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# DAIDALUS Observations From UAS Integration in the NAS Project Flight Test 4

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**Contents**



**List of Tables**



**List of Figures**

# Introduction

In order for large Unmanned Aerial Systems (UAS) to operate safely and seamlessly in the National Airspace System (NAS), all large UAS will need to comply with existing Federal Aviation Regulations (FAR) related to physical separation of aircraft. Most critical to the integration of UAS into the NAS are FAR 91.111 "No person shall operate an aircraft so close to another as to create a collision hazard," and FAR 91.113 "Vigilance shall be maintained by each person operating an aircraft as to see and avoid other aircraft." The National Aeronautics and Space Administration (NASA), in conjunction with standards body RTCA Inc., other federal agencies, as well as members of industry have worked to define a prototype UAS-specific manifestation of "See and Avoid," termed "Detect and Avoid" or DAA. Detect and Avoid involves using various sensors or combination of sensors and mathematical algorithms to replace human eyesight onboard the aircraft and provide maneuver guidance to the human operator in order to remain "well-clear" of other aircraft.

The NASA UAS Integration in the NAS (UAS in the NAS) project has been tasked with executing several research activities with the purpose of determining the minimum operational performance standards (MOPS) for a well-clear volume size and how to integrate the human operator into the man-machine system. Alert time is one of the key concepts defined in the MOPS and an extension of the well-clear volume designed to allow the human operator enough time to assess a conflict and negotiate a maneuver with air traffic control (ATC) to remain well clear. Variables such as sensor uncertainty and flight state estimation noise may cause alerting which is triggered too late for the human operator to remain well-clear. Short nuisance alerts, which do not last long enough to allow a human operator to respond, can potentially cause negative impacts on a fielded DAA system. Interoperability with systems which already exist in aircraft operating in the NAS is an additional goal of the DAA MOPS. The Traffic Alert and Collision Avoidance System (TCAS) is required capability on all transport category aircraft in the NAS which provides alerting and guidance in the form of resolution advisories (RA) for flight crews to reduce the risk of mid-air collisions. Implementing a DAA system without regard to TCAS would potentially cause extensive disruptions to traffic in the NAS, as flight crews would receive unnecessary guidance to maneuver and deviate from their flight paths. Flight Test 4 (FT4) is the latest in a series of flight tests by NASA, the FAA, Honeywell, and General Atomics for validating the MOPS for DAA. Validating the effectiveness of alerting time with real-world sensor input and investigating DAA-TCAS interoperability were two goals of NASA Langley's participation in FT4.

# Background

One of the known DAA-TCAS interoperability issues is in the different sizes of the DAA and TCAS vertical thresholds; the current DAA vertical threshold for corrective alerting and guidance is 450 ft. while the TCAS vertical threshold for corrective RAs between the altitudes 2,350 ft. and 20,000 ft. is 600 ft. Potential mitigations to DAA-TCAS interoperability issue would be to either modify the well-clear vertical threshold to align with or exceed the TCAS vertical threshold, or to add a time based alerting threshold to the vertical dimension for DAA alerting so that human UAS operators have sufficient early alerting to avoid a corrective RA. Table 1 provides the TCAS volume values for altitudes between 2,350 ft. and 20,000 ft.

*Table 1. TCAS Volume Values*

| Own Altitude (feet) | Sensitivity Level | Resolution Advisory Tau (Seconds) | Resolution Advisory DMOD (nmi) | Resolution Advisory ZTHR (feet) |
|---|---|---|---|---|
| < 1000 AGL | 2 | N/A | N/A | N/A |
| 1000 - 2350 AGL | 3 | 15 | 0.2 | 600 |
| 2350 - 5000 | 4 | 20 | 0.35 | 600 |
| 5000 - 10000 | 5 | 25 | 0.55 | 600 |
| 10000 - 20000 | 6 | 30 | 0.8 | 600 |
| 20000 - 42000 | 7 | 35 | 1.1 | 700 |
| > 42000 | 7 | 35 | 1.1 | 800 |

The Well-Clear Volume (WCV) as defined by the RTCA Special Committee 228 (SC-228) is comprised of a horizontal distance threshold (HMD*), a horizontal time component ($\tau^*_{mod}$), a vertical distance threshold (ZTHR), and a vertical time component (TCOA). Well-clear between ownship and an intruder aircraft is maintained as long as the intruder is outside HMD* and the geographic region defined by $\tau^*_{mod}$ when solved for distance and is also outside ZTHR or outside the TCOA threshold. The DAA MOPS drafted by SC-228 places HMD* = 4000 ft, $\tau^*_{mod}$ = 35 seconds, ZTHR = 450 ft, and TCOA = 0 seconds at the time of writing.

Additionally the DAA MOPS stipulate that an alerting and guidance algorithm provide the human operator with alerting at a minimum lead time before the WCV is penetrated. Alerting is tiered into preventive alerts (PA) and corrective alerts (CA) at the caution level and a warning alert (WA) to be displayed before the WCV is penetrated. Preventive alerts currently have the same alerting time requirements as corrective alerts and will not be a focus of the current analysis. Corrective alerts must be displayed to the UAS operator a minimum of 20 seconds prior to penetrating the WCV and persist for a minimum of four seconds. Corrective alerts must also not be displayed earlier than 75 seconds prior to penetrating the WCV. Warning alerts must be displayed at a minimum of 15 seconds prior to penetrating the WCV and must persist for a minimum of 4 seconds. Warning alerts must also not be displayed earlier than 55 seconds prior to penetrating the WCV. It is acknowledged that the surveillance sensors used for DAA will on occasion produce alerts earlier and later than the alert time entered into the algorithm due to uncertainty of an intruder's position and velocity. Therefore, the alert time parameter in DAIDALUS must be sufficiently longer than the minimum times prescribed in the MOPS to prevent missed or late alerting which would present a hazard to air traffic in the NAS.

The DAA algorithm used for NASA Langley's FT4 encounters was the Detect and AvoID Alerting Logic for Unmanned Systems or DAIDALUS. DAIDALUS was developed by researchers at NASA Langley to enable UAS operators to perform DAA maneuvers to remain well-clear. Based on the algorithm for the TCAS family of systems, DAIDALUS provides vertical and lateral guidance to avoid a Loss of Well-Clear (LoWC) to UAS operators as well as determining the severity of alert levels for air traffic projected to lose well-clear. For FT4, DAIDALUS guidance came in the form of corrective "bands," which represent a range of headings, altitudes, and vertical speeds which will result in a LoWC, displayed on a generic cockpit display of traffic information (CDTI). Operationally, UAS operators will maneuver to place the air vehicle's heading, altitude or vertical speed outside, or away from the corrective bands. When a LoWC has occurred or is unavoidable, DAIDALUS will display well-clear recovery (WCR) guidance bands. WCR guidance bands are a complimentary set of bands which represent a range of headings, altitudes, and vertical speeds which provide the most expedient path to regain well-clear status. UAS operators will maneuver to place the air vehicle's heading inside, or towards the WCR bands when they are displayed. Figure 1 provides an example of the DAIDALUS DAA display with corrective and recovery bands used in FT4 where the amber corrective bands are displayed between approximate headings of 255° to 084° and the green recovery bands are displayed between approximate headings of 085° to 254°.

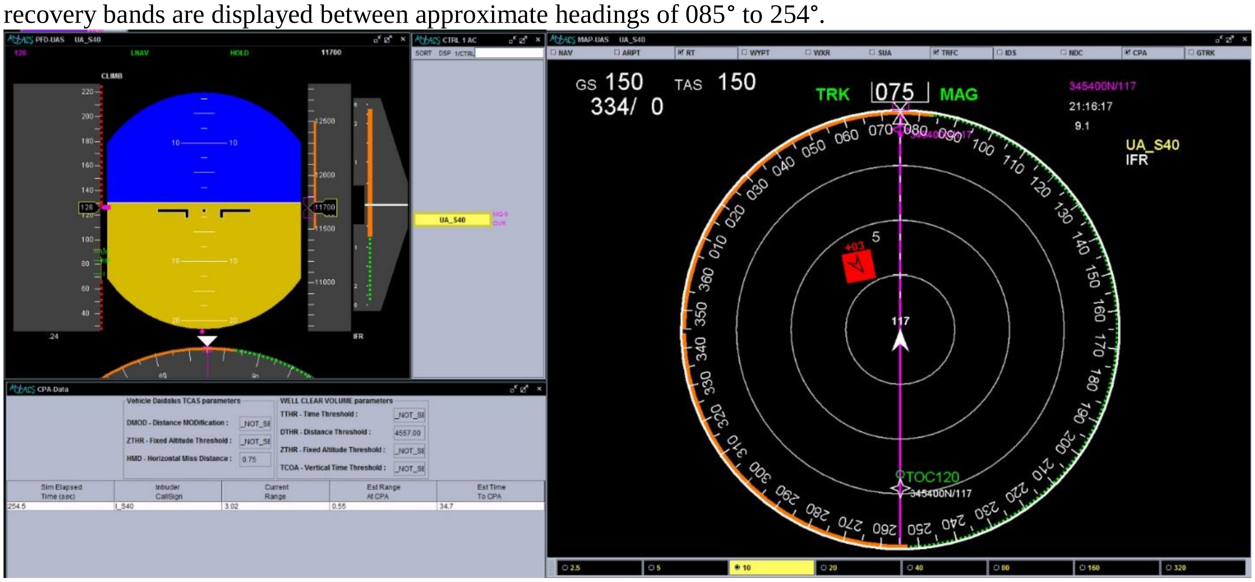


*Figure 1. The DAIDALUS MACS DAA Display Used in FT4.*

DAIDALUS ingests flight state data from air surveillance sensors onboard the air vehicle to predict the future flight states of traffic and determine whether and when the intruder's future position will be within the WCV. The flight state information needed for DAIDALUS to provide meaningful alerting and guidance include the latitude, longitude, altitude, ground speed, ground track, and vertical speed for both the ownship air vehicle and "intruder" aircraft detected by the onboard sensors. DAIDALUS is a state-based algorithm, meaning it projects the current flight state of the intruder aircraft and assumes that flight state will remain constant for each calculation time frame. While this approach should provide adequate alert timing and guidance for intruders on a straight-line trajectory, cases where an intruder is maneuvering may cause late DAA alerting as intruder "intent" information is not available to DAIDALUS.

# Method

Flight Test 4 was conducted at NASA Armstrong Research Center in Edwards, California from April to June of 2016. Several aircraft participated in the flight test, being utilized for varying performance and sensor equipage. Each DAA encounter consisted of NASA's MQ-9 "Ikhana" ownship being controlled by a human operator viewing DAA guidance from within the Ground Control Station (GCS). The Ikhana operators either flew according to a predetermined course labeled on the test card or selected a maneuver based on the guidance provided by the system under test. The Ikhana vehicle was outfitted with an Automatic Dependent Surveillance-Broadcast (ADS-B) system, TCAS II system capable of generating preventive and corrective RAs, an onboard traffic radar developed by General Atomics, and a sensor fusion tracker developed by Honeywell. A Beechcraft C-90 King Air, B-200 Super King Air, and T-34C Mentor turboprop aircraft were used as medium speed intruders. A Gulfstream III cabin class jet operated as the high speed intruder, while a TG-14 motorglider was used as the low speed intruder. A Beechcraft C-12 Huron was used as an intruder equipped with a Mode-C only transponder. The flight cards discussed in the current analysis utilized the C-90, B-200 King Airs and the T-34C as intruders. Additionally all aircraft participating in FT4 were equipped with an independent differential Global Positioning System (dGPS) which recorded highly accurate flight state information.

DAIDALUS was integrated into the NASA developed Multi-Aircraft Control System (MACS) installed on a standalone computer in the GCS. A monitor displaying the MACS software with the DAIDALUS implementation was placed within the UAS operator's field of view. The DAIDALUS MACS software subscribed to flight state messages from NASA's Live-Virtual-Constructive (LVC) network. The LVC network received ownship and surveillance data downlinked from the Sense-and-Avoid Processor (SAAP) onboard the Ikhana aircraft before it logged and published flight state messages to the DAA systems participating in the flight test. The inclusion of the LVC network flight state enabled flight state data "playback" as a way to observe the effect of different DAA algorithm parameters on alerting and guidance.

The current analysis focused on single ship encounters with either no maneuver (fly-through), an accelerating intruder, or encounters with a predetermined vertical maneuver. The fly-through encounters are designed to provide a full cross-section of a DAA encounter, from initial detection to LoWC and closest point of approach (CPA). Geometry for the fly-through encounters varied between 0°, 45°, 90°, 135°, and 180° azimuths relative to the nose of the ownship. The surveillance sensors which fed DAIDALUS with flight state information varied between a fusion of ADS-B, RADAR, and TCAS and a fusion of RADAR and TCAS. There was a 300 ft. vertical offset and a 2430 ft. horizontal offset in each fly-through encounter for safety. The Ikhana's operators were instructed to maintain course, altitude, and airspeed and not respond to any of the guidance or alerting from DAIDALUS. The offset also provided a glance at how sensor noise and uncertainty impacts encounters where both aircraft are not co-altitude. The accelerating intruder encounters involved an intruder at 45°, 90°, and 135° azimuths with 300 ft. vertical offset which performed a level acceleration from approximately 130 kts to 180 kts ground speed at a predetermined waypoint. The Ikhana operators were instructed to follow the DAIDALUS guidance and fly within 10° of the edge of the avoidance bands. Direction of the maneuver was left up to the Ikhana operators' discretion. The predetermined vertical maneuver encounters involved a level intruder 1000 ft. below the Ikhana on a parallel course with a 2430 ft. horizontal offset. The Ikhana operators were instructed to descend at 500 feet per minute and level off once a DAA warning alert was triggered. These encounters were designed to evaluate the alerting time afforded in an encounter with a moderate vertical closure rate with different TCOA values.

# Results

## Fly-Through Encounters

For the non-maneuvering Fly-Through encounters, DAIDALUS was configured with values representative of a minimally acceptable fielded UAS system, as defined by the draft SC-228 MOPS document. The DAIDALUS parameters were configured as follows: HMD* = 0.66 nmi, $\tau^*_{mod}$ = 35 seconds, ZTHR = 450 ft., Corrective Alert Time: 40 seconds, Warning Alert Time: 20 seconds, and TCOA = 0. Encounter geometries flown were as follows: 0°, 45°, 90°, 135°, and 180° off the nose of the Ikhana ownship. Figure 2 illustrates the encounter geometries flown for the fly-through encounters. The Ikhana was flown at 160 kts ground speed while the intruder aircraft was flown at 180 kts ground speed for all fly-through encounters. The 0°, 45°, and 90° encounters were flown with the fused combination of RADAR, TCAS, and ADS-B, and the fused combination of RADAR and TCAS sensors. Each encounter utilized a 0.4 nmi horizontal and 300 ft. vertical offset between the aircraft for safety. Table 2 displays all of the fly-through encounter geometries, sensor combination, and closest points of approach.

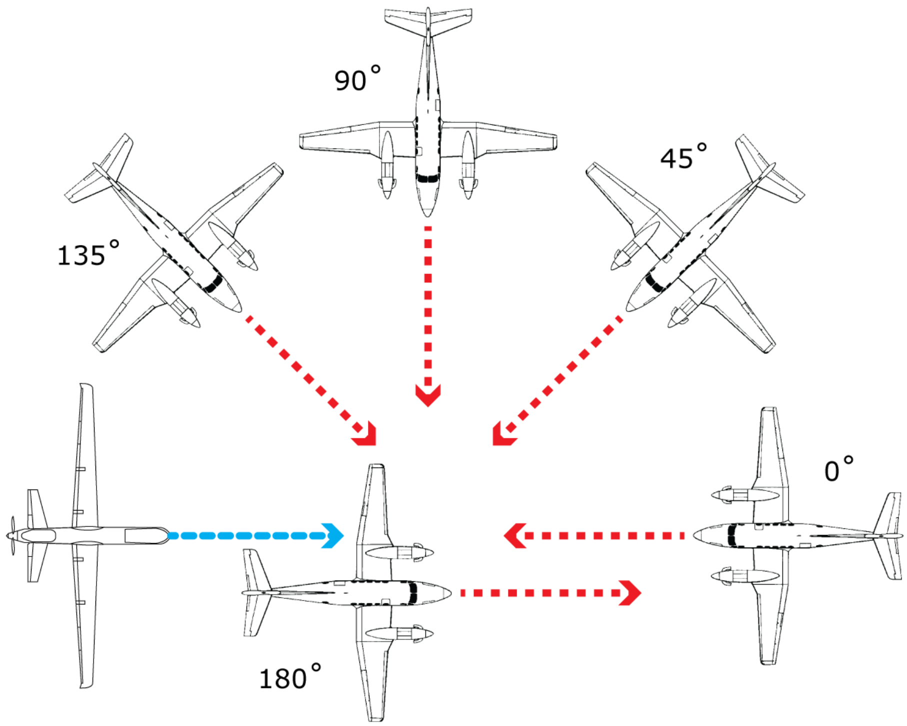


*Figure 2. Illustration of Fly-Through Encounter Geometries*

*Table 2. Fly-Through encounter geometry, sensor combination and closest point of approach.*

| Flight Date | Flight Card | Geometry | Sensor | CPA (nmi) |
|---|---|---|---|---|
| 6/9/2016 | 73 | 0° | RADAR/TCAS/ADS-B/Tracker | 0.38 |
| 6/9/2016 | 78 | 0° | RADAR/TCAS/Tracker | 0.34 |
| 6/9/2016 | 74 | 45° | RADAR/TCAS/ADS-B/Tracker | 0.21 |
| 6/9/2016 | 79 | 45° | RADAR/TCAS/Tracker | 0.25 |
| 6/9/2016 | 75 | 90° | RADAR/TCAS/ADS-B/Tracker | 0.73 |
| 6/9/2016 | 80 | 90° | RADAR/TCAS/Tracker | 0.75 |
| 6/9/2016 | 76 | 135° | RADAR/TCAS/ADS-B/Tracker | 0.39 |
| 6/17/2016 | 77 | 180° | RADAR/TCAS/ADS-B/Tracker | 0.47 |

All fly-through encounters except the two 90° intruder encounters (flight cards 75 and 80) entered the HMD* threshold of 0.66 nmi, meaning the 90° intruder encounters either did not lose well-clear or lost well-clear only through entering the geographic area defined by $\tau^*_{mod}$ when solved for distance. A detailed analysis and explanation of why these encounters did not reach their planned closest points of approach is included in this section.

Range at first DAA alert can provide an estimation of distances that UAS operators will either begin negotiating with ATC or begin maneuvering to avoid manned aircraft. Alerting range can impact NAS operations if alerting begins while within the range that a manned aircraft pilot would be able to make visual contact. It may be desirable for a UAS operator to initiate an avoidance maneuver before both aircraft enter visual range of each other to avoid simultaneous and incompatible maneuvers. Figure 3 and Figure 4 contain the ranges between the Ikhana ownship and the intruder aircraft at the time of first corrective and warning alert generated by DAIDALUS. One of the 90° encounters did not trigger a corrective alert, most likely due to the ownship unexpectedly maneuvering. As expected for both corrective and warning alerts, the range at first alert decreases as the intruder's heading approaches the heading of the ownship and the closure rate drops. In the head-on (0°) and 45° encounters the corrective alerts for all sensors fused and RADAR and TCAS fused were triggered at comparable ranges. For warning alerts however it appears the RADAR and TCAS fused head-on and 45° encounters occurred at slightly shorter range than the encounters with all sensors fused.

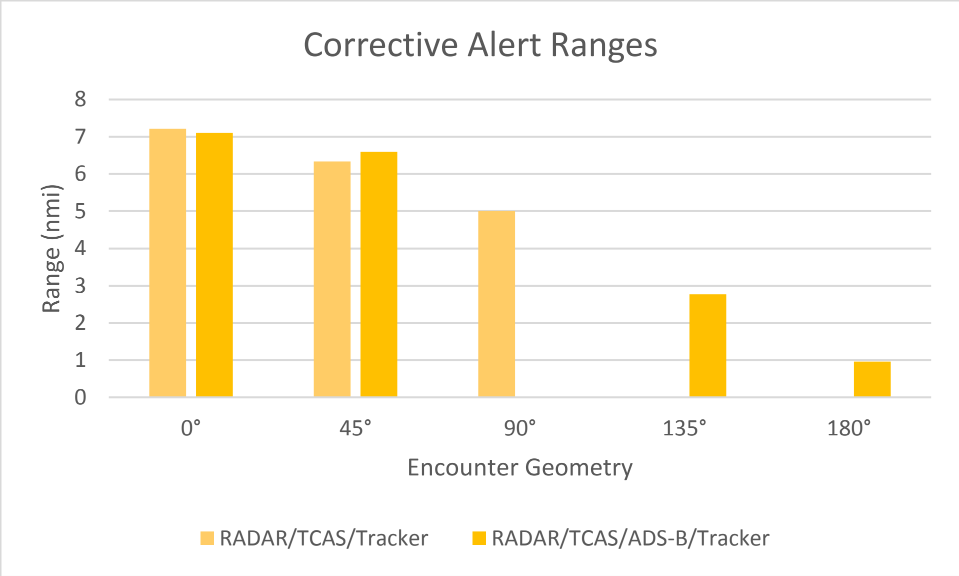


*Figure 3. Corrective DAA alert ranges.*

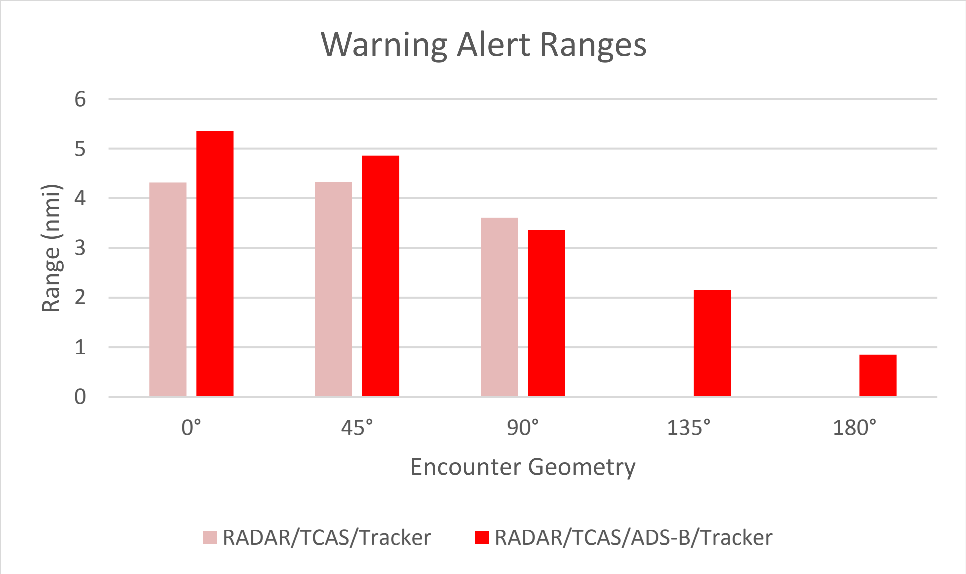


*Figure 4. Warning DAA alert ranges.*

Alerting time is a measure of how much time DAIDALUS provides the UAS operator to either negotiate with ATC or execute an avoidance maneuver. Alerting time is determined by measuring the time elapsed from the first occurrence of an alert to the time when the well-clear volume is penetrated. Corrective alerts were expected at 40 seconds to loss of well-clear and warning alerts expected 20 seconds to loss of well-clear for the fly-through encounters. Figure 5 and Figure 6 contain the corrective and warning alerting times for the fly-through encounters.

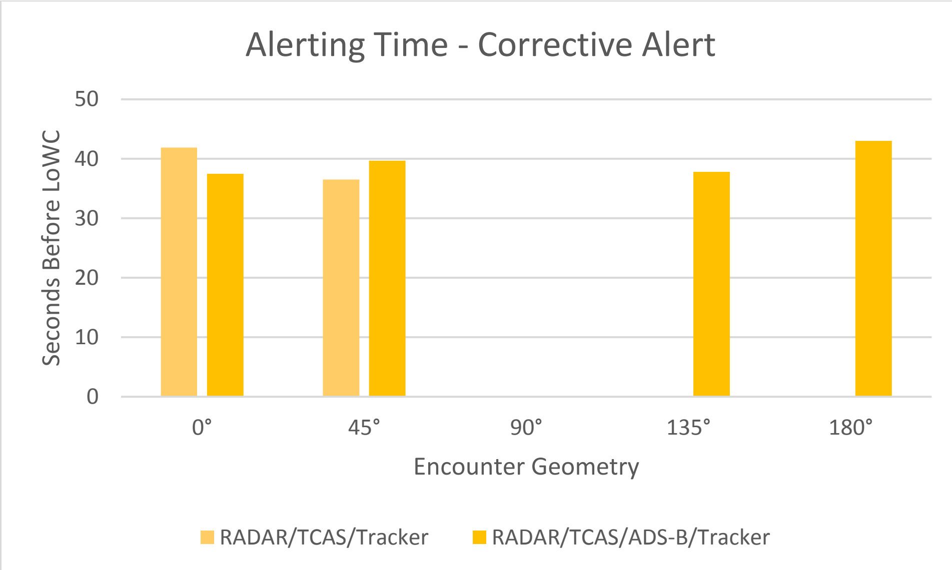


*Figure 5. Corrective Alerting Time*

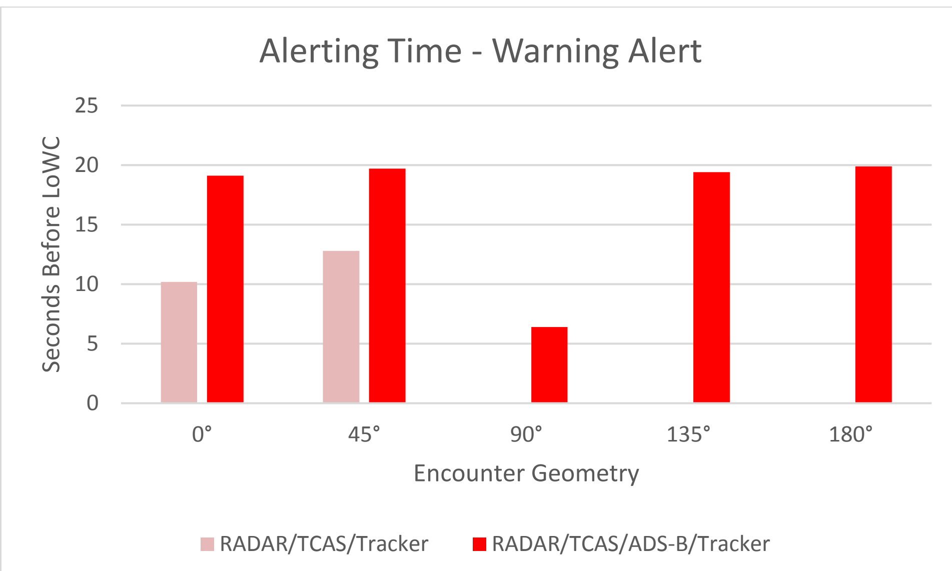


*Figure 6. Warning Alerting Time*

All corrective alerts triggered in the fly-through encounters met the draft minimum criterion of alerting greater than 20 seconds to penetration of the WCV. The average corrective alerting time was 39.4 seconds, just below the DAIDALUS corrective alert time parameter of 40 seconds. Corrective alerting time measurement was impossible for the two 90° two encounters, flight cards 75 and 80, as encounter 75 (RADAR/TCAS/ADS-B/Tracker) did not trigger a corrective alert due to inadvertent maneuvering of the Ikhana and encounter 80 (RADAR/TCAS/Tracker) did not lose well-clear according to the airborne surveillance data due to the timing of the beginning of the encounter. Although encounter 80 could not be scored against a logged LoWC, the estimated time to penetration of the WCV generated by DAIDALUS suggested the first corrective alert occurred 38.3 seconds before the projected LoWC. This suggests that the corrective alert for encounter 80 would have met the minimum alerting time prescribed in the MOPS had both aircraft continued on a linear trajectory. Warning alerts were triggered in all encounters, although scoring encounter 80 was impossible due to no LoWC being logged in the surveillance data. The estimated time to penetration of the WCV generated by DAIDALUS suggested the warning alert in encounter 80 occurred 15.4 seconds to LoWC, approximately the minimum time allowed prescribed in the draft MOPS before a LoWC occurrence.

To judge the level of interoperability between the current DAA minimum standards and the TCAS collision avoidance system, the times of DAA alerts and TCAS corrective RAs were compared. The time between a DAA warning alert and a TCAS corrective RA would be the minimum amount of time a UAS operator flying in the NAS would have to maneuver to avoid triggering a potentially disruptive Resolution Advisory in other aircraft operating in the vicinity of the unmanned vehicle. Figure 7 shows the amount of DAA warning alert lead time in seconds before a TCAS RA was triggered in the Ikhana. The results suggest UAS operators would have on average 23 seconds to command a maneuver in the air vehicle and avoid triggering a corrective RA. The 180° overtake geometry incurred the lowest lead time between DAA warning alert and TCAS RA, which is a direct result of the low closure rate between the aircraft and the TCAS DMOD size for sensitivity level 6 being larger than the DAA HMD* size. The 180° overtake encounter was also the only encounter where the TCAS RA was triggered after the well-clear volume was penetrated. This result appears to indicate that larger HMD* values should be utilized at altitudes above 10,000 ft. to avoid nuisance alerts from TCAS.

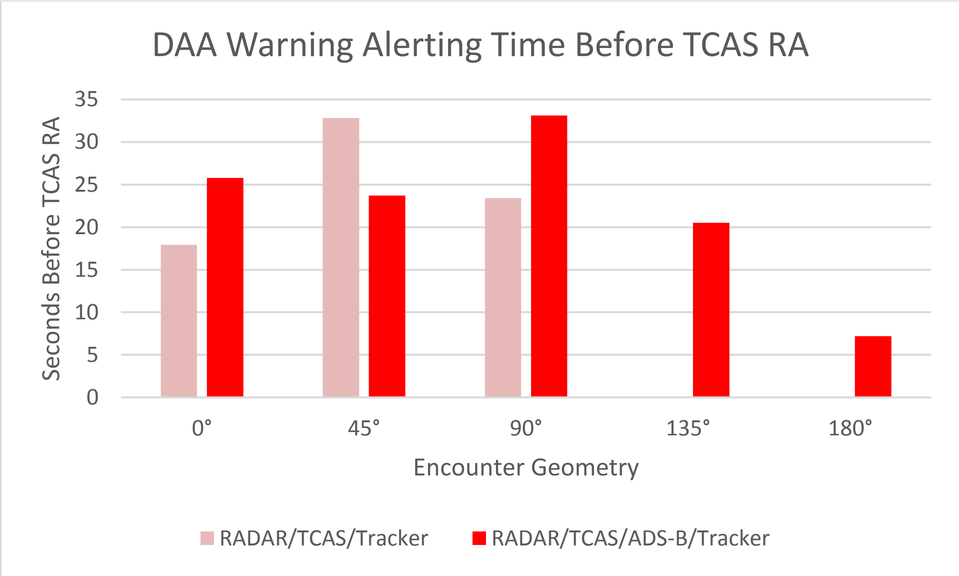


*Figure 7. DAA warning alert lead time before TCAS Resolution Advisory.*

Three of the fly-through encounters experienced warning alerts later than the prescribed minimum: cards 75 (90°-RADAR/TCAS/ADS-B/Tracker) at 6.4 seconds to LoWC, 78 (0°-RADAR/TCAS/Tracker) at 10.2 seconds to LoWC, and 79 (45°-RADAR/TCAS/Tracker) at 12.8 seconds to LoWC. To investigate the reasons behind these late alerts, a time history chart of ownship alerting, heading, time to LoWC and guidance bands was utilized. The X-Axis represents time in seconds since the start of the flight day. The Y-Axis represents heading in degrees relative to the pre-planned ownship heading for each encounter. The heading of the Ikhana is represented as a gray line if no DAA alert is present, yellow if corrective alert is present, and red if a warning alert is present. The sensed heading of the intruder aircraft is represented as a green line. The position of the DAIDALUS avoidance bands for each time step are represented as orange bars and the recovery bands as the green bars. Time to LoWC is represented as purple triangles with the zero heading representing zero seconds to WCV penetration. Figure 8 presents the alerting and guidance time history for encounter 75.

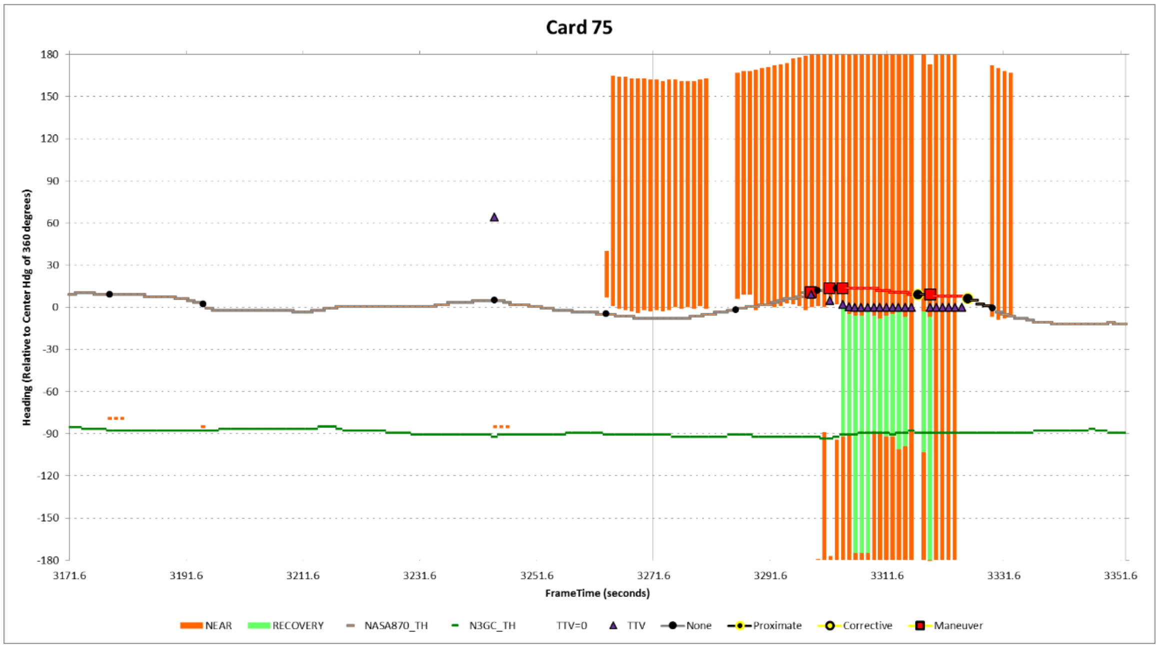


*Figure 8. Guidance and alerting time history chart for 90° encounter 75*

It appears from the alerting and guidance time history chart that the Ikhana's heading deviated from the planned heading of 360° and was in a gradual oscillation throughout most of the encounter. The oscillation starting at encounter time 3271.6 appears to have caused the missed corrective and late warning alerts. Had the Ikhana flown a constant heading, the encounter likely would have had timelier alerting or not alerted at all. During the encounter the alert level cycled between warning and preventive alerts, an undesirable behavior caused by noise in the vertical speed as the preventive alert is only triggered between 450 ft. and 700 ft. above and below the Ikhana. It is possible that recent requirements in the DAA MOPS regarding alert persistence would have prevented this behavior, however DAIDALUS did not incorporate these improvements for FT4. Another behavior uncovered in this encounter started at encounter time 3320.6 seconds when the green recovery bands disappeared and the orange avoidance bands were displayed for all 360° on the DAIDALUS-MACS heading display. The 360° guidance bands implies that in this situation, DAIDALUS determined that all headings will result in an HMD* penetration, which resulted in an interruption in the recovery guidance. The latest version of DAIDALUS resolves this interruption by progressively reducing the size of the distance threshold once well-clear recovery guidance is displayed. However, this band saturation mitigation strategy was not implemented for FT4.

An alerting and guidance time-history for heading, altitude and vertical speed for encounter 79 is displayed in Figure 9, Figure 10, and Figure 11 respectively. Figure 9 shows that encounter 79 progressed as planned with headings for the Ikhana and the intruder showing minor deviations throughout the encounter. The corrective alert was triggered at 36.5 seconds to WCV penetration, however the corrective alert was dropped for approximately 6 seconds until the warning alert was triggered late at 12.8 seconds to WCV penetration. Figure 10 shows that the sensed altitude of the intruder aircraft was stable at 400 ft. above the Ikhana during the 6 seconds of alerting interruption, meaning the intruder was within the vertical corrective and warning alerting threshold for DAIDALUS. In Figure 11 it is apparent during that same time period the estimated vertical speed of the intruder changed from descending into the Ikhana's altitude to climbing away from the Ikhana. This change in vertical speed is what likely caused the interruption in alerting and late warning alert.

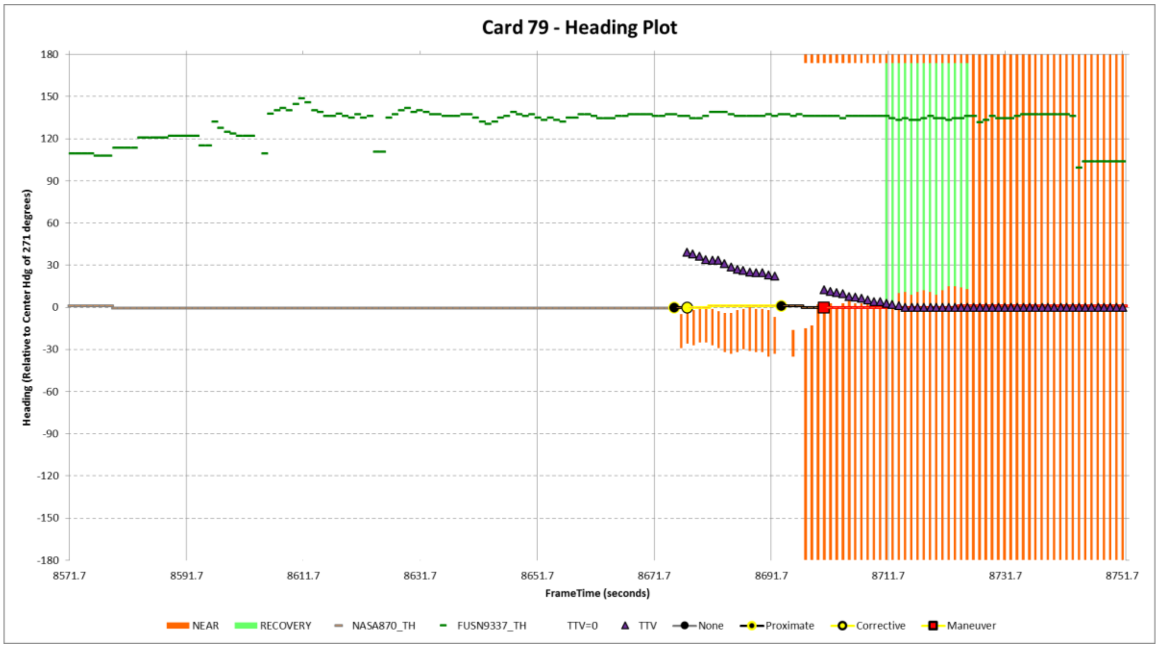


*Figure 9. Alerting and guidance time history for 45° encounter 79 - Heading Plot*

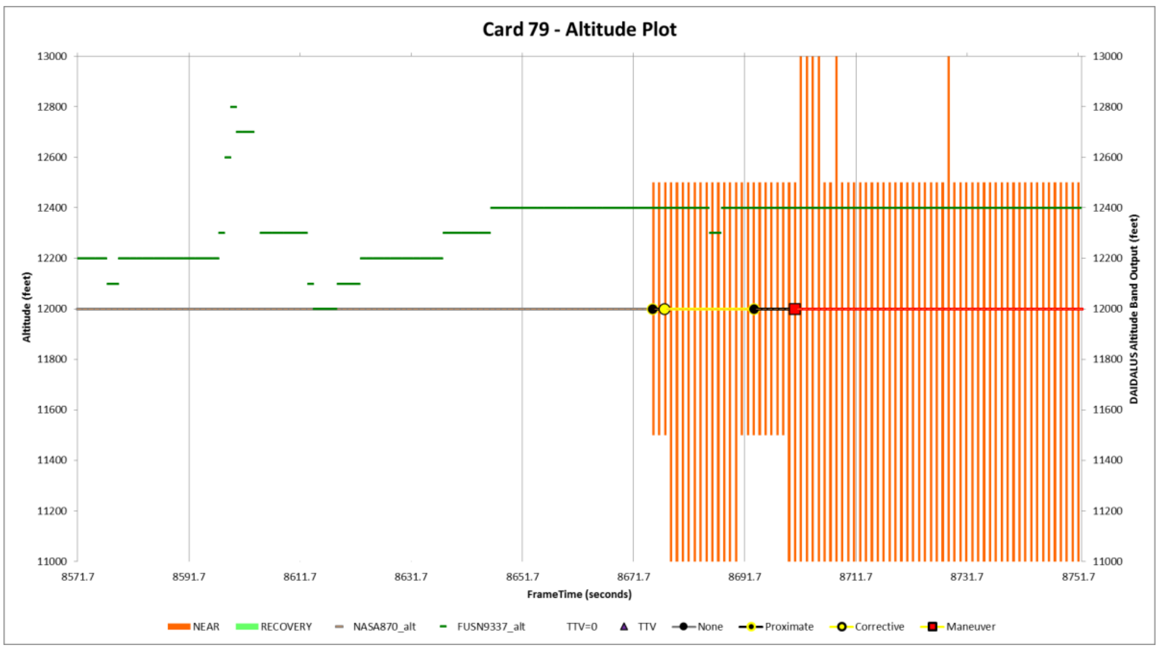


*Figure 10. Alerting and guidance time history for 45° encounter 79 - Altitude Plot*

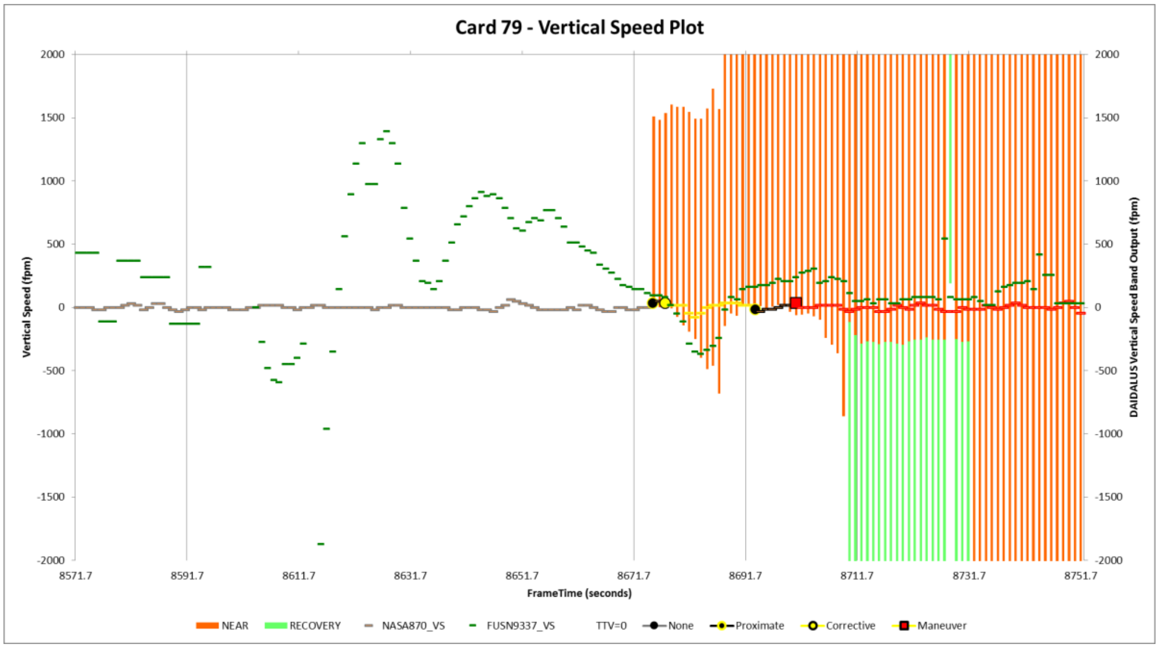


*Figure 11. Alerting and guidance time history for 45° encounter 79 - Vertical Speed Plot.*

Figure 12 shows the alerting and guidance heading plot history for encounter 78. Encounter 78 experienced a gap in alerting similar to encounter 79 which resulted in a late DAA warning alert at 10.2 seconds until well-clear volume penetration. During the 15 second gap in alerting and guidance both the Ikhana's heading and the sensed intruder heading were relatively stable and unchanging. The vertical speed plot for encounter 78 in Figure 13 shows a similar pattern to encounter 79 where the sensed vertical speed of the intruder aircraft indicates a climb away from the Ikhana while the sensed altitude remained constant through the interruption.

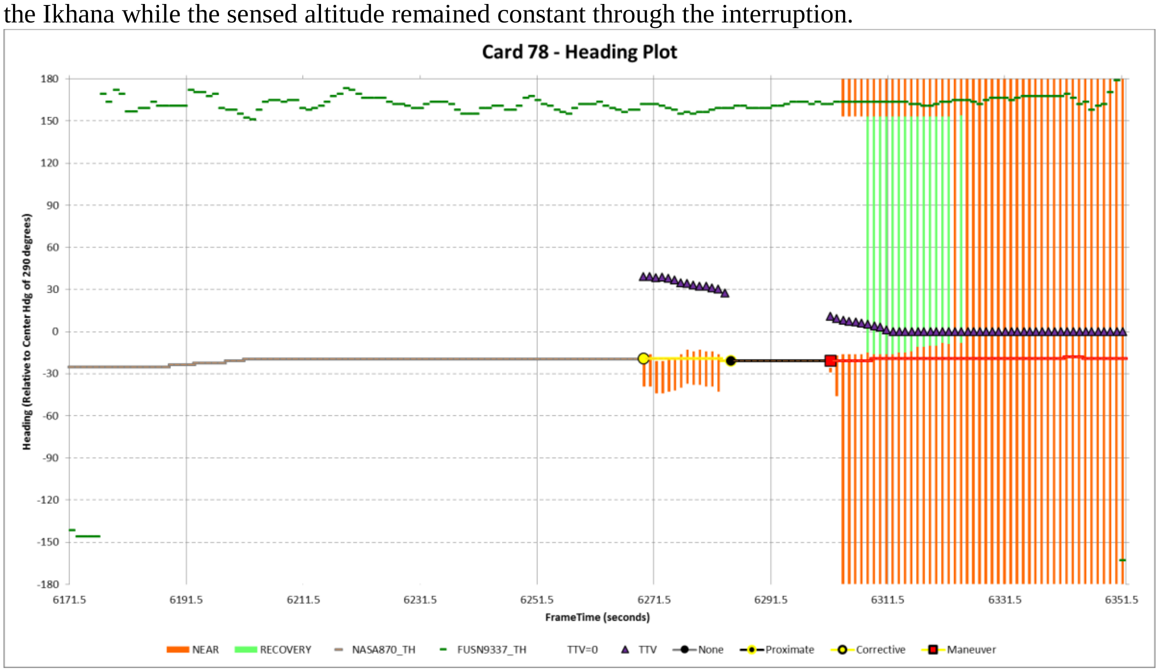


*Figure 12. Alerting and guidance heading time history plot for 0° encounter 78*

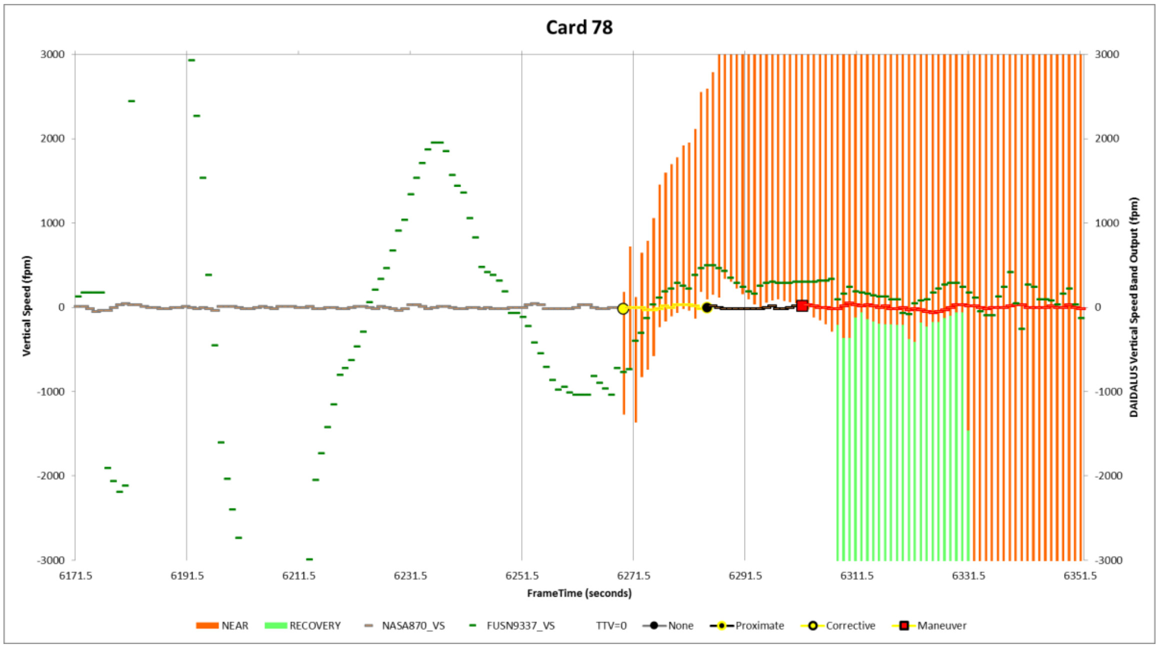


*Figure 13. Alerting and guidance vertical speed plot for 0° encounter 78*

## Accelerating Intruder Encounters

For the accelerating intruder encounters the well-clear volume size was configured in DAIDALUS to be larger than the minimally accepted, but within the allowed size. The WCV size was changed to ensure the accelerating intruder aircraft would trigger DAIDALUS alerting and guidance due to uncertainty in intruder aircraft performance. The DAIDALUS parameters were configured as follows: HMD* = 1.0 nmi, $\tau^*_{mod}$ = 35 seconds, ZTHR = 450 ft., Corrective Alert Time: 40 seconds, Warning Alert Time: 20 seconds, and TCOA = 0. Each encounter started with the Ikhana and the intruder aircraft level at 130 kts ground speed at 45°, 90° and 135° azimuths. When the intruder crossed a predetermined waypoint, the pilot executed a 50 kt ground speed acceleration. The Ikhana operator then waited until a DAA warning alert was triggered in DAIDALUS at which point the lateral avoidance maneuver began. The Ikhana operators were also instructed to maneuver back to the original course after the initial avoidance maneuver as the guidance allowed. Table 3 represents the accelerating intruder encounters flown in FT4. The two 45° encounters were the only runs to both lose well-clear and fly within the lateral HMD* distance threshold. The three remaining encounters did not fly within the WCV. Encounter 150 experienced a networking error which possibly removed ADS-B surveillance data from the sensed position ingested by DAIDALUS, although whether or not the ADS-B data was used is unclear based on the results.

*Table 3. Accelerating intruder encounters*

| Flight Date | Flight Card | Geometry | Sensor | CPA (nmi) |
|---|---|---|---|---|
| 9/9/2016 | 148 | 45° | RADAR/TCAS/Tracker | 0.97 |
| 9/9/2016 | 150 | 45° | RADAR/TCAS/ADS-B/Tracker | 0.94 |
| 9/9/2016 | 149 | 90° | RADAR/TCAS/Tracker | 2.25 |
| 9/9/2016 | 151 | 90° | RADAR/TCAS/ADS-B/Tracker[1] | 2.8 |
| 9/9/2016 | 152 | 135° | RADAR/TCAS/ADS-B/Tracker | 1.52 |

*Note 1: Encounter 151 experienced an anomaly which likely removed the ADS-B surveillance data from the sensed position and velocity*

Encounter 151 (90°) provides an example of a desired outcome for a scenario where the intruder performs a level acceleration into the ownship. Figure 14 provides the alerting and guidance time history for encounter 151.

The intruder accelerated for 49 seconds from 126 kts to 190 kts ground speed starting at encounter time 13915.2 seconds. The avoidance bands appear and slowly grow and shift towards the Ikhana's heading until the corrective alert was triggered at an estimated time to LoWC of 37.6 seconds. The corrective alert was displayed by DAIDALUS for a total of 16.5 seconds before the warning alert was triggered. At 19.4 seconds estimated time to LoWC the warning alert was triggered and the Ikhana operator began a single 42° turn to remain well clear approximately 4 seconds afterwards. A LoWC was not logged by the surveillance data and the Ikhana returned to its course without any further alerts being triggered.

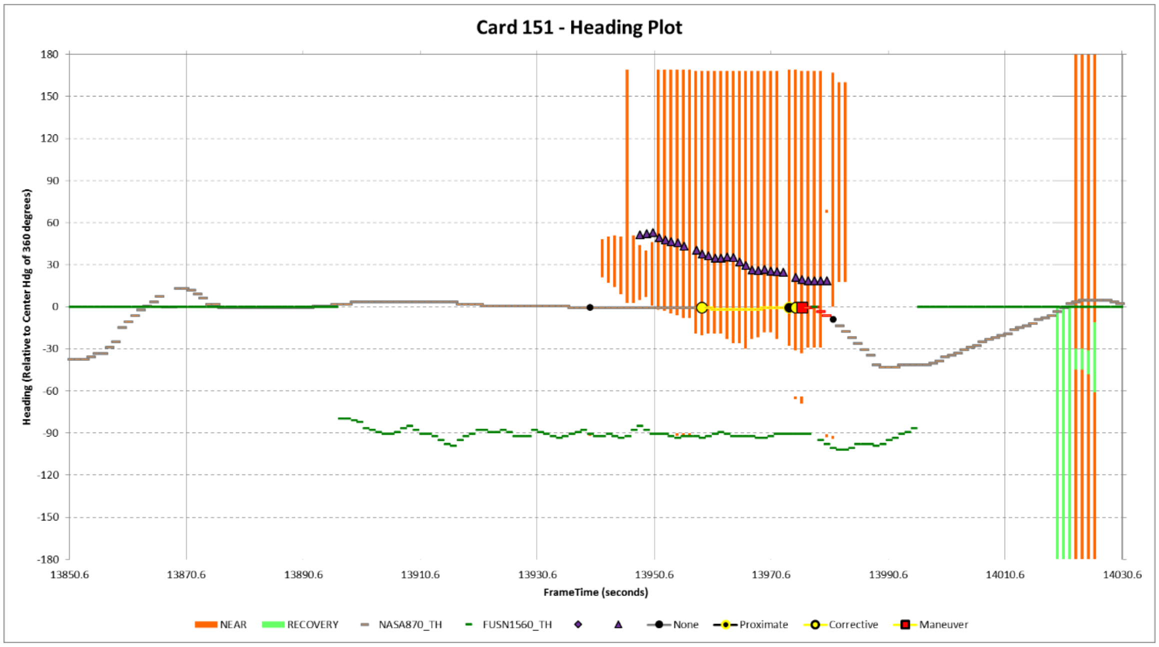


*Figure 14. Alerting and guidance time history for 90° encounter 151 - heading plot*

Encounter 148 demonstrates an encounter where the corrective alert is completely missed and the warning alert is triggered late. Figure 15 presents the alerting and guidance time history heading plot for encounter 148. The intruder accelerated from approximately 136 kts to 200 kts ground speed starting at encounter time 11928 seconds. A warning alert was triggered at 11.8 seconds before losing well-clear. An apparent anomaly occurred 4 seconds after the warning alert was triggered where 360° recovery bands were displayed by DAIDALUS. Analysis of the encounter video revealed two sensed tracks being generated on top of each other. The two separate tracks' predicted future flight states could have diverged in a way where DAIDALUS was temporarily "boxed-in" and could not generate a well clear resolution. The Ikhana operator began a 41° turn approximately 4 seconds before the first LoWC was logged. Once again the Ikhana operator maneuvered to attempt to return to course and generated another LoWC occurrence due to an apparent spike in sensed intruder ground speed from 211 kts to 265 kts. The sensed ground speed spike is indicative of the higher level of sensor uncertainty associated with the RADAR/TCAS fused combination when compared to tracks generated by ADS-B.

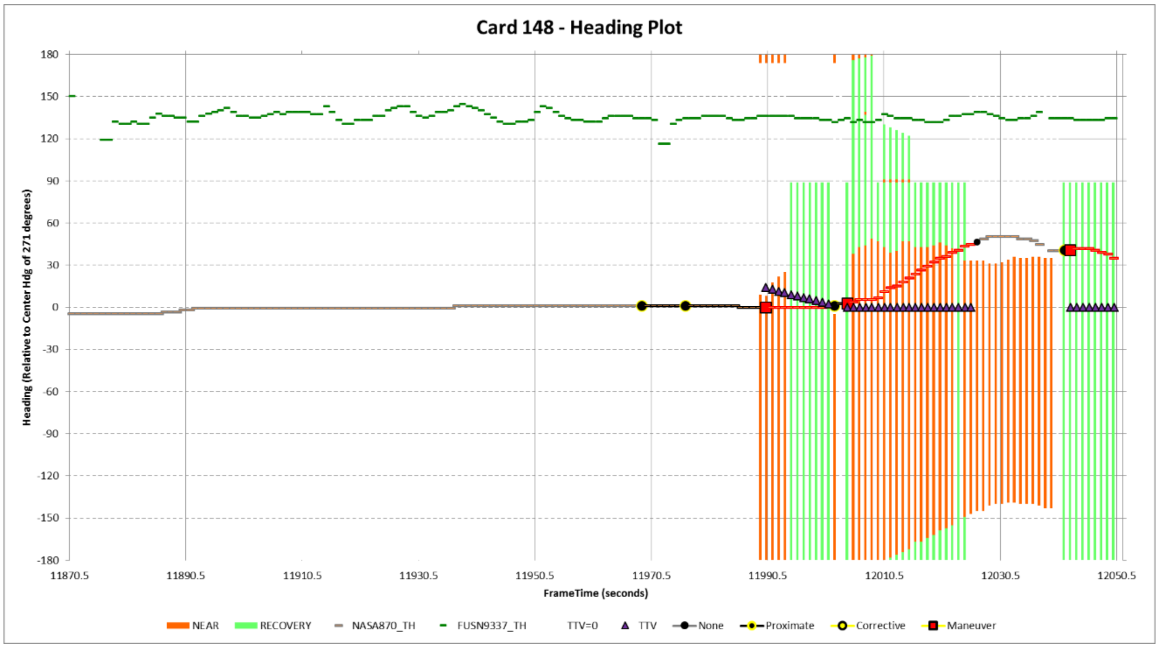


*Figure 15. Alerting and guidance time history heading plot for 45° encounter 148*

Encounter 150 provides an example of an encounter where the Ikhana narrowly avoids a LoWC with an initial maneuver but loses well clear when attempting to return to the initial course. Figure 16 provides an alerting and guidance time history heading plot for encounter 150. The intruder began a 36 second acceleration from 159 kts to 205 kts ground speed starting at encounter time 12563 seconds. The first corrective alert was triggered 39.7 seconds to the eventual LoWC and the warning alert was triggered 23.5 seconds to LoWC. The Ikhana operator executed a 33° turn following the edge of the bands after the first warning alert was triggered which eventually resulted in the Ikhana's CPA being outside the hazard zone defined by the HMD* and $\tau^*_{mod}$. The initial maneuver resulted in the Ikhana remaining well-clear from the intruder, although when the Ikhana operator attempted to return to course the alerting returned and a LoWC was subsequently logged. The Ikhana operator likely observed the edge of the avoidance bands begin to recede and maneuvered in anticipation of the bands receding further. An explanation of the behavior of the bands in this case appears to be a minor course correction of the intruder aircraft at the time of the start of the Ikhana's recovery back to its original course. The Ikhana's close proximity to the edge of the well-clear volume (0.6 seconds to LoWC before the Ikhana was projected to be well-clear) allowed the slight maneuver to cause a LoWC. This case presents display and operational questions to manufacturers who would be fielding a DAA system which will be discussed in later in the paper.

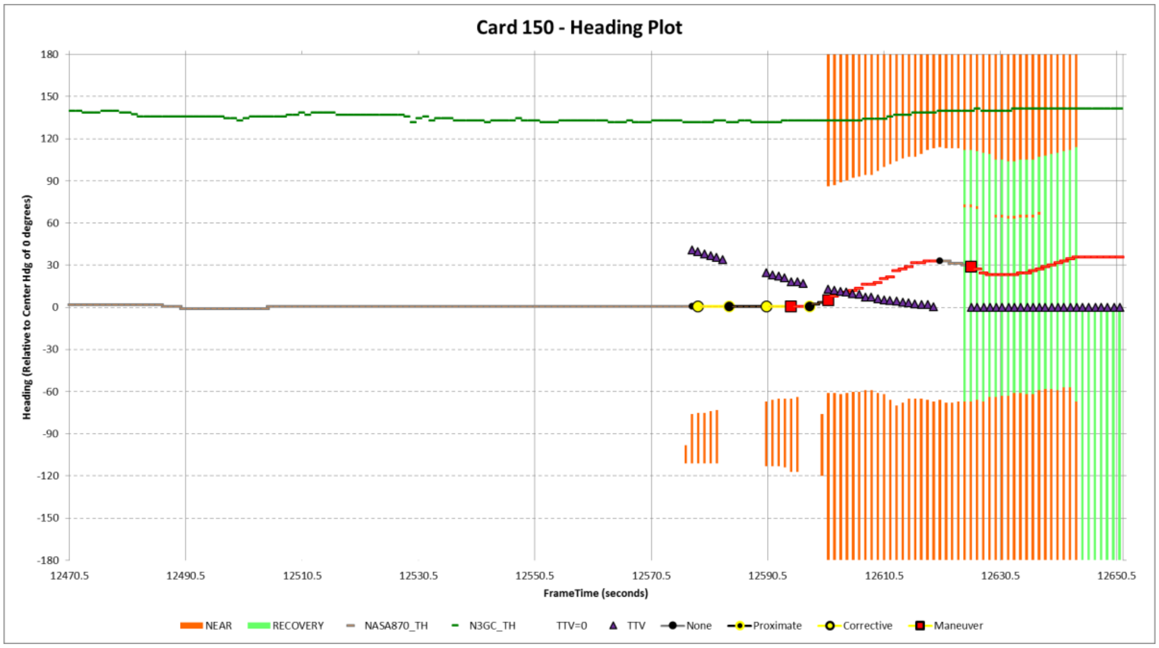


*Figure 16. Alerting and guidance time history heading plot for 45° encounter 150*

## Vertical Maneuver Encounters

The vertical maneuver encounters involved the Ikhana ownship and an intruder aircraft on parallel paths and identical ground speeds with 1000 ft of vertical separation. The Ikhana operator was instructed to initiate a descent at 500 ft./min and level off when a DAA warning was triggered. For the vertical maneuver encounters the LVC data replay capability was utilized to run the surveillance data collected in live flight through the DAIDALUS algorithm with different parameters. In this case DAIDALUS was flown in live flight with the following parameters: HMD* = 0.66 nmi, $\tau^*_{mod}$ = 35 seconds, ZTHR = 450 ft., Corrective Alert Time: 40 seconds, Warning Alert Time: 20 seconds, and TCOA = 0. The surveillance data was then replayed through DAIDALUS post-hoc with TCOA values of 20 seconds and 35 seconds.

| Flight Card | TCOA (seconds) | Sensor | Warning Alert Relative **Altitude (ft)** | **TCAS RA Relative Altitude (ft)** | **Ikhana TCAS Message** |
|---|---|---|---|---|---|
| 100 | 0 | RADAR/TCAS/ADS-B/Tracker | 700 | 500 | Level Off |
| 100 | 20 | RADAR/TCAS/ADS-B/Tracker | 720 | 500 | Level Off |
| 100 | 35 | RADAR/TCAS/ADS-B/Tracker | 700 | 500 | Level Off |
| 102 | 0 | RADAR/TCAS/ADS-B/Tracker | 700 | 600 | Level Off |
| 102 | 20 | RADAR/TCAS/ADS-B/Tracker | 700 | 600 | Level Off |
| 102 | 35 | RADAR/TCAS/ADS-B/Tracker | 800 | 600 | Level Off |
| 104 | 0 | RADAR/TCAS/Tracker | 800 | 600 | Climb |
| 104 | 20 | RADAR/TCAS/Tracker | 800 | 600 | Climb |
| 104 | 35 | RADAR/TCAS/Tracker | 800 | 600 | Climb |
| 99 | 0 | RADAR/TCAS/ADS-B/Tracker | 900 | 600 | Level Off |
| 99 | 20 | RADAR/TCAS/ADS-B/Tracker | 800 | 600 | Level Off |
| 99 | 35 | RADAR/TCAS/ADS-B/Tracker | 800 | 600 | Level Off |

presents the vertical descent encounters flown in FT4. The primary goal of the vertical descent encounters was to evaluate whether extending the vertical well-clear volume to include the TCOA variable provided additional alerting lead time before a TCAS Resolution Advisory was triggered. Only one encounter triggered a "Climb" TCAS resolution message in the Ikhana which would have required the Ikhana operator to reverse the descent.

| Flight Card | TCOA (seconds) | Sensor | Warning Alert Relative **Altitude (ft)** | **TCAS RA Relative Altitude (ft)** | **Ikhana TCAS Message** |
|---|---|---|---|---|---|
| 100 | 0 | RADAR/TCAS/ADS-B/Tracker | 700 | 500 | Level Off |
| 100 | 20 | RADAR/TCAS/ADS-B/Tracker | 720 | 500 | Level Off |
| 100 | 35 | RADAR/TCAS/ADS-B/Tracker | 700 | 500 | Level Off |
| 102 | 0 | RADAR/TCAS/ADS-B/Tracker | 700 | 600 | Level Off |
| 102 | 20 | RADAR/TCAS/ADS-B/Tracker | 700 | 600 | Level Off |
| 102 | 35 | RADAR/TCAS/ADS-B/Tracker | 800 | 600 | Level Off |
| 104 | 0 | RADAR/TCAS/Tracker | 800 | 600 | Climb |
| 104 | 20 | RADAR/TCAS/Tracker | 800 | 600 | Climb |
| 104 | 35 | RADAR/TCAS/Tracker | 800 | 600 | Climb |
| 99 | 0 | RADAR/TCAS/ADS-B/Tracker | 900 | 600 | Level Off |
| 99 | 20 | RADAR/TCAS/ADS-B/Tracker | 800 | 600 | Level Off |
| 99 | 35 | RADAR/TCAS/ADS-B/Tracker | 800 | 600 | Level Off |

Figure 17 shows the DAA warning alert lead time before a TCAS RA was triggered for all vertical descent encounters and TCOA values. There appeared to be no effect of extending the vertical well-clear threshold for the vertical rates achieved in these encounters. The minor differences between the TCOA values were all less than 1.2 seconds and could be explained by track interpolation in the MACS software. The warning alert lead time before TCAS RA varied between the encounters from approximately 25 seconds to approximately 5 seconds. The wide range of alert lead time was likely due to the poor vertical rate estimation of the intruder.

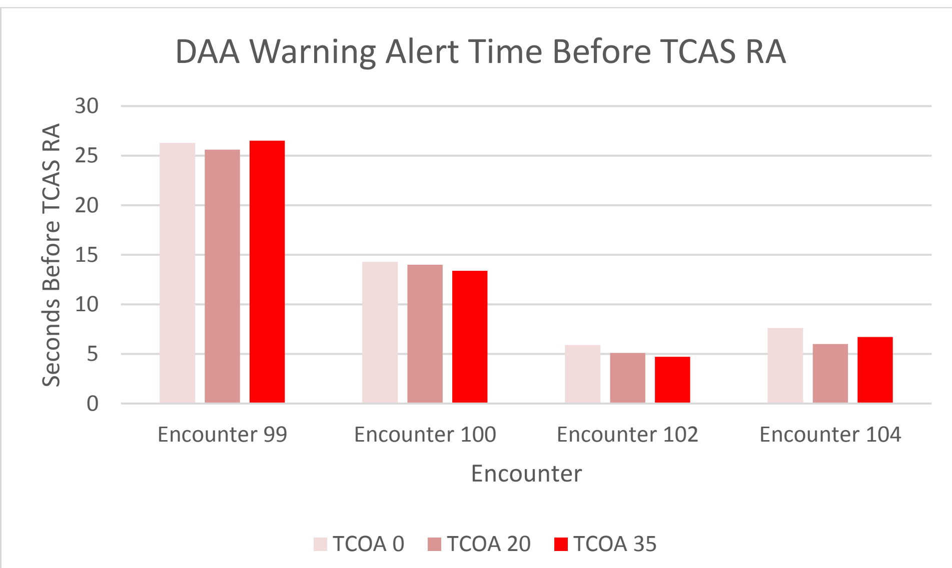


*Figure 17. DAA warning alert lead time before TCAS RA*

## Discussion

Overall the UAS in the NAS Flight Test 4 was successful in demonstrating the feasibility of the draft Detect and Avoid Minimum Operational Performance Standards in real world conditions. FT4 was the first time the

DAIDALUS DAA algorithm was flown with a MOPS representative system, as FT3 used an extended well-clear volume to ensure the encounters could be completed successfully. DAIDALUS was able to generate timely and valid guidance using RADAR/TCAS and RADAR/TCAS/ADS-B sensor combinations, suggesting a fielded DAA system would be able to detect and avoid both non-cooperative aircraft (with only a transponder onboard) and those with cooperative ADS-B systems which broadcast flight state messages. The encounters analyzed in this paper also demonstrate several idiosyncrasies of DAA which will need to be taken into consideration for a fielded DAA system.

The non-maneuvering fly-through encounters were designed to evaluate the ability of a DAA system to meet the minimum performance standards outlined in the draft MOPS. Generally the fly-through encounters demonstrated that the DAIDALUS alerting and guidance can generate effective well-clear resolutions given existing airborne surveillance sensors. As expected the ranges at which corrective and warning alerts were triggered show that range decreases as closure rate decreases. There were not dramatic or unexpected differences in range between sensor combinations in corrective or warning alert, although differences would be expected between sensors as the closure rate between the ownship and the intruder aircraft increases. It remains to be seen how alerting the UAS operator at these ranges will impact manned aircraft which are reliant on human vision to avoid aircraft in the NAS. Measurement of corrective alerting time found the sensors afforded timely alerting to the UAS operator given the DAIDALUS alert parameters. Measurement of warning alerting time for the fly-through encounters found the RADAR/TCAS sensor combination is more likely to experience late alerting that the RADAR/TCAS/ADS-B combination would not. A solution to sensor uncertainty is needed in order to prevent late alerting occurrences like the ones observed in FT4. Closer analysis of the alerting and guidance found the RADAR/TCAS sensor is also more likely to cause alert "jitter" where the displayed alert flashes between an alerted state and a non-alerted state. This behavior is concerning as it might cause the human operator to either attenuate the alerts or distrust them. The draft DAA Phase 1 MOPS currently require alert hysteresis and an optional time criterion for displaying an alert to minimize alert jitter, however neither of these were implemented for DAIDALUS in FT4. Fly-through encounter 75 demonstrated the limitations of the DAIDALUS state-based DAA alerting, as the intruder made shallow S-turn corrections throughout the encounter which eventually caused a late warning alert.

The intruder level acceleration encounters were designed to exploit another potential weakness of a state-based (as opposed to an intent-based) alerting algorithm which could be experienced in the NAS, as an aircraft transitioning from the terminal environment to cruise would be accelerating. The analysis have revealed the current DAA solution is able to tolerate an intruder's rapid ground speed changes to a certain extent. Only two of the encounters logged a loss of well-clear and in each case the DAIDALUS algorithm was able to provide a well-clear solution to the UAS operator. Late alerting and shifting well-clear guidance can be expected in encounters similar to this, however without actually knowing the intentions of all potential intruders in the NAS, changing alerting and guidance is impossible to avoid completely.

TCAS interoperability was another subject of interest for FT4 analysis. The goal of interoperability between DAA and collision avoidance is to provide sufficient alert time and miss-distance for the UAS operator to avoid triggering collision avoidance alerts, and overall the fly-through encounters produced good interoperability. The one exception observed was the encounter where the Ikhana was overtaking the intruder. The DAA warning was triggered only 6 seconds before the TCAS RA, leaving minimal time for a prospective UAS operator to avoid the TCAS alert. Additionally the TCAS RA was triggered while the Ikhana was still well-clear of the intruder aircraft. This occurrence demonstrates the interoperability gap between DAA and TCAS alerting above 10,000 ft, as the TCAS miss distance is larger than the minimum DAA miss distance. A fielded DAA system could close this interoperability gap by increasing the HMD* value to be equal to or greater than the TCAS miss distance above 10,000 ft. The vertical descent encounters flown in FT4 exposed another DAA-TCAS interoperability gap, this time in the differences between the DAA and TCAS ZTHR value. The minimum DAA ZTHR is 450 ft. while the TCAS ZTHR below 42,000 ft. is 600 ft. One potential mitigation strategy to resolve this issue, extending the DAA WCV vertical dimension with a time component, was explored in this data analysis and found to offer no difference between varying TCOA values for the vertical speeds attained in the flights. This result confirms the assertion by Munoz and Narkowicz (2016) that TCOA would not have a measurable impact on alerting at vertical rates lower than 1400 feet per minute. The DAA warning lead time before TCAS RA for the vertical rates varied greatly, an indication that vertical rate estimation remains a challenge to DAA systems. A sensor uncertainty mitigation strategy which assumes a larger vertical volume than the minimum ZTHR could potentially provide timelier alerting and close the vertical DAA-TCAS interoperability gap.

# References

Munoz, C., Narkawicz, A. *Formal analysis of well-clear boundaries for unmanned aircraft*. Proceeedings of the 8th NASA Formal Methods Symposium (NFM, 2016), Lecture Notes in Computer Science, Vol. 9690, pp. 221-226, 2016

# REPORT DOCUMENTATION PAGE

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**14. ABSTRACT**

In order to validate the Unmanned Aerial System (UAS) Detect-and-Avoid (DAA) solution proposed by standards body RTCA Inc., the National Aeronautics and Space Administration (NASA) UAS Integration in the NAS project, alongside industry members General Atomics and Honeywell, conducted the fourth flight test in a series at Armstrong Flight Research Center in Edwards, California. Flight Test 4 (FT4) investigated problems of interoperability with the TCAS collision avoidance system with a DAA system as well as problems associated with sensor uncertainty. A series of scripted flight encounters between the NASA Ikhana UAS and various “intruder” aircraft were flown while alerting and guidance from the DAA algorithm were recorded to investigate the timeliness of the alerts and correctness of the guidance triggered by the DAA system. The results found that alerts were triggered in a timely manner in most instances. Cases where the alerting and guidance was incorrect were investigated further.

**15. SUBJECT TERMS**

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