. mitigated collision risk divided by unmitigated collision risk) of 6.7%. For the other two sets of higher horizontal minima, the collision risk is much less because the PCDR did not resolve conflicts based on the higher minima, so the number of LOSs in the denominator is large. These results suggest that collision risk alone may not be a sensitive enough metric for differentiating the sets of separation minima.

Table VI shows the collision risk between UAM flights and non-UAM flights averaged over the five South-Flow days. Table VII shows the same averaged over the five North-Flow or Mixed-Flow days. For all three sets of separation minima, the collision risk is less than the acceptable unmitigated collision risk of 2.2% for UAS operations. No significant difference is found between the SF and NF days. These results suggest that the collision risk for a minimum horizontal separation as low as 0.6 nmi between a UAM and a traditional flight might be acceptable.

E. Time-Available-before-Maneuvering Analysis

The time available before a maneuver can be initiated to avoid a loss of separation for a given set of separation minima is measured as the time from the first prediction of a conflict to the time of the first actual LOS for a look-ahead time chosen to be one minute in this initial study. This is based on T-TSAFE's prediction of the conflicts at one-second intervals without knowledge of any future states of the UAM flights in the scenarios. The goal is to see whether the metric may help differentiate different sets of separation minima.

Table VIII shows the average Time Available before Maneuvering (TAM) for the UAM-UAM LOSs for the scenarios with and without PCDR for the three sets of separation minima with the added PBS. As can be seen, TAM for UAM pairs without PCDR was 11% higher when the horizontal separation minimum was increased from 1200 ft to 1800 ft. With PCDR, TAM was 48% higher when the horizontal separation minimum was increased from 1200 ft to 1800 ft. TAM was 6% higher when going from 1800 ft to 2200 ft with and without PCDR. TAM was 25% less when PCDR was applied for the case of 1200-ft minimum, while no change was found when PCDR was applied for the cases of 1800-ft and 2200-ft minimum. This is consistent with the fact that the PCDR used 1200 ft as the horizontal separation minimum. These behaviors suggest that this metric could be effective for differentiating different separation minima. More data are needed, though. In particular, the related metric of false-alert rates should be analyzed.

TABLE IV. UNMITIGATED UAM-UAM COLLISION RISK WITHOUT PCDR

Sep. Minima	*P*(NMAC|LOS)	No. of LOSs	No. of NMACs
1200 ft / 500 ft	0.27	6584	1799
1800 ft / 500 ft	0.14	13171	1799
2200 ft / 450 ft	0.12	15385	1799

TABLE V. UAM-UAM COLLISION RISK WITH PCDR

Sep. Minima	*P*(NMAC|LOS)	No. of LOSs	No. of NMACs
1200 ft / 500 ft	0.018	225	4
1800 ft / 500 ft	0.00048	8317	4
2200 ft / 450 ft	0.00036	11051	4

TABLE VI. COLLISION RISK BETWEEN UAM AND NON-UAM FLIGHTS FOR SF TRAFFIC

Sep. Minima	*P*(NMAC|LOS)	No. of LOSs	No. of NMACs
1.5 nmi / 500 ft	0.0038	1360	5.2
1.0 nmi / 500 ft	0.0078	665	5.2
0.6 nmi / 500 ft	0.017	313	5.2

TABLE VII. COLLISION RISK BETWEEN UAM AND NON-UAM FLIGHTS FOR NF TRAFFIC

Sep. Minima	*P*(NMAC|LOS)	No. of LOSs	No. of NMACs
1.5 nmi / 500 ft	0.0034	2082	7
1.0 nmi / 500 ft	0.0072	966	7
0.6 nmi / 500 ft	0.017	412	7

TABLE VIII. AVERAGE TIME TO MANEUVER FOR UAM-UAM LOSSES OF SEPARATION WITH AND WITHOUT PCDR

Sep. Minima	Average Time to Maneuver (seconds)	
	No PCDR	***With PCDR***
1200 ft / 500 ft	27.2	21.3
1800 ft / 500 ft	31.5	30.9
2200 ft / 450 ft	33.2	33.0

V. SUMMARY AND CONCLUSIONS

Twenty scenarios of UAM and real-world traditional traffic were evaluated using a fast-time simulation program to generate conflicts among Urban Air Mobility (UAM) aircraft and with traditional aircraft for several sets of separation minima, including a form of performance-based separation. Each scenario was comprised of 24 hours of simulated UAM traffic merged with recorded real-world traffic of a pre-pandemic day in D10 airspace. NASA-modeled airspace constraints and route structure were enforced on the UAM traffic, which had a demand scale of UAM maturity level 4. Pre-departure Conflict Detection and Resolution (PCDR) was applied to the UAM traffic for half of the scenarios. Ten days of recorded traffic at Dallas Forth-Worth (DFW) international airport were selected, including North-Flow, South-Flow, and mixed-flow configurations. The losses of separation observed in these simulations were identified, classified, and analyzed.

The unmitigated collision risk between two UAM aircraft was measured at 12% to 27% without PCDR for sets of UAM horizontal separation minima from 2200 ft down to 1200 ft, which may be too large to differentiate the sets. The collision risk for the 1200-ft horizontal separation minimum set was observed to be 1.8% with PCDR, yielding a risk ratio of 6.7%. The results for other sets were inconclusive, as the PCDR function used only the 1200-ft set. The collision risks between a UAM and a non-UAM aircraft for horizontal separation minima between 0.6 nmi and 1.5 nmi were less than 1.7%, with or without PCDR, suggesting lateral separation minima between a UAM and a traditional flight may acceptably be reduced to 0.6 nmi. For all sets of separation minima, the vertical separation minimum was 500 ft, except when the horizontal minimum was 2200 ft, in which case it was 450 ft.

The UAM scenario without PCDR may not be practical, given the large number of losses of separation and near mid-air collisions observed between UAM flights in these simulations—likely too many for a tactical conflict management function to resolve without causing excessive interruptions of service. UAM flight pairs departing or arriving the same vertiport should be identified and special procedures and performance-based separation minima applied. An approach to performance-based separation applied to UAM flight pairs on parallel routes demonstrates how the same approach can be applied to future UAM corridor tracks so that reduced separation may be applied for conformed aircraft. Large number of UAM–non-UAM losses of separation were also observed, suggesting that some procedural separation might be necessary when there are overlaps between UAM and traditional flights operating under visual flight rules. Large number of wake-turbulence losses of separation for North-Flow DFW traffic suggests that different sets of UAM routes may be needed when DFW switches between North and South flow configurations. The effects of diverging courses appear significant for North-Flow traditional traffic when the UAM route structure considers only the South-Flow traffic.

Preliminary analysis shows that the time available before a maneuver can be initiated to avoid a projected loss of separation may be used together with other safety metrics to differentiate between different sets of separation minima.

An ongoing study is considering scenarios in which tactical maneuvers are applied to resolve conflicts. These mitigations prompt more deviations and trajectory uncertainties relative to the flight-plan routes. Other metrics, including false-alert rates, in addition to the time available before maneuvering, will be evaluated with UAM simulated traffic data from the mitigated scenarios of larger uncertainties. Scenarios with NASA's enhanced UAM route structure containing more detailed constraints on the vertiports and corridors will be studied as well with performance-based separation. Broader sets of separation minima for UAM flights will be investigated to help establish safe UAM separation standards.

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