

# Analysis of Interactions Between Urban Air Mobility (UAM) Operations and Conventional Traffic in Urban Areas: Traffic Alert and Collision Avoidance (TCAS) Study for UAM Operations

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**This paper presents a preliminary modeling and analysis of interactions between proposed UAM operations and present-day conventional traffic if UAM operations occurred along FAA-approved helicopter routes and altitude ceilings. It assesses the extent to which the UAM operations will trigger TCAS resolution advisories (RA) aboard the conventional aircraft in the Dallas/Fort Worth (DFW) terminal airspace. It is observed that under deterministic UAM operational conditions, no RAs will be triggered. Furthermore, the impact of UAM altitude uncertainty is also evaluated. It is observed that restricting the UAM cruise altitudes to 990 feet above Mean Sea Level (MSL) or below reduced the chance of triggering an RA to under five percent throughout the day, even in the presence of maximum altitude error of 30 feet.**

## I. Introduction

NASA, in collaboration with government and industry partners, is developing concepts for Urban Air Mobility (UAM) vehicles and technologies to support UAM vehicle operations across a network of takeoff and landing areas (TOLAs) in metropolitan regions. These UAM operations of the future will need FAA approval. Hence, the simplest approach to begin operations might be to start with already-existing approved routes, especially for flying into major airports. Can UAM vehicles fly these routes with minimal impact on present-day commercial air traffic (hereafter referred to as conventional traffic)?

This paper presents a preliminary modeling and analysis of interactions between proposed UAM operations and conventional traffic, if UAM operations were restricted to FAA-approved helicopter routes and altitude ceilings. UAM operations in Dallas/Fort-Worth (DFW) terminal airspace is chosen for the study. The goal of this work is to assess the extent to which proposed initial UAM operations may trigger Traffic alert and Collision Avoidance System (TCAS) resolution advisories (RA) aboard conventional aircraft in the DFW terminal area. A range of operational scenarios at DFW is evaluated with combinations of UAM vehicle route, speed, altitude, and direction along the DFW “spine route.” The analysis is done for both South flow and North flow configurations of DFW. First, results are obtained under the assumption that UAM vehicles fly their routes precisely (i.e. no uncertainty). Then, the impact of altitude uncertainty on these results is also evaluated.

Different route alternatives are evaluated between DFW and Frisco, Texas in this paper. DFW-Frisco operation was selected as a test case based upon recommendations derived from traffic demand studies from potential UAM operators in the region. The focus of research presented here is only the impact of operations for this test case on triggering TCAS RAs on conventional aircraft. Interaction with Air Traffic Control(ATC) and other route alternatives and procedures are not studied. Associated work by Verma et. al. [1] explored potential routes and procedures in a Human-In-The-Loop (HITL) experiment expanding the above study region to include Dallas Lovefield (DAL) and Addison (ADS) airspace and Dallas downtown.

The rest of this paper is divided into five sections. Section II, Traffic alert and Collision Avoidance System (TCAS), provides a description of TCAS and how its logic is used in this study. Section III, DFW Airport Terminal Area Traffic, describes DFW runways and operational configurations. Section IV, Study Approach, provides a breakdown of

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modeling assumptions, UAM operational route scenarios, selection of study days and description of simulation set up. Section V, Results, first summarizes the results of the geometric analysis of the routes, followed by their verification using simulations without trajectory uncertainties. It also presents the results with altitude uncertainty. Section VI, Conclusions, discusses the overall findings and recommendations for future studies.

## II. Traffic alert and Collision Avoidance System (TCAS)

In conventional operations, TCAS is the last layer to prevent mid-air collisions between aircraft other than the pilot. The design of the TCAS logic is a trade-off between providing necessary safe separation between aircraft and preventing unnecessary advisories. Unnecessary advisories reduce trust in the system and may increase crew and controller workload to unacceptable levels. The system monitors the amount of horizontal and vertical separation and uses the rates of change in horizontal and vertical separation to predict the closest point of approach between the ownship and surrounding aircraft. A Traffic Advisory (TA) or a Resolution Advisory (RA) is issued based on thresholds for estimated time for an intruder aircraft to enter a protected volume of airspace around a TCAS equipped aircraft ( $\tau_{mod}$ ) and time to co-altitude ( $\tau_{vert}$ ) [2]. The boundary of the protected volume is defined by a slant range distance called DMOD.

During a TA, on a conventional aircraft, TCAS displays the intruder aircraft and notifies the pilot about a potential conflict through visual and audio alerts. The pilot is expected to respond to a TA by (1) establishing visual contact with the intruder and other aircraft in the vicinity and (2) maintaining current assigned clearance. During an RA, TCAS issues maneuvers to the pilot to increase or maintain current vertical separation. The pilot is expected to immediately respond to the indicated maneuvers unless doing so would unduly jeopardize the safe operation of the flight. When both aircraft are equipped with TCAS II, aircraft coordinate their RA's through Mode S datalink to ensure that complementary RAs are selected. Due to the assumption that TCAS II is available only on conventional aircraft, RA coordination functionality will not be discussed in this work.

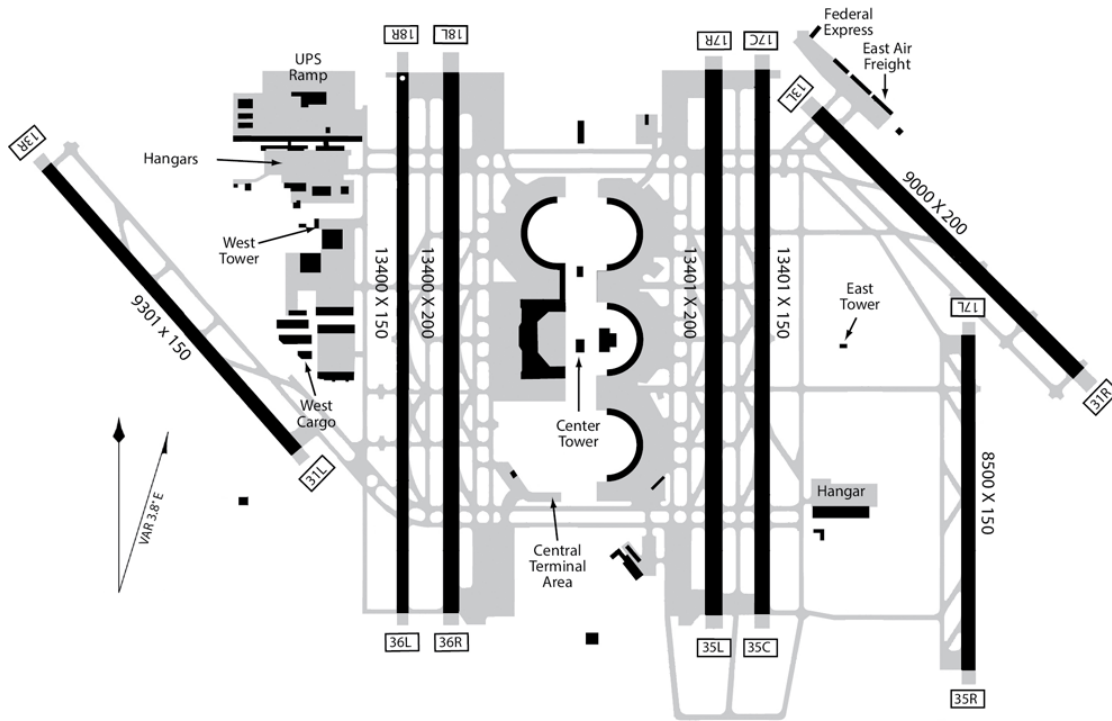
**Table 1 TCAS II Version 7.1 Sensitivity Levels and Thresholds for Resolution Advisories [2]**

Ownship Altitude (ft)	SL	Tau(sec)	DMOD(nmi)	ZTHR(ft)
<1000 (AGL)	2	N/A	N/A	N/A
1000-2350 (AGL)	3	15	0.20	600
2350-5000	4	20	0.35	600
5000-10000	5	25	0.55	600
10000-20000	6	30	0.80	600
20000-42000	7	35	1.10	700
>42000	7	35	1.10	800

To balance the tradeoff between necessary protection and unnecessary advisories, TCAS uses an altitude-based Sensitivity Level (SL), which controls the tau (time) thresholds for TA and RA issuance, and therefore the dimensions of the protected airspace around each TCAS-equipped aircraft (Table 1). DMOD and ZTHR are the slant range and vertical separation threshold of the protected airspace as per the TCAS II manual [2]. The higher the SL, the larger the amount of protected airspace and the longer the alerting thresholds. While an aircraft is in close proximity to ground, the SL of TCAS alert and avoidance parameters depends on the altitude of the ownship aircraft above ground level (AGL). TCAS does not provide RAs below 1000ft AGL (SL=2). Between 1000-2350 ft AGL (SL=3), TCAS issues RAs, if both  $\tau_{mod}$  and  $\tau_{vert}$  are less than 15 seconds threshold, or  $\tau_{mod}$  is less than 15 seconds and current altitude separation is less than 600 feet (vertical separation threshold).

## III. DFW Airport Terminal Area Traffic

The study described in this paper uses nominal operation assumptions and procedures for DFW airport as described in this section.



**Fig. 1 DFW Runway Map**

### A. DFW Runways

The DFW airport has seven physical runways shown in figure 1. These runways are operated in the South-flow and North-flow configurations. The runways in South-flow configuration are designated as, 13L, 13R, 17L, 17C, 17R, 18L and 18R. The runways in the North-flow configuration are designated as, 31L, 31R, 35L, 35C, 35R, 36L and 36R. These designations indicate the runway heading with respect to north. The two inner runways 18L/36R and 17R/35L are primarily used for departures. Runways 18R/36L and 17C/35C are primarily used for arrivals [3]. Adjacent primary departure and arrival runways are about 0.2 miles (1200 ft) apart. In North flow operations, runway 35R is used for arrivals as the amount of traffic increases but it is less desirable being shorter and far from terminals and its use requires aircraft to cross runways. As a rule of thumb, easterly arrivals use runway 17C/35C and westerly arrivals use runway 18R/36L. Considering the geometry of the runways, arrival and departure procedures at DFW and the expected nominal trajectories of UAM vehicles along helicopter routes (see figure 2), interactions between commercial aircraft and UAM are most likely to happen between aircraft arriving/departing on runways (18R,17C)/(18L,17R) in South flow and arriving/departing from runways (36L,35C)/(36R/35L) in North Flow.

### B. Departures

Ninety five percent of all departures from DFW are jets using RNAV routes [4]. Departures typically are provided temporary level-off altitudes of 10,000ft, if their track crosses under arriving aircraft. After crossing they are cleared to climb to their cruise altitude. The average duration of a 10,000 ft level off is about 1.7 minutes, traveling a distance of 9.4 nmi based on an assumed airspeed of 331 knots [4].

### C. Arrivals

The arrivals use Runways 13R, 18R, 17C and 17L in South flow and 31R, 35C, 35R, and 36L in North flow configurations. All approaches follow a 3 degree glide slope procedure [5]. Hence, aircraft arriving with a stable approach are below 1000 ft AGL, 3.16 nm before the touchdown zone.

## IV. Study Approach

In this study, two routes for UAM flights operating between the city of Frisco, Texas and DFW airport were analyzed. Frisco was selected based on recommendations derived from traffic studies by potential UAM operators in the region. UAM-conventional aircraft interactions were evaluated from a TCAS perspective. UAM-UAM interactions were not studied as they are out of scope for this work.

### A. Assumptions and Test Cases

The following assumptions were made:

- All UAM vehicles in the simulation were modeled as the same aircraft type.
- All UAM fly along published helicopter routes.
- UAM trajectories are completely deterministic in the simulation for the first set of results and identification of sensitive areas.
- Only altitude uncertainty is considered for the second set of results for the identified sensitive areas.
- The altitude errors are assumed to be normally distributed with zero mean and varying standard deviations.
- Conventional aircraft are modeled with TCAS II version 7.1.
- UAM vehicles are not modeled with the above TCAS system but do provide the state information required by the TCAS system on board the conventional aircraft.
- Conventional aircraft adhere to published area navigation (RNAV) routes.

Same aircraft type assumption has low impact on the relevance of this study, as we only need a representative performance model. In future, a wider range of vehicles could be summoned based on trip length and traffic demand. However, manufacturing and maintenance costs alone will likely push towards a preferred UAM vehicle. Existing helicopter routes are a useful starting point as they are already designed for vehicles that operate at low altitudes with Vertical Take-Off and Landing (VTOL) capability. Eventually, other routes and procedures can be explored (for example see [1]). Since vertical separation was identified as a major factor that could potentially trigger RAs, from the first set of results, altitude uncertainty was a good first candidate to study.

Four UAM operational route scenarios were evaluated:

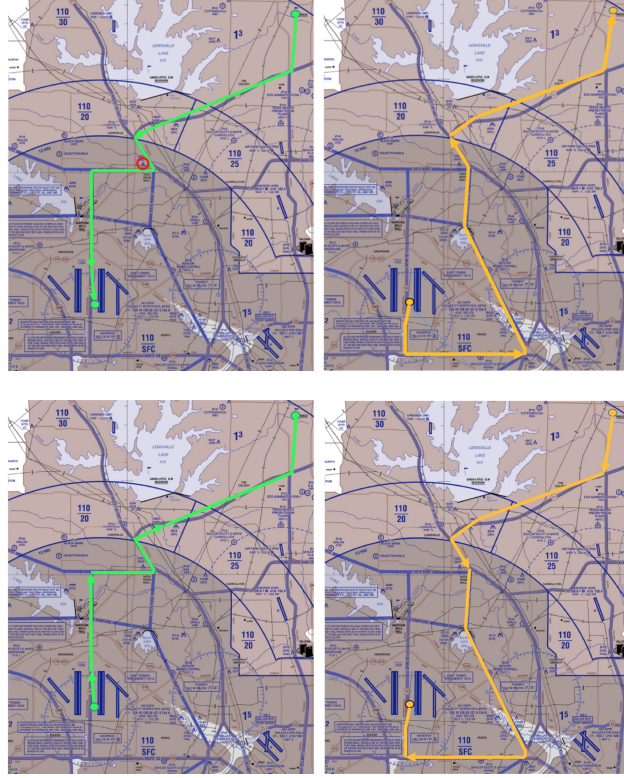
- 1) Frisco, Texas to DFW entering DFW from the North (Figure 2, Scenario 1);
- 2) DFW to Frisco exiting DFW towards the South (Figure 2, Scenario 2);
- 3) DFW to Frisco exiting DFW towards the North (Figure 2, Scenario 3); and
- 4) Frisco to DFW entering DFW from the South (Figure 2, Scenario 4).

Each of these scenarios was studied for every DFW runway operation condition listed below for a total of 16 simulation test cases (4 UAM operation scenarios X 4 runway operation conditions). Conventional traffic data for each runway operation condition was derived from the dates mentioned in parenthesis.

- Nominal Day in South Flow (June 03, 2017).
- Nominal Day in North Flow (November 11, 2017).
- Off-Nominal Day in South Flow (July 20, 2017).
- Off-Nominal Day in North Flow (August 7, 2017).

Nominal days were characterized by moderate meteorological (temperature between  $85^{\circ}F$  -  $95^{\circ}F$  and low precipitation) and traffic flow conditions. The off-nominal days had maximum temperatures close to  $100^{\circ}F$ , clear skies, and minimal weather impacted operations, allowing for the highest traffic flow with least impact on airport operations. On these days, owing to higher temperatures, conventional aircraft may not have been able to climb as quickly as they could on nominal days, which was expected to cause closer encounters and potentially more TCAS RAs. Furthermore, August 7 had the highest conventional traffic in North Flow configuration for the entire year and therefore was also used for the altitude uncertainty study.

These test cases together account for different routes, flow directions of UAM traffic between Frisco and DFW and flow variations of conventional traffic. Additionally, in the vicinity of the airport, all UAM flying into DFW were modeled to cruise at 1000 ft MSL, and all UAM flying out were modeled to cruise at 900 ft MSL. This separates UAM vehicles flying into DFW by 100 ft from UAM vehicles flying out. The cruise airspeed of all UAM vehicles was modeled at 130 knots. Although it is important to assess whether this UAM-UAM vertical separation is sufficient, it is beyond the scope of this study. However, it ensures that UAM vehicles taking off and flying against arriving conventional traffic, are at a higher vertical separation, compared to UAM vehicles flying in the same direction.



**Fig. 2 Flight routes between Frisco, Texas and DFW airports overlaid on FAA Sectional Charts [6]**  
(Clockwise from top left: Scenario 1, Scenario 2, Scenario 4 and Scenario 3)

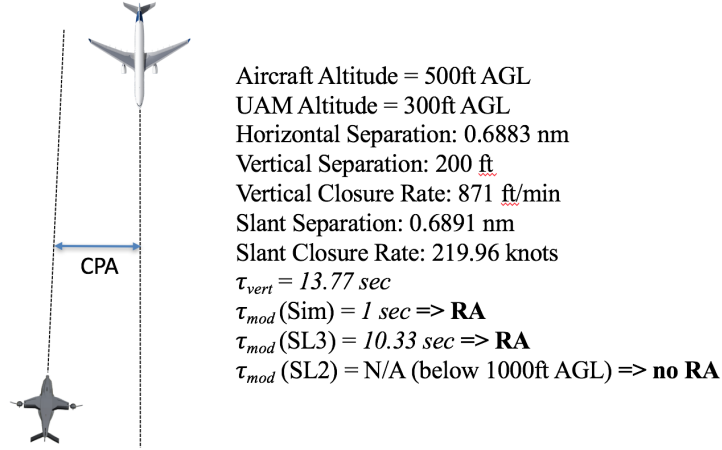
## B. Simulation Platform and Software Components

Study simulations used the SaaControl fast-time simulation software developed by NASA as a testing tool for modeling Detect-And-Avoid (DAA) capability of Unmanned Aircraft Systems (UAS-NAS project [7]). Conflict avoidance algorithms (TCAS as one), surveillance and atmospheric models, and pilot response models have been integrated into its core module. SaaControl is capable of running faster-than-real-time NAS-wide simulations. In this study, it detects potential conflicts from raw input traffic data: flight plans for UAM and track data files for conventional aircraft. For the TCAS logic, FAA-supplied TCAS II version 7.1 software was used with a software wrapper developed by NASA, to integrate it into NASA simulation platforms. The wrapper packages TCAS II into a JAVA library callable by clients. It takes aircraft states from a client, calls TCAS II, and returns TCAS responses to the client.

## C. Analysis Approach

The analysis was accomplished in three stages. First, TCAS sensitivity level in the simulator was higher than a real system. The value of sensitivity parameter DMOD was 0.66 nm as per UAS in NAS project [7], which would be highly conservative for the near surface operations in this study.  $\tau_{mod}$  measures the time it takes two aircraft to come closer than DMOD distance. Second, scenarios that produce RAs from above were filtered using geometric aircraft configuration data from the simulator, with the thresholds for a SL 3 TCAS operation, even below 1000 ft AGL (which would technically be SL 2 – No RAs). Third, the correct TCAS SL was used, based on actual AGL altitude of both aircraft consistent with what would be used by a real TCAS II system on a conventional aircraft. If there are no RAs in a higher analysis stage, there can't be any in the next stage. The first two stages are useful for identifying the sensitive areas in the system. However, the results presented in the next section are based on the third and least conservative stage, which is how TCAS would behave in a real scenario.

As an example, a sample encounter scenario is shown in figure 3 with the associated encounter parameters. Recall that if  $\tau_{mod}$  is less than the threshold and either  $\tau_{vert}$  is less than the threshold or the current vertical separation is less than the threshold, then a TCAS RA is issued. TCAS  $\tau_{mod}(\text{Sim})$  is evaluated using a DMOD of 0.66 nm as used in UAS-NAS project [7]; in this example, that results in a value of 1 sec, which is below all  $\tau_{mod}$  thresholds. From the



**Fig. 3 A Sample Scenario (CPA is Closest Point of Approach)**

first stage of analysis, the simulation will flag an RA because both  $\tau_{mod}$  and  $\tau_{vert}$  are less than the threshold of 15 sec. TCAS  $\tau_{mod}(\text{SL})$  is derived based on SL-specific DMOD. For SL 3, DMOD is 0.2 nm. At the second stage of analysis, an RA is also issued because both times are below the threshold of 15 sec (SL 3). However, since DMOD is smaller, the projected time for slant range to go below it is greater. Finally, in a real scenario, since the commercial aircraft is below 1000 ft AGL, no RA shall be issued. Results derived following this analysis are presented in the next section.

## V. Results

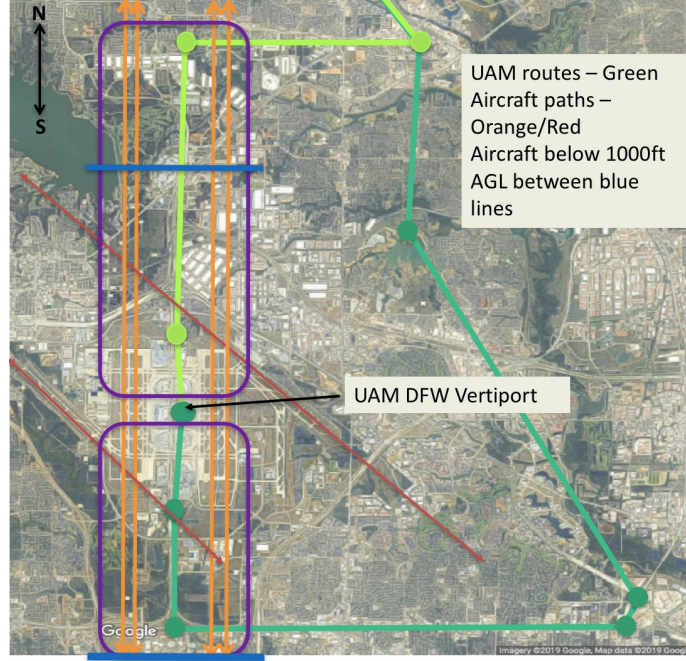
Outside the DFW surface-to-2500 MSL class B airspace, under the assumption that conventional aircraft adhere to published RNAV routes, they are far above the 1000-ft MSL ceiling/cruise altitude of the UAM aircraft and therefore well separated ( $> 1000 \text{ ft}$ ) in altitude. Hence, the analysis here is focused only on the interactions near DFW. The region of interest along with the sensitive areas is shown in figure 4. The thick blue lines indicate the vertical planes between which the arriving conventional traffic is below 1000 ft AGL. They are 3.16 nm from the touchdown zone of their respective runways. This distance was computed from the 3-degree approach glide slope described in section III.C. All analysis for deterministic UAM trajectories is primarily geometric and hence applies to both nominal and off-nominal days. However, those days were simulated as a secondary confirmation to ensure that no corner cases were neglected.

The elevation of DFW airport is 607 ft MSL. TCAS will not issue RAs when the conventional aircraft is below 1607 ft MSL (i.e.  $< 1000 \text{ ft MSL}$ ). It will operate at SL=3 for conventional aircraft between 1607-2957 ft MSL. The UAM vehicles simulated in this study are below 1607 ft MSL during their entire trajectory portion under consideration, i.e. in the vicinity of DFW. Thus, in principle, RAs can technically be issued only at SL=3 in the worst case. If the conventional aircraft is above 2957 MSL (SL=4), a TCAS RA will not be triggered with a UAM. In order for the conventional aircraft at 2957 MSL to become co-altitude with the UAM vehicle at 1607 MSL within the  $\tau_{vert}$  threshold of 20 seconds, the conventional aircraft would have to descend faster than 4000 ft/min. This is much higher than a typical descent rate of 800 ft/min that such an aircraft would use on a 3-degree final approach glide slope. Even before the aircraft has intercepted the final glide slope, it would descend at a much lower final descent rate [9]. Therefore, the modeling assumptions for this study prevent the time and altitude separation thresholds from ever being violated, if the conventional aircraft is above 2957 MSL near DFW.

### A. Departures Analysis

Departing conventional aircraft primarily use runways 18L and 17R in South Flow (35L and 36R in North Flow) (Figure 1) and are above 1000 ft AGL 20 secs after departure, based on a climb rate of roughly 50 ft/sec [4]. Since the departure runways have a minimum separation of 0.44 nm from the UAM flight paths in their take-off zones, departing conventional aircraft are well separated horizontally from the UAM aircraft. After take-off, the conventional aircraft climb at rates between 2000-3000 ft/min, much faster than the 500 ft/min ascent/descent rate assumed for UAM flights. They are above the incoming UAM flight altitudes in less than 10 sec. Hence, they are always diverging and well separated by 1000ft AGL, the altitude where the TCAS system would start producing any RAs. Therefore, under the assumptions in this study, departing conventional aircraft will not produce RAs, even with UAM trajectory uncertainties.





**Fig. 4 Region of Interest [8].** UAM flight routes in green (North approach/departure – fluorescent green, South approach/departure – dark green), conventional aircraft paths in orange and red and the sensitive areas for analysis, North (figure 5) and South (figure 8) of UAM DFW vertiport, marked with purple boxes. Between the North and South blue lines, conventional aircraft are below 1000 ft AGL.

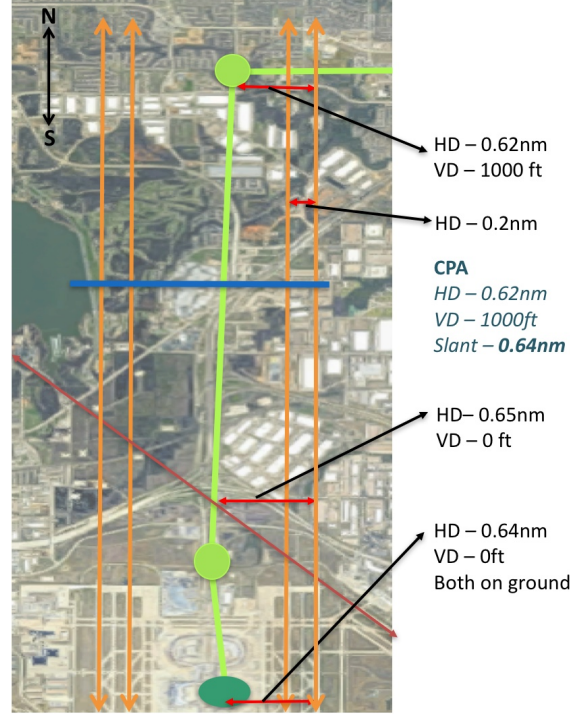
## B. Arrivals Analysis

Results in this section were determined assuming no UAM trajectory uncertainties. In every case where  $\tau_{mod}$  was violated and either the vertical separation threshold or  $\tau_{vert}$  was violated, the conventional aircraft was always below 1000 ft AGL, where TCAS RAs are inhibited. Therefore, under the assumptions of this study, arriving conventional aircraft will also not produce any RAs, if the UAM trajectories are deterministic.

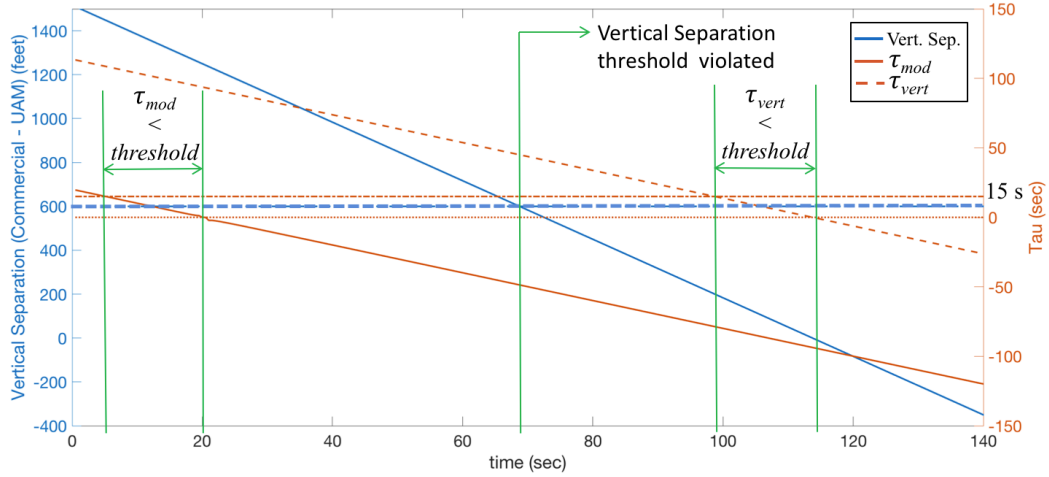
North of DFW (figure 5), UAM flights departing against the direction of arriving conventional traffic are separated horizontally by a minimum of 0.44 nm (0.64 nm from the outer runway - 0.2 nm separation between the adjacent parallel runways) and primarily follow parallel trajectories. For interaction scenarios south of the blue line, the aircraft are therefore well separated horizontally. Furthermore, conventional aircraft are below 1000 ft AGL with TCAS operating at SL 2 as described at the start of this section. Hence, they issue no RAs. North of the blue line in the same figure, the conventional aircraft are above 1000 ft AGL and have TCAS operating at SL 3. Even where  $\tau_{mod}$  goes below thresholds (e.g. where the UAM turns right and flies below conventional aircraft arrival path), the vertical separation is greater than 600 ft and the time to co-altitude is greater than the SL 3 threshold of 15 seconds to trigger any RAs.

Such a sample encounter where  $\tau_{mod}$  goes below thresholds is shown in figure 6. The evolution of vertical separation (solid blue line) is plotted on the left axis. At SL 3, the vertical separation threshold, ZTHR is 600 ft (dashed blue line).  $\tau_{mod}$  (solid red line) and  $\tau_{vert}$  (dashed red line) are plotted on the right axis. The SL 3 time thresholds are violated below  $\tau = 15$  sec, i.e. when  $\tau_{mod}$  and  $\tau_{vert}$  are between the dotted red lines. When  $\tau_{mod}$  is between 0 and 15 sec, neither the vertical separation threshold nor the  $\tau_{vert}$  threshold is violated. Hence, this encounter will not trigger an RA.

Figure 7 illustrates this is true even at a high descent rate. Assume that the conventional aircraft is at AGL altitude  $A_C$  in feet ( $>1000$  ft) and the UAM is cruising in level flight at AGL altitude  $A_U$  in feet. Any aircraft above 1000 ft, under normal operation, should not descend at a rate (ft/min) greater than its AGL altitude, i.e. maximum descent rate or maximum vertical closure rate,  $V_{ZC} = A_C$  in ft/min. Hence time to co-altitude,  $\tau_{vert} = \text{separation}/(\text{closure rate per min}/60) = \text{separation}/(\text{closure rate in sec}) = ((A_C - A_U)/A_C)*60 = (1 - A_U/A_C)*60$  seconds. For maximum  $A_U = 400$  ft and minimum  $A_C > 1000$  ft, minimum  $\tau_{vert} > 36$  sec. Hence time to co-altitude is always greater than 36 seconds, which is more than double the time threshold for SL 3. The vertical separation threshold of 600 ft is also not violated because  $A_C - A_U > 600$  ft.



**Fig. 5 Sensitive Area North of DFW. UAM flight route in green, conventional aircraft landing and take-off paths in orange and dark red. Bright red arrows denote horizontal separations. South of blue line, conventional aircraft are below 1000 ft AGL.**



**Fig. 6 A sample encounter North of DFW (north of blue line in figure 4). Note: Actual onboard TCAS II RA logic will ignore diverging aircraft, hence  $\tau_{mod}$  and  $\tau_{vert}$  will only be computed when they are non-negative.**

South of DFW (figure 8), the UAM flight route intersects with conventional aircraft runway approaches after the conventional aircraft is already below 1000 ft AGL (north of blue line) with TCAS operating at SL 2. Hence, no RAs will be issued. South of blue line (region not shown in figure 8), the conventional aircraft are separated by at least 0.5 nautical miles horizontally and more than 600 ft vertically. Following the same explanation as the SL 3 situation north of DFW (see figure 7), the vertical violation criteria is never satisfied. Hence, no RAs are issued.

These results cover all combinations of UAM vehicle routes, altitudes and directions studied. They also account for variations in UAM vehicle cruise speeds. When conventional aircraft are below 1000 ft AGL, there will be no RAs irrespective of the closure rates (slant and vertical). When they are above 1000 ft AGL, the lack of RAs is due to vertical closure rates and adequate vertical separation. The entire analysis is therefore agnostic to UAM cruise speeds.



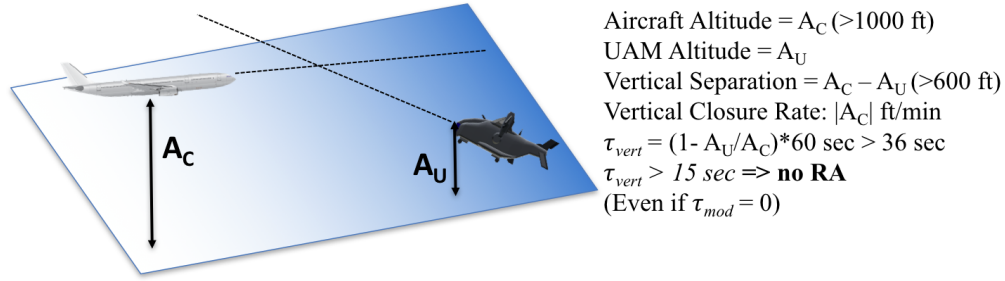


Fig. 7 Worst case scenario, when conventional aircraft is above 1000 ft AGL

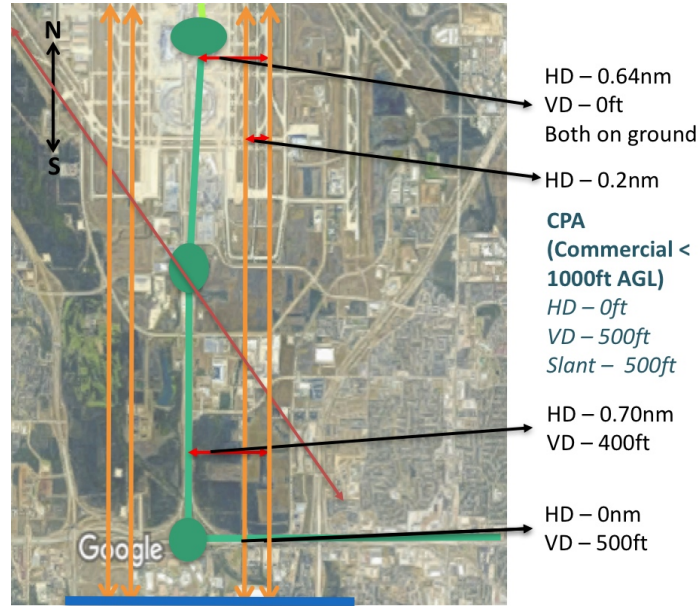


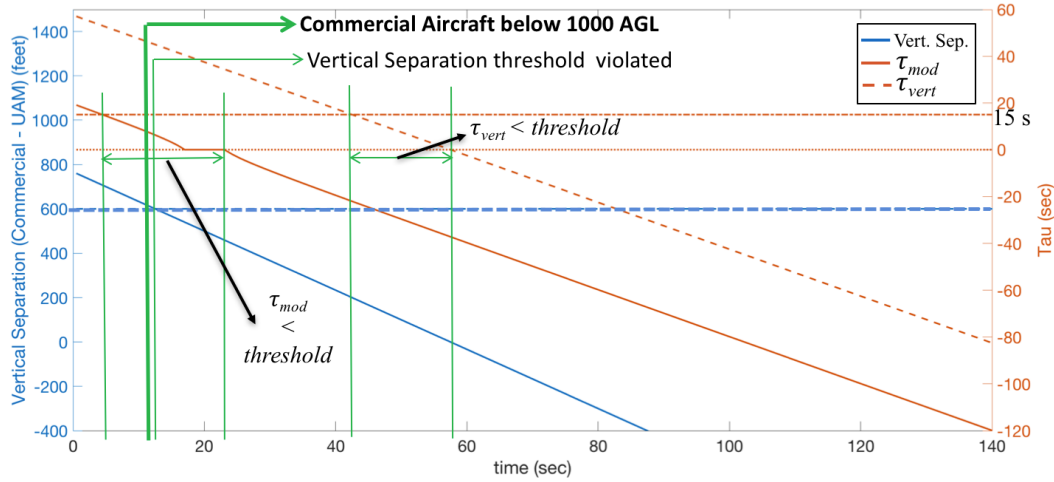
Fig. 8 Sensitive Area South of DFW. UAM flight route in green, conventional aircraft landing and take-off paths in orange and dark red. Bright red arrows denote horizontal separations. North of blue line, conventional aircraft are below 1000 ft AGL.

### C. Altitude Uncertainty Analysis

Although  $\tau_{vert}$  was never violated when the conventional aircraft were above 1000 ft AGL, it is noteworthy that the vertical separation threshold (600 ft) was very close to violation at the intersection of the UAM route and the conventional aircraft arrival path south of DFW, when the UAM vehicles fly into DFW (at 1000 ft MSL). A sample encounter from this sensitive area is shown in figure 9. Although there is a time when  $\tau_{mod}$  is less than 15 sec and the vertical separation is less than 600 feet, the conventional aircraft is already below 1000 ft AGL at that time. Hence, TCAS will ignore the UAM vehicle and not trigger an RA. However, if the UAM vehicle had a vertical position error of even 10 ft, it would have triggered an RA in this scenario. Hence, the natural next step is to explore the impact of trajectory uncertainties.

In this paper, only altitude uncertainty was explored. Vertical GPS errors with available technologies today are less than 10 m ( $\approx 30$  ft) even in the worst case. This was simulated by introducing errors in the altitude of UAM vehicles. The errors were assumed to be normally distributed with zero mean and standard deviation (StD) varying from 5 ft to 30 ft. The maximum error allowed was thrice of the chosen StD. Hence, even though the maximum errors in reality shouldn't exceed 30 ft, errors were simulated up to 90 ft.

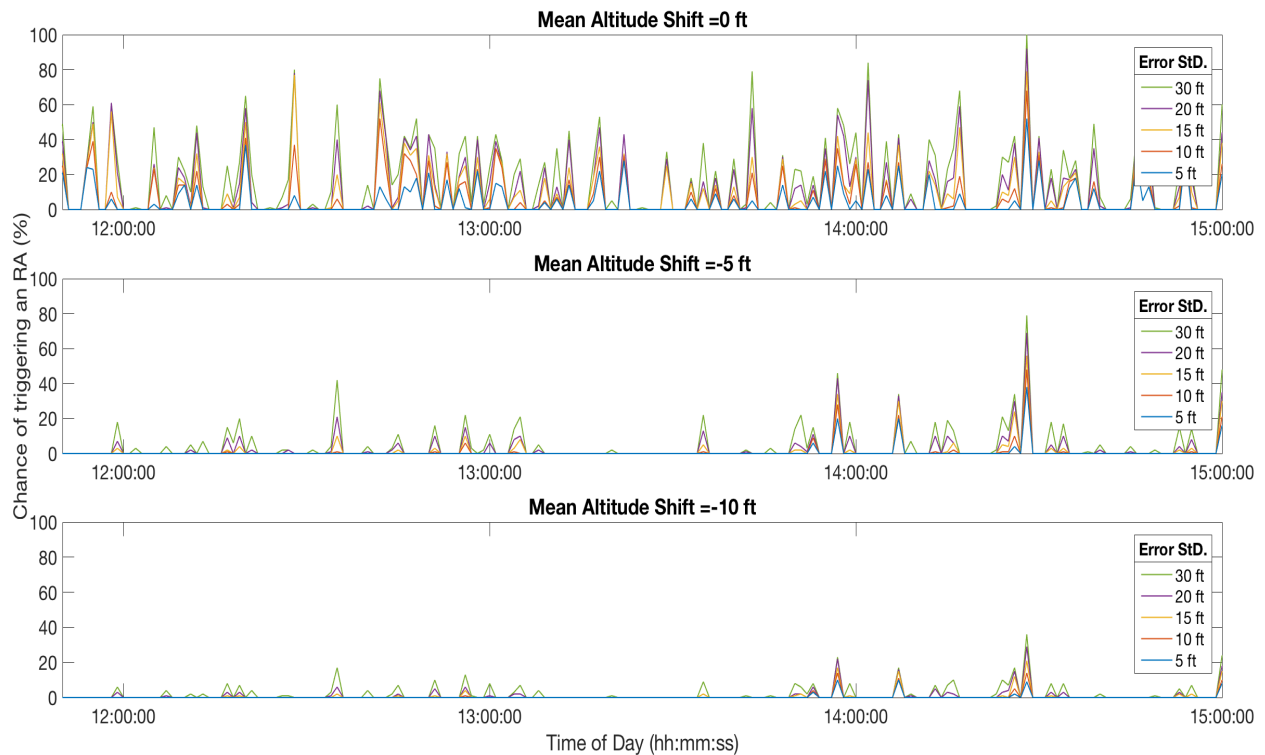
It is noteworthy that UAM vehicles departing DFW were modeled to cruise at 900 ft MSL (293 ft AGL) and hence, even with a maximum error of 90ft, they wouldn't trigger RAs at the sensitive area identified above. Hence, analysis



**Fig. 9** A sample encounter South of DFW (north of blue line in figure 4). Note: Actual onboard TCAS II RA logic will ignore diverging aircraft, hence  $\tau_{mod}$  and  $\tau_{vert}$  will only be computed when they are non-negative.

was only done for Scenario 4, where UAM vehicles fly from Frisco to DFW and enter DFW from the South, passing below the conventional aircraft arrival paths at 1000 ft MSL (393 ft AGL). Furthermore, encounters were simulated with the conventional aircraft track data for August 7, 2017. That day had the highest North Flow traffic of the year and hence, maximum potential encounters.

Figure 11 top row shows the probability of triggering an RA for a UAM vehicle departing Frisco at the times shown on the horizontal axis, as the altitude error StD varies from 5 ft to 30 ft. The probability variation followed the conventional traffic demand change through the day. During lean times (before 9a and after 7:30p), even a 30 ft error StD did not produce more than forty percent risk of triggering an RA. During the peak conventional traffic rush between



**Fig. 10** Risk of triggering RAs on a typical day of operation - Noon-3p

9a and 7:30p, it is observed that even a 5-ft error StD produced over twenty percent risk of triggering RAs at certain times. This risk increased to over forty percent, when the error StD was increased to 10 ft or more. A potential solution to this problem could be that the UAM fly into DFW at a slightly lower altitude below the arrival paths. To justify this recommendation, the above analysis was repeated by lowering the UAM vehicle mean altitude by 5 ft and 10 ft, respectively. It was observed that, in general, lowering the mean altitude by twice the allowable error StD substantially reduced the risk of triggering RAs. As an example, in figure 11, third row, lowering the UAM vehicle mean altitude by 10 ft, reduced the chance of triggering an RA to under ten percent throughout the day, even with a 10-ft error StD (maximum error 30 ft). For clarity, figure 10 shows a zoomed version of the variation from noon to 3p.

## VI. Conclusions

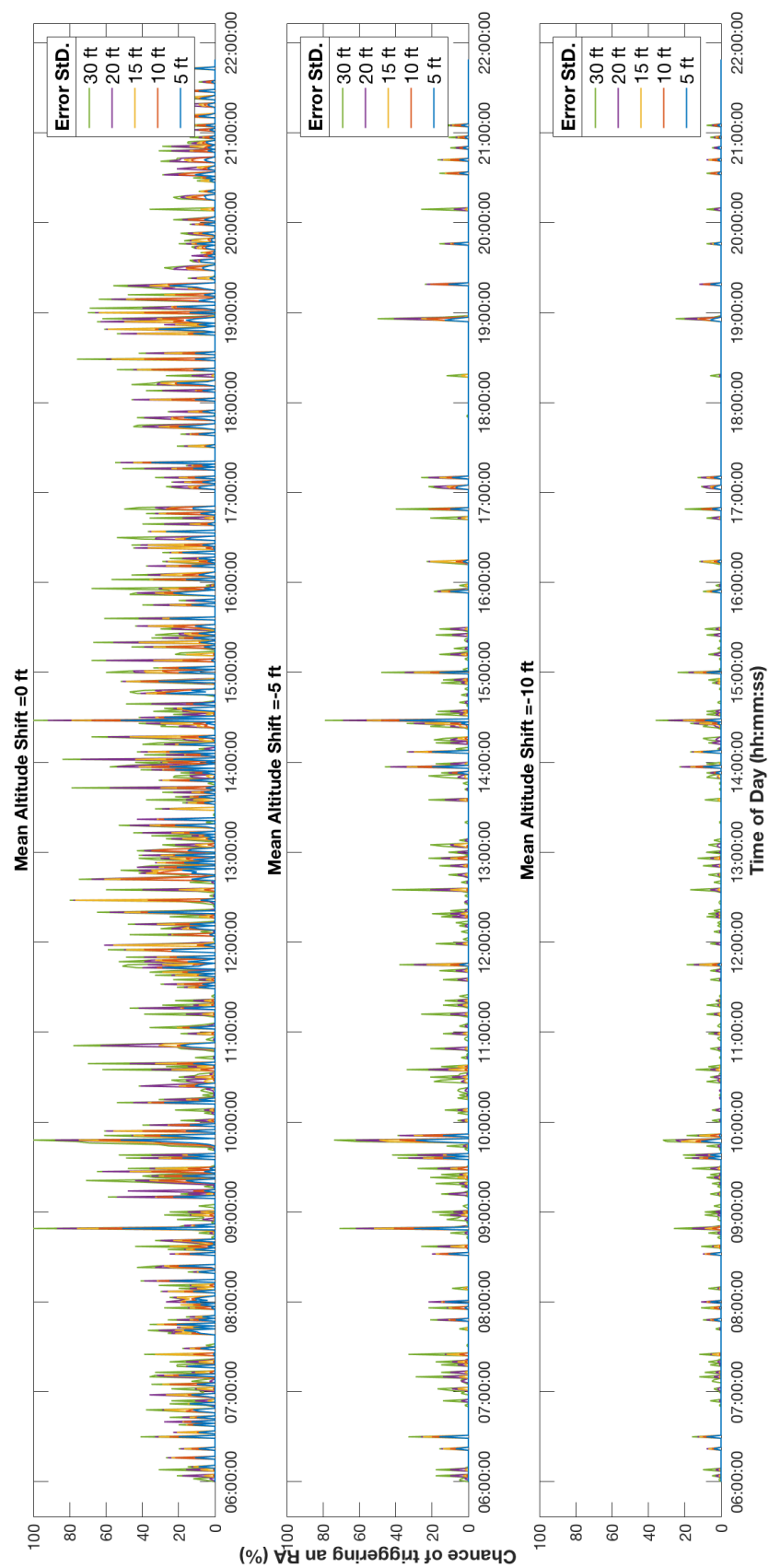
The study found that using a basic model of UAM performance, UAM vehicles simulated to operate from Frisco to DFW utilizing existing helicopter routes as shown in figure 2, triggered no RAs on conventional aircraft. These results were obtained under the assumption of deterministic UAM vehicle trajectories, i.e. zero error in observed and true position of the UAM vehicles. Meteorological conditions, such as wind, which could affect this accuracy, were ignored. These results suggest a very high navigational performance requirement on UAM, if operations were to be enabled with high UAM trajectory determinism.

From the altitude uncertainty study, it was also observed that the above performance requirements could be slightly relaxed by operating the UAM vehicles at or below 990 ft MSL (383 ft AGL), if they can adhere to a maximum altitude error of 15 ft from their trajectory. Furthermore, the primary reason for the lack of RAs is that conventional aircraft are either already, by procedure, well separated horizontally and vertically; or are below 1000 ft AGL otherwise (which suppresses RAs). Even though this is true for DFW based on its particular runway configuration, a similar analysis can be performed at any other airport to determine the sensitive regions for TCAS RA alerts.

It should be noted that TCAS II ignores intruders below 360 ft AGL. This means any UAM flights below 967 ft MSL (around DFW) are automatically ignored by current TCAS operation criteria. This can be interpreted in two ways. In the short term, UAM flights around any airport in the country can be kept below 360 ft AGL to enable early operations, if necessary, without triggering RAs. In the long term, this could create potential issues with high density of near-ground traffic and therefore, might necessitate an update to the TCAS logic to account for the same. Therefore, this is also an important area for further investigation.

## References

- [1] Verma, S. A., Keeler, J. N., Edwards, T. E., and ulchinos, V. L., "Exploration of Near Term Potential Routes and Procedures for urban Air Mobility," *AIAA Aviation Technology, Integration, and Operations Conference*, 2019.
- [2] Federal Aviation Administration, "Introduction to TCAS II Version 7.1 booklet," , 2011. Feb 28.
- [3] "DFW Airport Aircraft Noise," <https://www.dfwairport.com/aircraftnoise/>, 2019. Accessed: 2019-04-14.
- [4] Roach, K., and Robinson, J., "A terminal area analysis of continuous ascent departure fuel use at Dallas/Fort Worth international airport," *10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*, 2010, p. 9379.
- [5] "DFW Airport Runway Charts," <https://www.globalair.com/airport/apt.runway.aspx?aptcode=DFW>, 2019. Accessed: 2019-04-14.
- [6] "FAA Helicopter Routes Map for Dallas-Fort Worth Area," [http://aeronav.faa.gov/content/aeronav/heli\\_files/PDFs/Dallas-Ft\\_Worth\\_Heli\\_7\\_P.pdf](http://aeronav.faa.gov/content/aeronav/heli_files/PDFs/Dallas-Ft_Worth_Heli_7_P.pdf), 2019. Images produced by the U.S. Government and in the public domain.
- [7] Abramson, M., Refai, M., and Santiago, C., "The Generic Resolution Advisor and Conflict Evaluator (GRACE) for Detect-And-Avoid (DAA) Systems," *17th AIAA Aviation Technology, Integration, and Operations Conference*, 2017, p. 4485.
- [8] Google Maps, "Dallas/Fort Worth International Airport Area Satellite View," <https://www.google.com/maps/@32.9162036,-97.0537879,20210m/data=!3m1!1e3>, 2019. Accessed: 2019-05-16.
- [9] "Eurocontrol Aircraft Performance Database," <https://contentzone.eurocontrol.int/aircraftperformance/details.aspx?ICA0=B738&ICA0Filter=B738>, 2019. Accessed: 2019-04-14.



**Fig. 11 Risk of triggering RAs on a typical day of operation**