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# Comparative Analysis of ACAS-Xu and DAIDALUS Detect-and-Avoid Systems

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# Abstract

The Detect and Avoid (DAA) capability of a recent version (Run 3) of the Airborne Collision Avoidance System-Xu (ACAS-Xu) is measured against that of the Detect and AvoID Alerting Logic for Unmanned Systems (DAIDALUS), a reference algorithm for the Phase 1 Minimum Operational Performance Standards (MOPS) for DAA. This comparative analysis of the two systems' alerting and horizontal guidance outcomes is conducted through the lens of the Detect and Avoid mission using flight data of scripted encounters from a recent flight test. Results indicate comparable timelines and outcomes between ACAS-Xu's Remain Well Clear alert and guidance and DAIDALUS's corrective alert and guidance, although ACAS-Xu's guidance appears to be more conservative. ACAS-Xu's Collision Avoidance alert and guidance occurs later than DAIDALUS's warning alert and guidance, and overlaps with DAIDALUS's timeline of maneuver to remain Well Clear. Interesting discrepancies between ACAS-Xu's directive guidance and DAIDALUS's "Regain Well Clear" guidance occur in some scenarios.

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# Nomenclature

| | |
|---|---|
| ACAS | Airborne Collision Avoidance System |
| ADS-B | Automatic Dependent Surveillance - Broadcast |
| DAA | Detect And Avoid |
| DAIDALUS | Detect and AvoID Alerting Logic for Unmanned Systems |
| $D_{\text{mod}}$ | modified distance |
| FAA | Federal Aviation Administration |
| FT2 | ACAS-Xu Flight Test 2 |
| GPS | Global Positioning System |
| HMD$^*$ | Horizontal Miss Distance Threshold |
| LoWC | Loss of Well-Clear |
| MOPS | minimum operational performance standard |
| PIC | pilot in command |
| RA | Resolution Advisory |
| RWC | Remain Well-Clear |
| STM | Surveillance and Tracking Module |
| TCAS | Traffic Alert and Collision Avoidance System |
| CPA | closest point of approach |
| TRM | Threat Resolution Module |
| UAS | unmanned aircraft system |
| VMD* | vertical miss distance threshold |
| WC | Well-Clear |
| WCV | Well-Clear Violation |
| fpm | Feet Per Minute |
| nmi | nautical mile |
| $\tau_{mod}$ | modified tau |

# 1 Introduction

Detect and Avoid (DAA) systems are a critical component of Unmanned Aircraft Systems (UAS) to remain Well Clear (WC) [1] from and avoid collisions with other airborne traffic. Manned aircraft rely on the pilot's sight to see and avoid aircraft in nearby airspace. DAA systems use surveillance sensors and algorithms to predict losses of DAA Well Clear (DWC) and provide alerting and guidance to the Pilot in Command (PIC) to ensure separation. Trade studies [2–5] and prototype DAA algorithms [6, 7] have been developed to explore and characterize the technical challenges of DAA. This technical work among others has enabled RTCA Committee 228 (SC-228) to publish Minimum Operational Performance Standards (MOPS DO-365) [1] [1] for DAA systems employed by UAS operating in non-terminal areas, referred to as Phase 1 MOPS. This MOPS applies to UAS equipped with Automatic Dependent Surveillance-Broadcast (ADS-B), active surveillance, and air-to-air radar systems that detect aircraft without transponders. Phase 2 work to extend the MOPS to additional UAS categories and operations is currently underway.

The alerting and guidance requirements in the DAA MOPS aim at avoiding losses of DWC. The Phase 1 MOPS define the DWC condition by the aircrafts' relative position and velocity. Specifically, it defines the DWC condition by three thresholds: projected horizontal miss distance, current altitude difference, and a nonlinear time to horizontal violation called modified tau. A detailed mathematical definition of DWC can be found in Appendix A. The Phase 1 MOPS defines three DAA alert and guidance levels, Preventive, Corrective, and Warning, in increasing severity [1]. Preventive and corrective alerts and guidance are caution-level (shown to the PIC in yellow/amber symbols). They are intended to provide awareness to the PIC that there is a predicted loss of DWC, but that there is sufficient time to coordinate with Air Traffic Control (ATC). The warning-level (shown to the PIC with a red symbol) alerts and guidance are intended to inform the PIC that an immediate maneuver is required. These caution and warning level alerts are in compliance with Advisory Circular guidance on the use of alerts. The guidance is of a suggestive nature, indicating a range of vertical and/or horizontal maneuvers predicted to result in a loss of DWC. Maneuvers outside the indicated range are suggested to the PIC to remain DWC. Figure 1 illustrates the heading and altitude guidance display to the PIC. The red color indicates ranges that are predicted to lead to a loss of Well Clear. If a loss of DWC is imminent and unavoidable by any maneuver, the DAA is required to issue suggestive guidance in order to expedite regaining DWC.

DAIDALUS [6] is a DAA algorithm developed by NASA Langley Research Center to support Phase 1 MOPS development. It serves as a reference of a MOPS-compliant DAA algorithm. DAIDALUS takes a deterministic approach to alerting and guidance calculations [6]. Aircraft states are represented as linear projections of deterministic models obtained from surveillance sources such as ADS-B, active

[1] The complete RTCA DO-365 document referenced may be purchased from RTCA, Inc., 1150 18th Street NW Suite 910, Washington, DC 20036, (202) 833-9339, www.rtca.org

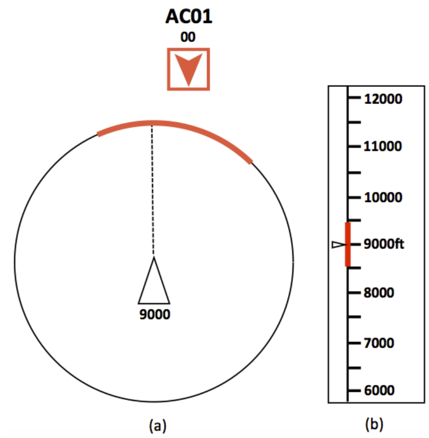


Figure 1. Illustration of Warning guidance information (a) heading (b) altitude (reprinted from MOPS DO-365 of RTCA with permission).

surveillance, or radar. Manned aircraft traffic is projected on constant-velocity trajectories to a look-ahead time of 180 seconds. DAIDALUS provides discrete alert levels for all nearby traffic based on time to intersection of a given alert zone. These alerts align with alerting definitions defined in the Phase 1 DAA MOPS with buffered volumes and timelines. DAIDAIUS's guidance is of a suggestive nature in that it indicates a range of maneuvers (and non-maneuvers) that would lead to conflicts, without dictating a single maneuver for the pilot to follow. The types of maneuver include heading, altitude, climb rate, and airspeed for corrective and warning alert types as well as guidance to regain WC if a Loss of Well Clear (LoWC) is unavoidable [6]. All possible maneuvers within the UAS's performance are calculated at a given time step to detect maneuver regions that would result in a LoWC with projected traffic within the look-ahead time. Figure 2 summarizes DAIDALUS's high-level design principles.

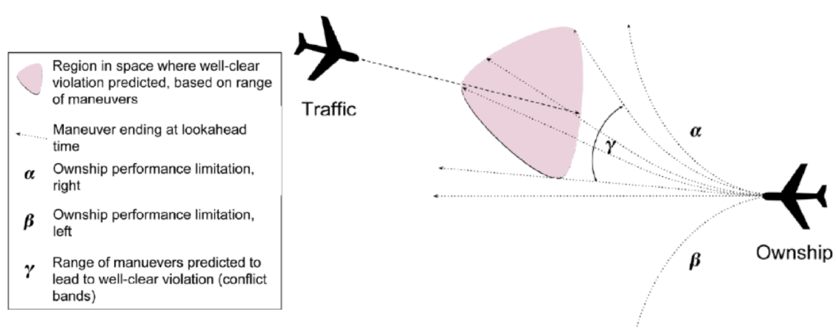


Figure 2. DAIDALUS alert and guidance design principles [6]

The Aircraft Collision Avoidance System X (ACAS-X) [7] is envisioned by the Federal Aviation Administration (FAA) to be a critical component that supports the safety of the Next-Generation Air Transportation System (NextGen). ACAS-X will replace the currently deployed Traffic Alert and Collision Avoidance System II (TCAS-II) [8] in the near future. The UAS-variant of ACAS-X, called ACAS-Xu, is currently under development. Recently, ACAS-Xu's capability has been extended from the collision avoidance time regime to longer look-ahead times so as to provide DAA alert and guidance. This extension aims at meeting the DAA functional requirement defined by the Phase 1 MOPS. In contrast to the deterministic approach used by DAIDALUS, ACAS-Xu uses cost analysis, dynamic programming, and probabilistic state distributions to calculate alerting statistics and guidance. ACAS-Xu represents aircraft states and dynamics non-deterministically [9]. Aircraft and sensor models are applied to surveillance data sources to develop probability distributions of aircraft states. The Surveillance and Tracking Module (STM) correlates and associates aircraft states as well as their probability distributions. These state distributions are applied to pre-calculated dynamic programming tables to estimate relevant alerting information, such as time to LoWC or Near Mid-Air Collision (NMAC). The Threat Resolution Module (TRM) then uses a combination of state distributions and statistical output from dynamic programming to select the best maneuver based on several cost factors [7, 10].

Both systems interact with the pilot in a combination of alerts and suggestive guidance. ACAS-Xu also issues directive guidance called Resolution Advisories (RA), indicating the severity, sense, and strength of a necessary maneuver. These RAs can occur in horizontal, vertical, or mixed type maneuvers as selected by the Nucleus module [7]. Complimentary to RAs, ACAS-Xu's suggestive guidance is calculated in the horizontal dimension, indicating ranges of headings that the PIC should avoid to prevent a LoWC in the near future.

This report compares the DAA alerting and guidance performance of DAIDALUS and ACAS-Xu algorithms using flight test data flown with scripted encounters. The performance of both systems is also measured against the Phase 1 MOPS for alerting and guidance. The results reveal striking similarities and some differences between the two systems, and can inform further development of both.

# 2 Methods

The comparison in this work uses flight test data flown with scripted encounters. ACAS-Xu alerting and guidance data were generated and collected in real time during the flight test. DAIDALUS alerting and guidance data were generated after the flight test, by processing the flight test collected aircraft data through DAIDALUS. The following sub-sections describe the data generation and collection processes in detail.

## 2.1 ACAS-Xu Flight Test 2

ACAS-Xu Flight Test 2 (FT2) was conducted between June and August of 2017 over Edwards Air Force Base in order to test new capabilities implemented in ACAS-X Run 3. A total of 250 scripted encounters were flown. A small percentage of these encounters were flown with the intention to test the new DAA alerting and guidance capabilities. These DAA additions included suggestive and directive horizontal maneuver guidance to meet DAA corrective alert timelines.

This work analyzes data from a total of seven of the 250 encounters, including six of the mitigated DAA encounters and one unmitigated (fly-through), not-DAA-specific encounter. Table 1 shows test cards for these seven encounters. Test cards with the prefix RWC were designed to test new DAA capabilities in ACAS-Xu Run 3. Among these encounters, RWC-03, RWC-12, and DA-62 were head-on (with a safety horizontal offset), RWC-09 and RWC-18 were at a 90 degree angle, and RWC-06, and RWC-15 were at a 45-degree angle. Test card DA-62 was included in order to examine the behavior of the DAA systems in an unmitigated scenario where a LoWC occurs. Among the six RWC encounters, RWC-03, RWC-06, and RWC-09 were flown with ACAS-Xu configured in the DAA Mode, whereas RWC-12, RWC-15, and RWC-18 were flown with ACAS-Xu configured in the Policy Mode. The DAA Mode was meant to capture the DAA caution alert and advisories times defined by the MOPS, whereas the Policy mode was for the unadulterated ACAS Xu alert and advisory time.

Table 1. ACAS-Xu FT2 Scripted Flight Parameters [11]

| Card | Version | Priority | Response Delay (s) | Intruder | Rel Bearing | VMD (ft) | Lateral Sep (nmi) | Own Response | Int Response | Int Mode | Surveillance | Logic | Tracker |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RWC-03 | 2.5 | 3 | **25** | TCAS/Xa | 0 | 300 | 0.4 | Manual | None | TA/RA | All | Horizontal | Correlation |
| RWC-06 | 2.5 | 1 | **25** | TCAS/Xa | 45 | 300 | 0.4 | Manual | None | TA/RA | All | Horizontal | Correlation |
| RWC-09 | 2.5 | 2 | **25** | TCAS/Xa | 90 | 300 | 0.4 | Manual | None | TA/RA | All | Horizontal | Correlation |
| RWC-12 | 2.5 | 3 | **25** | TCAS/Xa | 0 | 300 | 0.4 | Manual | None | TA/RA | All | Horizontal | Correlation |
| RWC-15 | 2.5 | 1 | **25** | TCAS/Xa | 45 | 300 | 0.4 | Manual | None | TA/RA | All | Horizontal | Correlation |
| RWC-18 | 2.5 | 2 | **25** | TCAS/Xa | 90 | 300 | 0.4 | Manual | None | TA/RA | All | Horizontal | Correlation |
| DA-62 | 3.2 | 2 | Fly Through | TCAS/Xa | 0 | 200 | 0.6 | None | None | TA/RA | All | Nucleus | Correlation |

The seven encounters were flown with the three geometries outlined in Figure 3. Each encounter involved one UAS and a small manned utility aircraft similarly equipped to the UAS, running ACAS-Xa [7] and TCAS II [8]. These UAS and manned aircraft are referred to as ”Ownship” and ”Intruder”, respectively, throughout this analysis. The Ownship for each test was a Mode-S and ADS-B equipped Ikhana Predator-B UAS running ACAS-Xu controlled by a test pilot on the ground. During these encounters, ACAS-Xu perceived Ownship to be unable to maneuver vertically, consequently only horizontal guidance was calculated, and tracks were produced from the ACAS Surveillance and Tracking Module (STM) correlation tracker with an ADS-B transceiver as its source. RWC encounters were mitigated, as the Ownship pilot was instructed to follow ACAS-Xu corrective guidance after a response delay timer had expired. The DA-62 encounter had similar geometric and equipage parameters to those with the RWC prefix, but Ownship was not perceived to have limited maneuverability and RA dimension was determined by the ACAS-X Nucleus module.

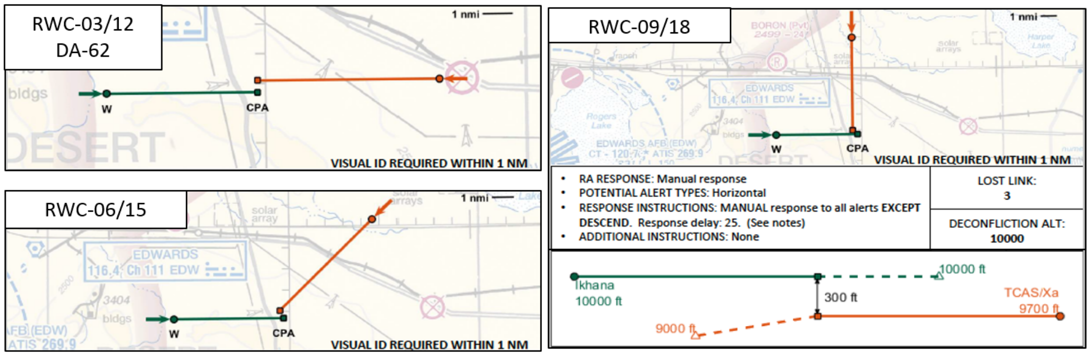


Figure 3. Scripted Flight Geometries [12]

## 2.2 Flight Data Processing

This analysis was conducted using data recorded from the ACAS-Xu FT2 flight test. Surveillance data, Ownship states, and ACAS-Xu output were recorded on-board the Ownship, downlinked, and recorded via the Live Virtual Constructive Distributed Environment (LVC_DE) interface. These LVC_DE messages included absolute aircraft states for all traffic including Ownship, updated at 1 Hz, and ACAS-Xu guidance and alerting data payloads.

DAIDALUS alerting and guidance was produced by feeding the LVC_DE messages to DAIDALUS in a post-processing fashion. DAIDALUS requires that traffic states be aligned to Ownship time steps. To support this, blocks of traffic states were linearly interpolated forward in-track to Ownship time assuming constant velocity. This simple "last block" linear interpolation technique produced only modest errors in position, 97 ft from GPS location on average (see Figure 4).

## 2.3 DAIDALUS Simulation

The behavior of DAIDALUS is highly configurable. Alerting thresholds, hazard zone parameters, and perceived aircraft performance can be configured to support different analysis scenarios. For this analysis, a standard configuration file[2] designed to be MOPS compliant with a 3-degree-per-second turn rate was applied. This configuration defines three alert zones—preventive, corrective, and warning—in increasing severity. Only the corrective and warning alerts are investigated in this work. Both alert zones were buffered to a 1-nmi Horizontal Miss Distance threshold (HMD*), with 60 and 30 second time to alert thresholds to corrective and warning alert zones respectively. Additionally, guidance to regain Well Clear was calculated

[2] WC_SC_228_nom_b.txt

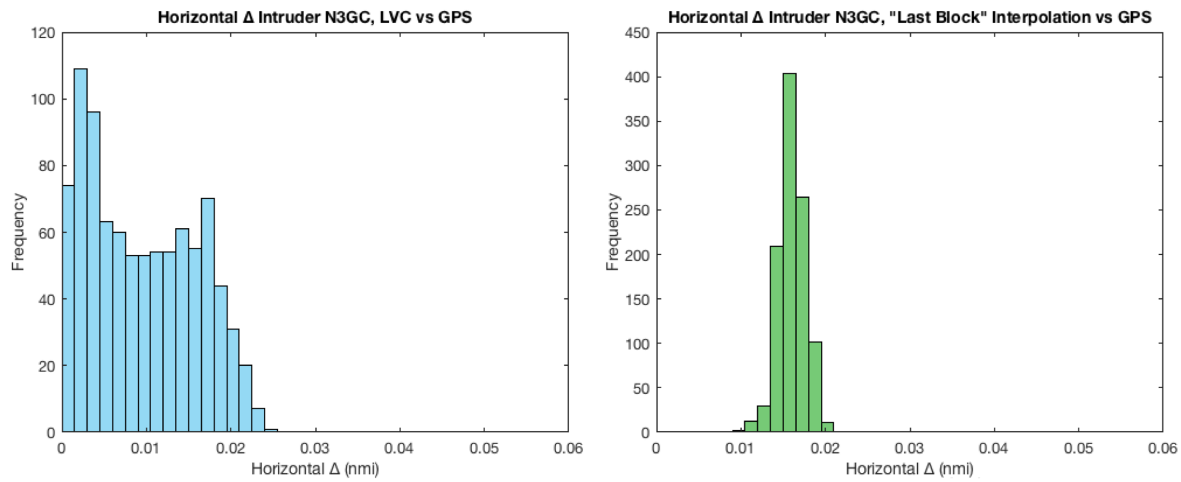


Figure 4. LVC_DE and Interpolated Position Error

and is referred to as recovery bands in this analysis. Using this configuration, guidance data and statistics were collected from DAIDALUS and compared to ACAS-Xu in terms of alerting times, guidance coverage, and other behaviors.

The DAIDALUS algorithm is provided as an open-source library[3] maintained in Java and C++ versions. This analysis was conducted using DAIDALUS release V-1.0.1-FormalATM-v2.6.2. A basic framework for controlling DAIDALUS was written in MATLAB using the DAIDALUS Java library. This framework was used to calculate guidance and alerting statistics from input scenario files generated from flight test data.

# 3 Analysis

DAA systems interact with the UAS pilot by displaying multi-level alerting and suggestive guidance information. The latter is based on the outcome of a range of maneuvers that the pilot should avoid, generally referred to as bands. These bands change severity based on an intruder's alert level and predicted time to intersection of an alert zone. Once the warning bands are saturated (meaning imminent loss of DWC) it is necessary for a DAA system to provide a range of maneuvers (recovery bands) that the PIC can maneuver to in order to regain DWC as soon as possible. Alerting and maneuver guidance performance and statistics of ACAS-Xu are compared against DAIDALUS.

## 3.1 Alerting

The Phase 1 DAA MOPS defines alerting requirements using the Hazard Zone and non-Hazard Zone (see Table 2). Appendix A describes their definitions in detail.

[3]http://www.github.com/nasa/wellclear

Phase 1 DAA MOPS outlines required performance for a DAA system applied to the test vectors outlined in Appendix P of the DAA MOPS [1]. The MOPS requires that a DAA system provide corrective and warning level alerts at an average of 55 and 25 seconds before intersection of the corrective and warning hazard zones respectively. The MOPS, nonetheless, does not dictate a specific way of alerting algorithm implementation. This performance of DAIDALUS and ACAS-Xu in the analyzed scenarios is referenced to performance benchmarks outlined within the MOPS.

Table 2. Parameters for DAA Alerting Requirements (reprinted from MOPS DO-365 of RTCA with permission)

| Alert Type → | | Preventive Alert | Corrective Alert | Warning Alert |
|---|---|---|---|---|
| Alert Level → | | Caution | Caution | Warning |
| Hazard Zone | $\tau^*_{mod}$ (Seconds) | 35 | 35 | 35 |
| | DMOD and HMD* (Feet) | 4,000 | 4,000 | 4,000 |
| | h* (Feet) | 700 | 450 | 450 |
| Hazard Zone Alert Times | Minimum Average Time of Alert (Seconds) | 55 | 55 | 25 |
| | Late Threshold ($THR_{Late}$) (Seconds) | 20 | 20 | 15 |
| | Early Threshold ($THR_{Early}$) (Seconds) | 75 | 75 | 55 |

DAIDALUS calculates alerts based on the predicted time to intersection of an alert zone by a projected intruder. The alert zone is chosen to be slightly larger than the alert's Hazard Zone to account for sensor and trajectory uncertainties. Appendix A describes the DAIDALUS alert zone parameters in detail. If this volume is to be violated within a specified minimum time an alert for that volume is presented with the highest level alert taking priority.

Figure 5 shows the alerting and guidance timelines of ACAS-Xu and DAIDALUS. The version of ACAS-Xu analyzed here provides two levels of alert, Remain Well Clear (RWC) and Collision Avoidance (CA). ACAS-Xu's collision avoidance alerts are provided on similar timelines to TCAS II. The horizontal DAA additions to ACAS-Xu are designed to extend these timelines to support look-ahead times applicable to DAA requirements. The new DAA alert, the RWC alert, is expected to be issued at approximately the same time as the start of a DAA corrective alert threshold. It continues to be issued during the progression of an encounter until either the conflict is cleared or a CA alert is issued. DAIDALUS, on the other hand, provides discrete alerts for each DAA threshold and Regain-WC guidance calculated at approximately the DAA WC threshold.
To facilitate comparison, the two ACAS-Xu alert levels are mapped to the corrective and warning alert levels for DAIDALUS, respectively (see Table 3.) It is important

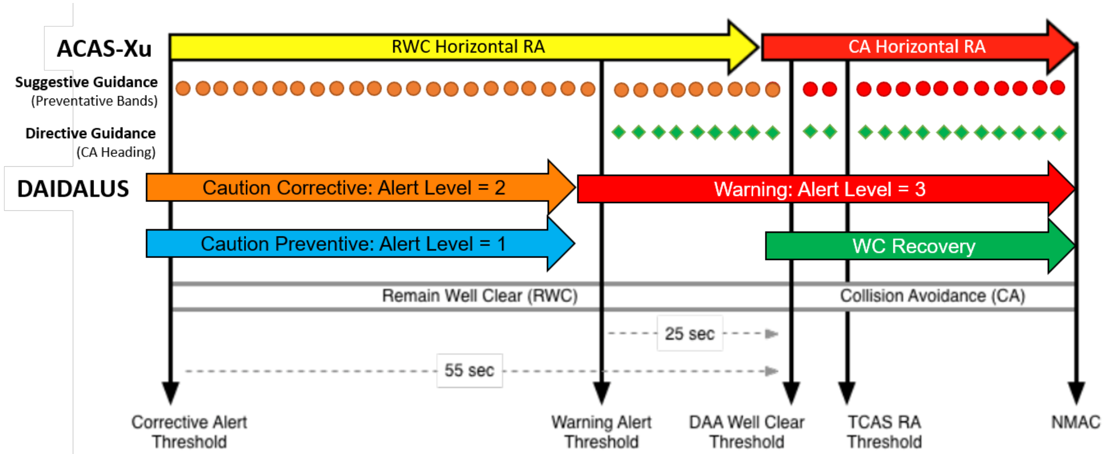


Figure 5. ACAS-Xu and DAIDALUS Alerting Timelines [10]

to note that ACAS-Xu CA alert is not intended to provide DAA warning level alerts. The comparison between ACAS-Xu Collision Avoidance and DAA warning is imperfect as these refer to the alerts pertaining to NMAC and intersection of the warning hazard zone respectively. As such it is not expected that ACAS-Xu meet Phase 1 DAA warning thresholds requirements in alerting or guidance. Phase 2 of the DAA MOPS is expected to address the RWC guidance techniques used by ACAS-Xu in separate requirements for the proven robust ACAS-X method.

Table 3. Equivalent DAA Alert Level

| Alert Level | ACAS-Xu | DAIDALUS |
|---|---|---|
| Corrective | Remain Well Clear (RWC) | Corrective |
| Warning | Collision Avoidance (CA) | Warning |

Figure 6 shows the alerting time before Closest Point of Approach (CPA) and LoWC in both alert levels for both systems during the seven encounters. The actual horizontal CPA was used as the reference point for CPA time. LoWC time is set to the time DAIDALUS's recovery bands start. This time is usually a few seconds before the aircraft enters the alerting zone. Both DAIDALUS and ACAS-Xu provide corrective level alerts before the corrective requirement threshold specified by the DAA MOPS. ACAS-Xu issues RWC alerts 3 seconds earlier than DAIDALUS's corrective alerts on average. This is before the 55 second corrective alert average threshold as expected. DAIDALUS issues warning alerts between 10 and 15 seconds earlier than ACAS-Xu's CA alerts. While ACAS-Xu's CA alerts fall outside of the DAA warning alert threshold, this is expected due to differences between the volumes of NMAC and DWC.

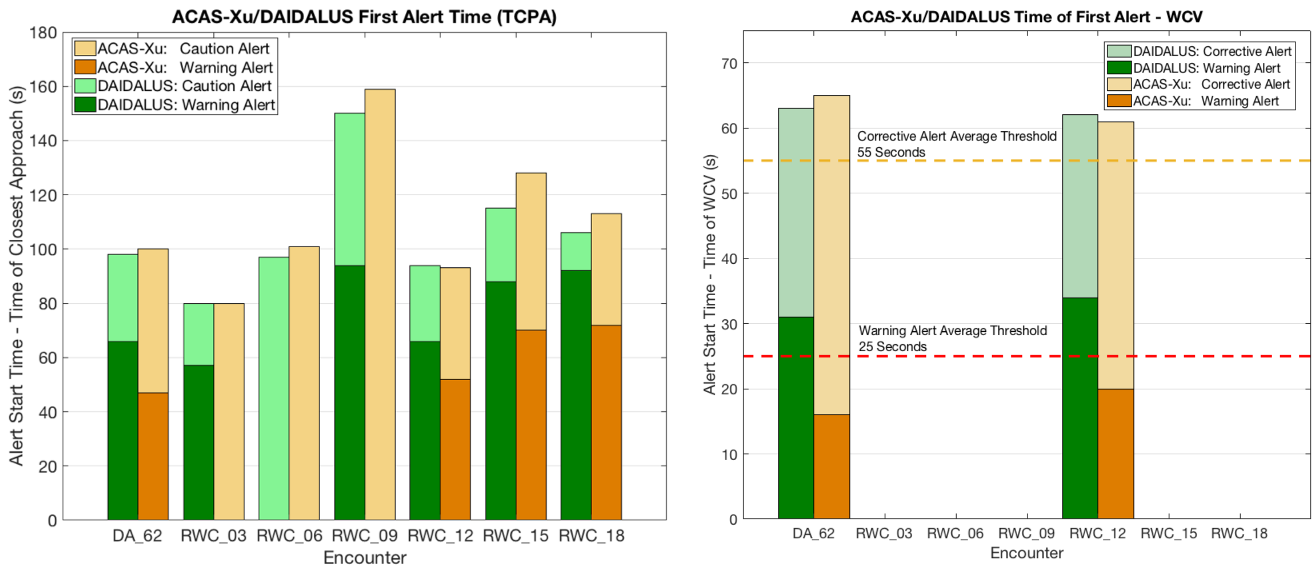


Figure 6. Alerting Time Before CPA and WCV

Interestingly, no CA alerts were observed for the three encounters (RWC-03, RWC-06, and RWC09) for which ACAS-Xu was configured in the DAA Mode. It was not clear whether this discrepancy was due to the ACAS-Xu configuration. The DAA Mode and Policy Mode are supposed to differ in the time for the caution level alert and guidance, not for the warning level (the CA alert). Moreover, Appendix B shows that RWC-03, RWC-06, RWC-09 all led to DAIDALUS's Regain-WC bands, whereas RWC-12, RWC-15, and RWC-18 never triggerred DAIDALUS's Regain-WC bands. This seems to indicate that differences in the execution of these two sets of encounters led to the different alerting behavior.

## 3.2 Maneuver Guidance

Only horizontal DAA guidance is compared between the two systems as the DAA vertical guidance of ACAS-Xu has not been implemented in Run 3. Inclusion of DAA guidance in the vertical dimension is planned for future releases of ACAS-Xu. Figure 7 shows the maneuver guidance for test card RWC-12. Horizontal maneuver guidance bands, in corrective and warning severities, with respect to Ownship heading are plotted along the Y-axis and time elapsed from the beginning of the test card along the X-axis. Negative headings correspond to left turns while positive headings correspond to right turns. These plots for test RWC-12 are representative of maneuver guidance performance observed across all scenarios. Similar plots for the remaining six scenarios can be found in Appendix B.

It was observed that DAIDALUS's corrective guidance and ACAS-Xu's RWC guidance occur within 3 to 5 seconds of each other in the same region. ACAS-Xu was

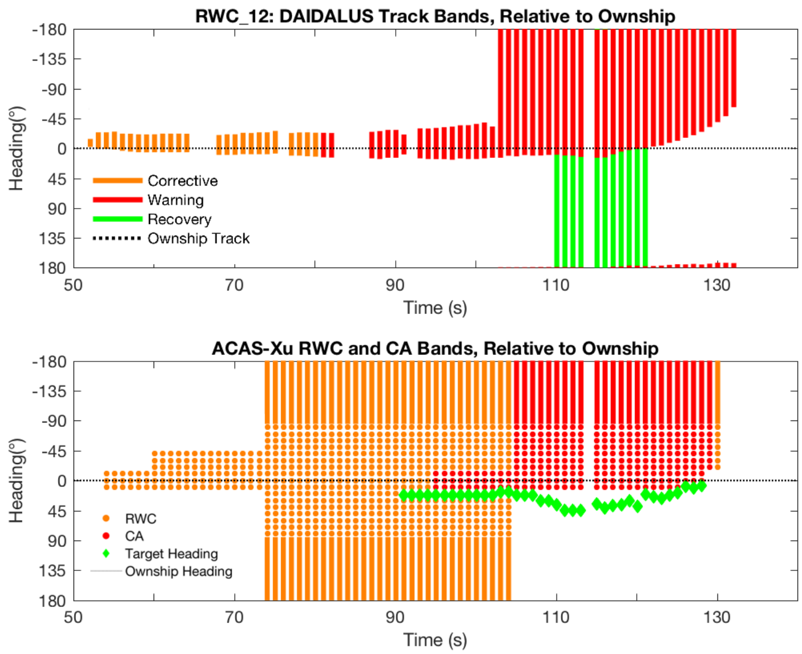


Figure 7. RWC-12 Maneuver Guidance

more conservative, suggesting larger corrective bands than DAIDALUS in both turn directions around Ownship's heading. As the aircraft converged and the range of conflict-free maneuvers moved outside of Ownship performance, the bands grew saturated in both directions, indicating to the pilot that coordination and mitigation is necessary.

DAIDALUS produced warning level bands at 81 seconds elapsed, approximately 30 seconds before LoWC. ACAS-Xu produced smaller CA bands in the same regions 15 seconds later on average than DAIDALUS and later than the average DAA warning alert threshold. This is consistent with the onset delay in the warning-level alerts reported in Section 3.1. CA bands calculated by ACAS-Xu were consistently 25 to 35 degrees smaller than those calculated by DAIDALUS before saturation.

Interesting behavior of ACAS-Xu's corrective level guidance bands is seen in several scenarios, including RWC-12 in Figure 7. Between approximately 75 and 90 seconds elapsed in RWC-12, ACAS-Xu's corrective bands were saturated in both directions, no directive CA heading was calculated, and no horizontal RA's were produced. During these 15 seconds there was no positive (i.e., recommended) guidance presented to the PIC. This indicates that there were no actions that the PIC could take in order to maintain or regain separation. This is in contrast to DAIDALUS's guidance bands which indicate possible maneuvers to the right and left during these times. Phase 1 DAA MOPS specifies that a DAA system shall always provide positive guidance information unless in the condition of NMAC[4] [1]. Future versions of ACAS-Xu should address this gap and make sure guidance is always available.

### 3.3 Regain Well-Clear Guidance

If the Ownship penetrates the RWC alerting zone deep enough, ACAS-Xu calculates horizontal directive guidance in the form of a heading to turn to. The horizontal directive guidance is also called a horizontal resolution advisory (RA). In general, ACAS-Xu may generate both horizontal and vertical resolution advisories. Its Nucleus module decides whether to issue a horizontal, a vertical, or a blended resolution advisory. In the case that a horizontal resolution advisory is issued, the PIC is expected to command the aircraft to these headings in order to maintain separation and avoid NMAC. In contrast, DAIDALUS calculates recovery bands once a loss of Well Clear is unavoidable (with horizontal maneuvers). These recovery bands indicate a range of maneuvers that the PIC should take in order to regain WC in a timely manner. Figure 7 shows the directive guidance of ACAS-Xu starting at 90 seconds, about 20 seconds before DAIDALUS issues the recovery bands. Among the other encounters analyzed, ACAS-Xu calculated CA maneuver guidance about 25 seconds before DAIDALUS issued the recovery bands (see Appendix B).

Figure 8 shows the normalized amount of directive guidance headings calculated by ACAS-Xu that agree with DAIDALUS Regain-DWC guidance bands.

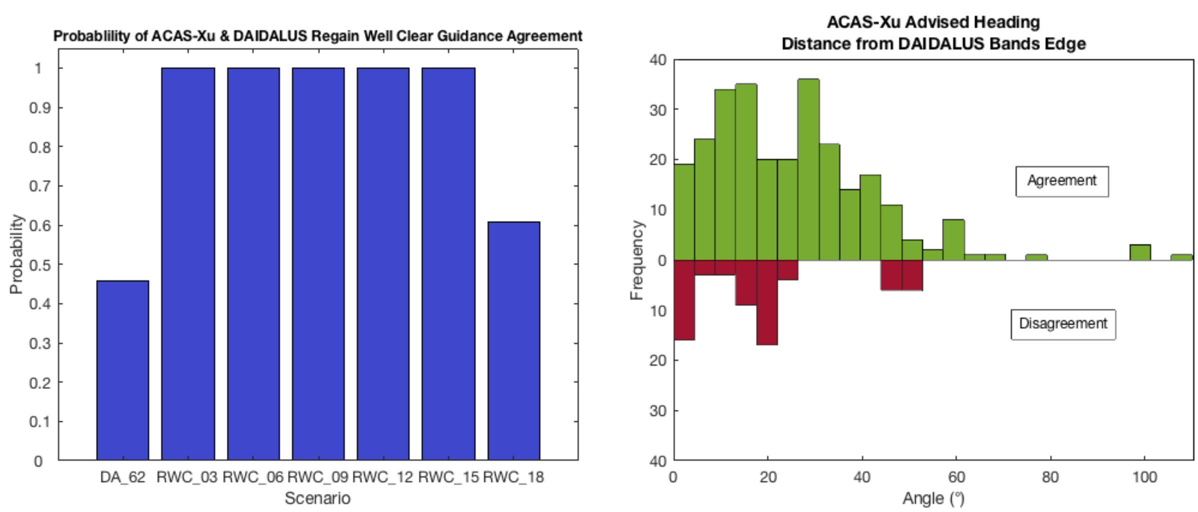


Figure 8. Regain Well Clear Guidance Outcomes

Agreement is considered to be when ACAS-Xu directive CA headings occur within a DAIDALUS DWC recovery band, or outside of DAIDALUS corrective or warning

[4]MOPS 238

bands. For quantitative comparison of regain DWC guidance, probability of intersection was calculated as the ratio of headings in agreement to the total number of calculated CA hearings. These headings are agreeable with DAIDALUS guidance, falling within DAIDALUS non-alerting or recovery bands with a 0.87 probability globally and in complete agreement in 5/7 scenarios as seen in the histogram on the left in Figure 8. The right histogram of Figure 8 indicates the frequency of an ACAS-Xu directive CA heading occurring at a given distance to the nearest DIADLUS corrective or warning band edge. ACAS-Xu directive headings appear to deviate minimally from the Ownship's current heading, diverting 25 degrees on average from the nearest DAIDALUS corrective or warning band edge.

# 4 Anomalies

## 4.1 Alerting Toggle

The deterministic aircraft model used by DAIDALUS is susceptible to uncertainties in aircraft state data in some situations. Figure 9 shows how DAIDALUS was observed to drop maneuver guidance and decrease alert level due to perceived Intruder vertical divergence. This behavior was observed in all RWC scenarios. These scenarios occurred with Ownship offset vertically 300ft above the intruder. When linearly projected, these intruders appeared to not intersect the 450ft Vertical Miss Distance threshold (VMD*) of the corrective alert zone during one of these negative peaks. This effect becomes less pronounced as CPA gets nears, less time is allowed for the projected Intruder to descend resulting in steady alerting and guidance.

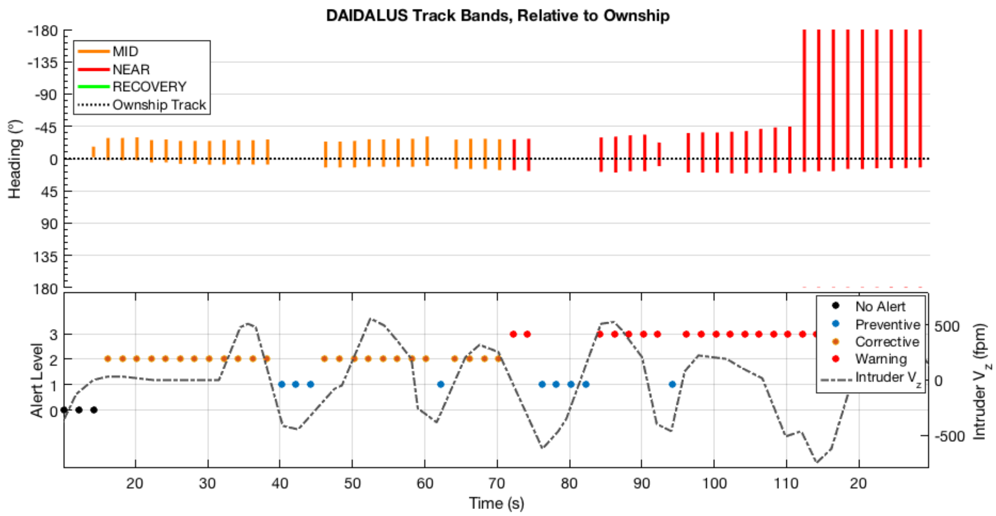


Figure 9. DAIDALUS Bands and Alerting With LVC_DE Source

This toggling behavior was not present when Intruder GPS logs were used as a surveillance source for DAIDALUS. Finer altitudes and smaller fluctuations in Intruder vertical climb rate kept the projected Intruder within the lower vertical bound of the hazard zone throughout the scenario. Similarly, as seen in Figure 10, scenario DA-62 which occurs with a smaller 200 ft vertical offset did not experience this behavior due to a wider buffer between the the Intruder altitude and the VMD* of the alert zone. Gaps in the bands of these plots are attributed to sporadic missed ADS-B updates, not an alerting toggle behavior. ACAS-Xu, using a probabilistic aircraft and alerting model, maintained guidance in all of these scenarios despite noisy and coarse surveillance data from ADS-B, radar, and unfavorable scenario geometry.

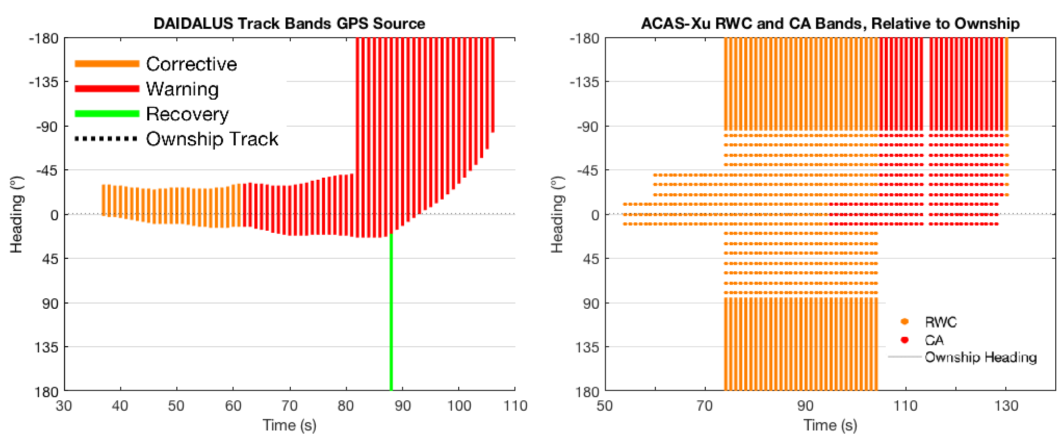


Figure 10. RWC-12: DAIDALUS and ACAS-Xu Bands

The hysteresis provided by ACAS-Xu's probabilistic approach could be a significant advantage in combating surveillance sources with high uncertainty or low resolution such ADS-B or radar.

### 4.2 Regain Well Clear Reversal

Encounter DA-62 is an unmitigated encounter with a head-on trajectory and a 0.6 nmi lateral offset (see Figure 3). Ownship flew from west to east and the intruder offset was to the north of the ownship at CPA. Horizontal guidance bands and directive CA guidance from ACAS-Xu for this encounter are shown on the left side of Figure 11. ACAS-Xu suggested a slightly Northerly relative target heading at 87 seconds elapsed, approximately 28 seconds before a LoWC. Interestingly, the directive heading fell within the range of CA bands during this period of time, while there appears to be conflict-free Southerly headings available. The directive heading was therefore inconsistent with the CA bands, an undesirable behavior. This behavior, nonetheless, was not observed in any other encounters analyzed. This heading strengthened from -20 to -42 degrees relative to Ownship heading then reverses direction at 129 seconds elapsed, 7 seconds past DAIDALUS's time of regain DWC, to +48 degrees relative to Ownship heading. In comparison, DAIDALUS (shown on the right side of Figure 11) suggested a Southerly turn throughout the encounter, calculating recovery bands between +6 and +40 degrees to right saturation, i.e. only Southerly turns.

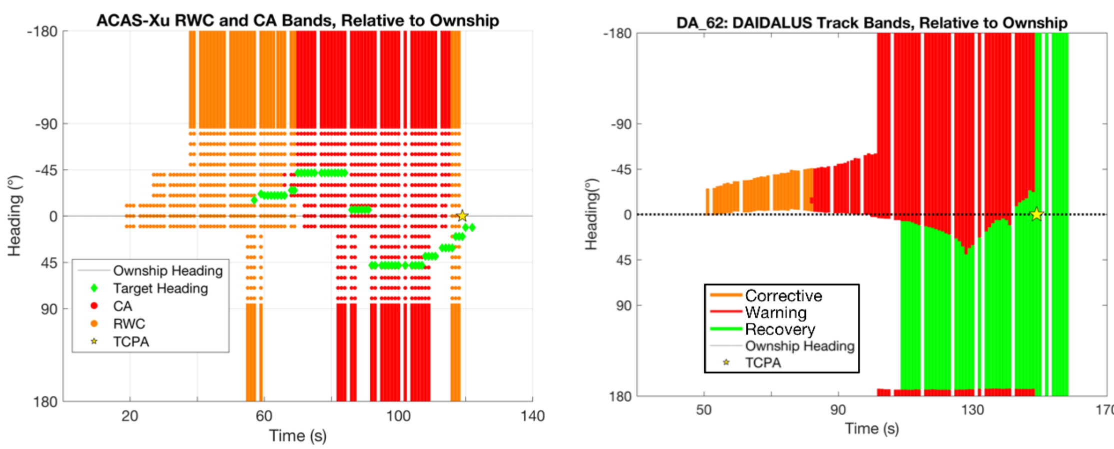


Figure 11. ACAS-Xu Guidance Reversal Behavior

# 5 Conclusions

The analysis presented in this paper compares the DAA alerting and guidance behavior of both ACAS-Xu Run 3 and DAIDALUS using flight test data from ACAS-Xu FT2 in July, 2017. Alerting comparison results show that ACAS-Xu's RWC alert starts at similar to slightly earlier times to DAIDALUS's corrective alert. ACAS-Xu's CA alert starts at 10-15 seconds later than DAIDALUS's warning alert, and overlaps with DAIDALUS's Regain-WC guidance times nearing LoWC. Guidance comparison results show ACAS-Xu's guidance is found to occur in similar locations and to be more conservative compared to DAIDALUS's, protecting a larger range of headings from maneuvering. In these test conditions, ACAS-Xu's horizontal directive guidance usually started while the RWC bands were saturated and 10-15 seconds before the CA bands begin. DAIDALUS's Regain-WC bands, on the other hand, are not calculated until violation of the warning alert zone is imminent or has occurred. ACAS-Xu's horizontal directive guidance sense agreed with that of DAIDALUS's Regain-WC bands in most analyzed encounters. However, there are notable discrepancies in the DA-62 where ACAS-Xu's directive heading cut well into both ACAS-Xu and DAIDALUS's bands. Further analysis of this scenario is suggested to uncover the cause of this disagreement.

ACAS-Xu's alerting and guidance appeared to be more resilient under the tested sensor uncertainties, leaving no gaps in its time series of alert and guidance while DAIDALUS stopped issuing alerts due to noise in the predicted vertical trajectories moving out of the alerting zone. The gaps in DAIDALUS's alerting and guidance may be remedied by filters that reduce the vertical state's uncertainty, either in the surveillance tracker or in the DAA system itself.

This comparative analysis reveals striking similarities and differences between the DAA performance of two distinct systems, ACAS-Xu and DAIDALUS. With the Phase 2 MOPS for DAA and MOPS for ACAS-Xu both in progress, the methodology and tools developed for this analysis will be useful for evaluation of upcoming versions of both systems.

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# Appendix A

## Well Clear, Hazard Zone, Alert Zone, and Non-Hazard Zone

The DAA Well Clear (DWC) zone for the UAS targeted in the Phase 1 MOPS is defined by thresholds of three parameters. It does not have distinct physical boundaries because the definition depends on two aircraft's relative position and velocity during an encounter. Figure A1 illustrates a DWC zone.

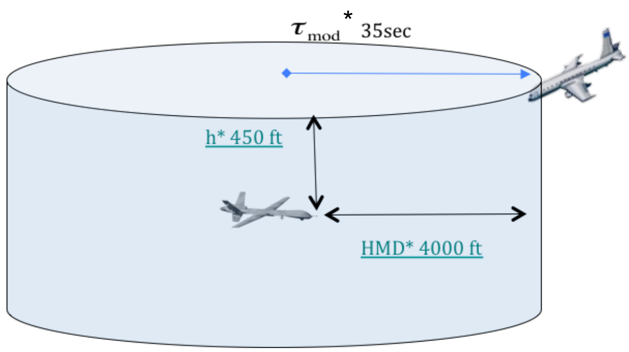


Figure A1. A schematic representation of the DWC zone.

The Horizontal Miss Distance (HMD) represents the two aircraft's predicted minimum horizontal distance during an encounter assuming constant velocities. The parameter $h$ represents the two aircraft's current altitude difference. The time metric modified tau, $\tau_{mod}$, is an estimated time taken for the two aircraft to intersect the "protection" disk. The range rate is negative for closing geometries. The positive incremental distance modifier $D_{\text{mod}}$ defines the radius of a "protection" disk around the Ownship such that any intruder with a horizontal range less than $D_{\text{mod}}$ is always considered "urgent". In this case, $\tau_{mod} = 0$. The thresholds, denoted by an asterisk, for the HMD, $h$, and $\tau_{mod}$ are 4000 ft, 450 ft, and 35 sec, respectively. All three parameters must simultaneously fall below their respective thresholds during an encounter for the two aircraft to violate the DWC. Alerting algorithms are designed to reduce the probability of violating DWC to a value required by the MOPS.

The definition of $\tau_{mod}$ is [13]

$$\tau_{mod} = \begin{cases} -\frac{r^2 - D_{\text{mod}}{}^2}{r\dot{r}}, r > D_{\text{mod}}, \\ 0, r \leq D_{\text{mod}} \end{cases} \tag{A1}$$

where $r$ and $\dot{r}$ are the horizontal range and range rate between the intruding aircraft and the UAS, respectively. The value of $D_{\text{mod}}$ must be equal to HMD$^*$ to avoid the undesirable on-and-off alert during an constant velocity encounter [14].

The Hazard Zone in Table 2 is defined in a similar way, using thresholds of the three variables HMD, $h$, and $\tau_{mod}$. The intruder and UAS are in the Hazard Zone when their HMD, $h$, and $\tau_{mod}$ values all fall below the respective thresholds. The average, early, and late alert times are relative to the time at which the Hazard Zone is violated.

DAIDALUS's alert zone is also defined in a similar way to the Well Clear and Hazard Zone, using thresholds of the three variables HMD, $h$, and $\tau_{mod}$. The HMD threshold is increased to 1.0 nmi to account for sensor and intruder intent uncertainties.

The Non-Hazard Zone in Table 2 is also defined in a similar way, except that the UAS in a Non-Hazard zone when any of the three variables is above its threshold.

# Appendix B

## Maneuver Guidance Plots

### RWC-03

Figure B1 shows maneuver guidance and Regain-WC guidance for scenario RWC-03. RWC-03 is a mitigated scenario with a head-on trajectory. The PIC conducted a right turn in accordance with ACAS-Xu suggestive guidance. Pilot mitigation prevents LoWC, meaning no DAIDALUS recovery bands are calculated for this scenario.

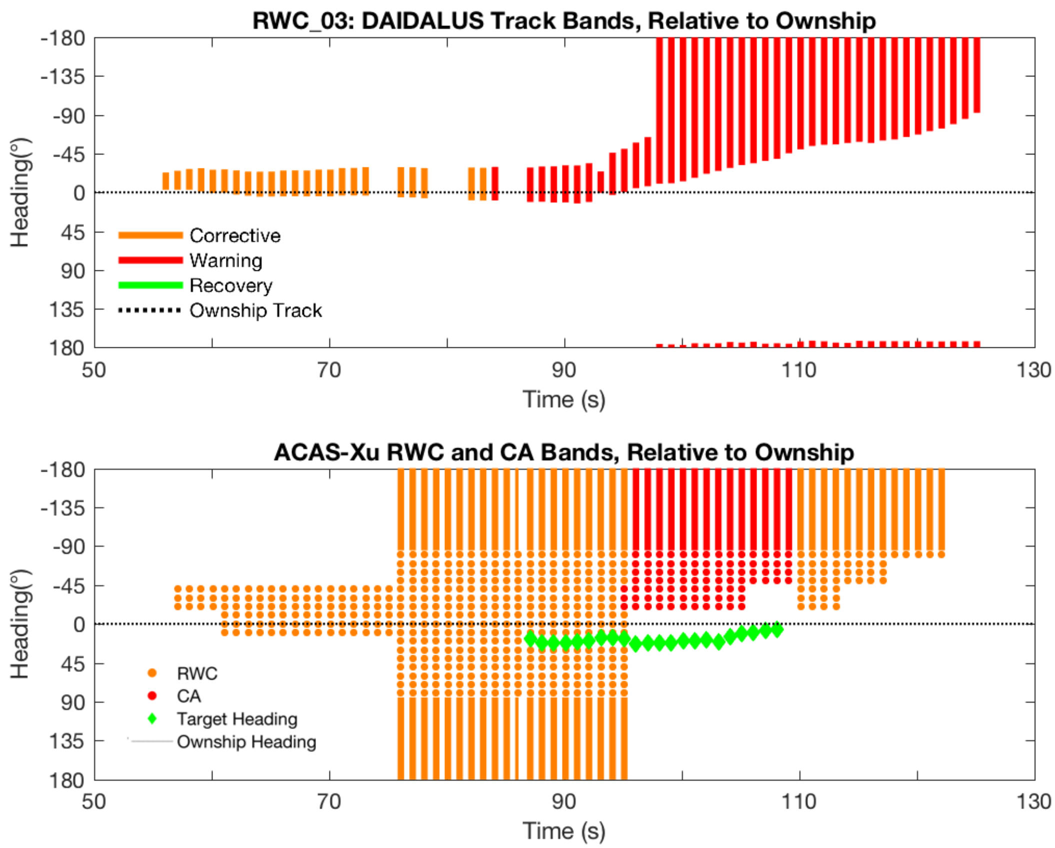


Figure B1. RWC-03 DAIDALUS and ACAS-Xu Guidance Bands

## RWC-06

Figure B2 shows maneuver guidance and Regain-WC guidance for scenario RWC-06. RWC-06 is a mitigated scenario with Intruder enclosing on Ownship from $45°$ North. Pilot mitigation prevents LoWC so DAIDALUS does not calculate recovery bands during this scenario.

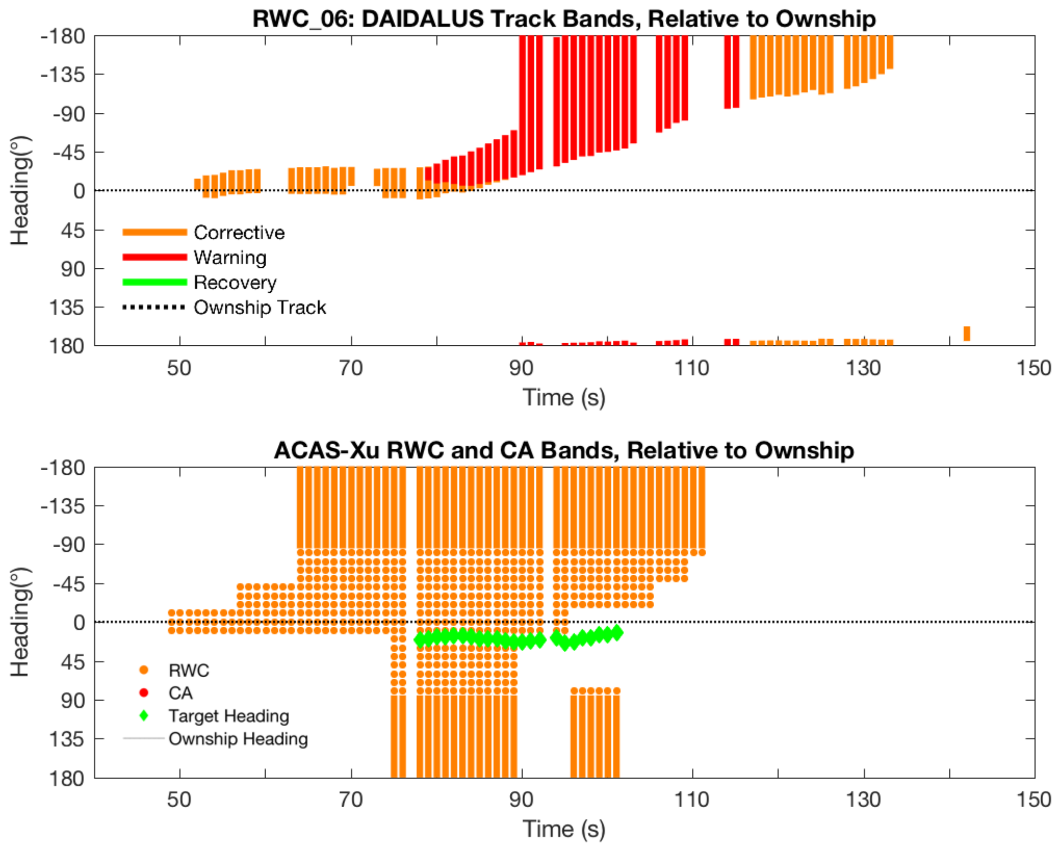


Figure B2. RWC-06 DAIDALUS and ACAS-Xu Guidance Bands

## RWC-09

Figure B3 shows maneuver guidance and Regain-WC guidance for scenario RWC-09. RWC-09 is a mitigated scenario with Intruder enclosing on Ownship from $90^\circ$ North. The differences between ACAS-Xu's CA and DAIDALUS's warning guidance can be seen clearly here. DAIDALUS produces warning guidance near the Ownship heading to left saturation throughout the scenario. In contrast, ACAS-Xu begins its CA guidance further from Ownship heading to left saturation as well.

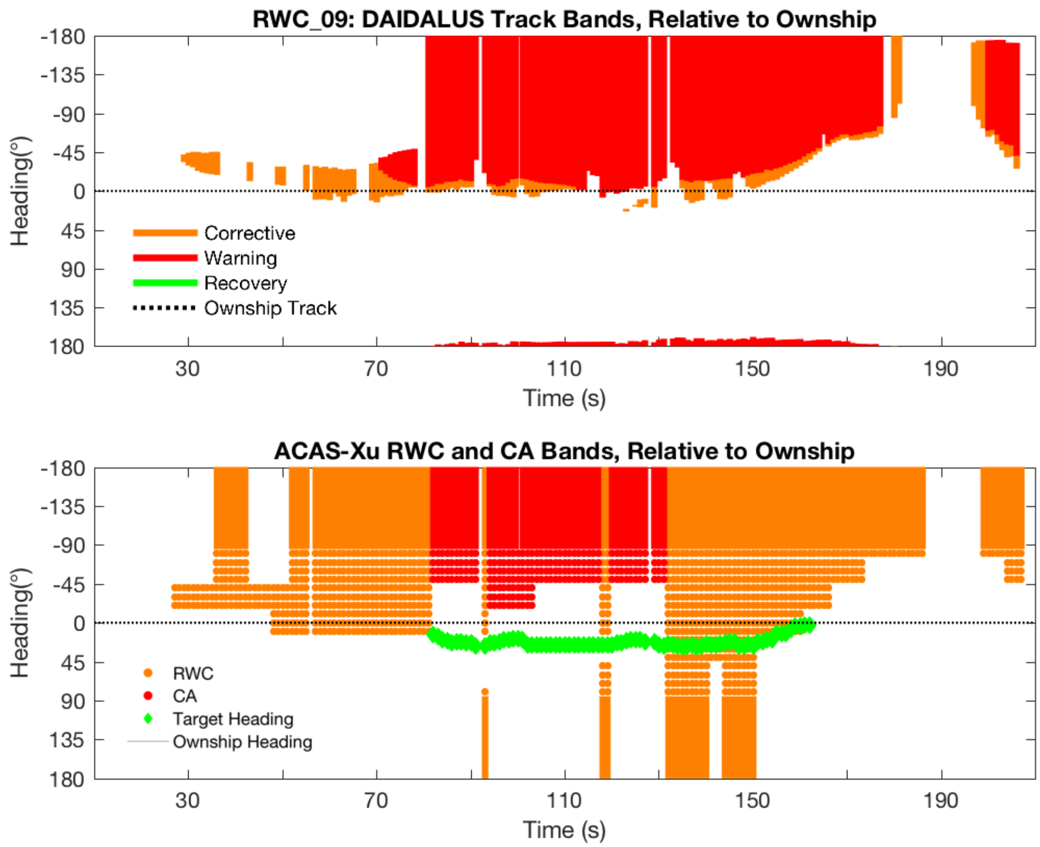


Figure B3. RWC-09 DAIDALUS and ACAS-Xu Guidance Bands

## RWC-12

Figure B4 shows maneuver guidance and Regain-WC guidance for scenario RWC-12. RWC-12 is a mitigated scenario with Ownship and Intruder on head-on trajectories. Very similar guidance performance is observed between ACAS-Xu and DAIDALUS.

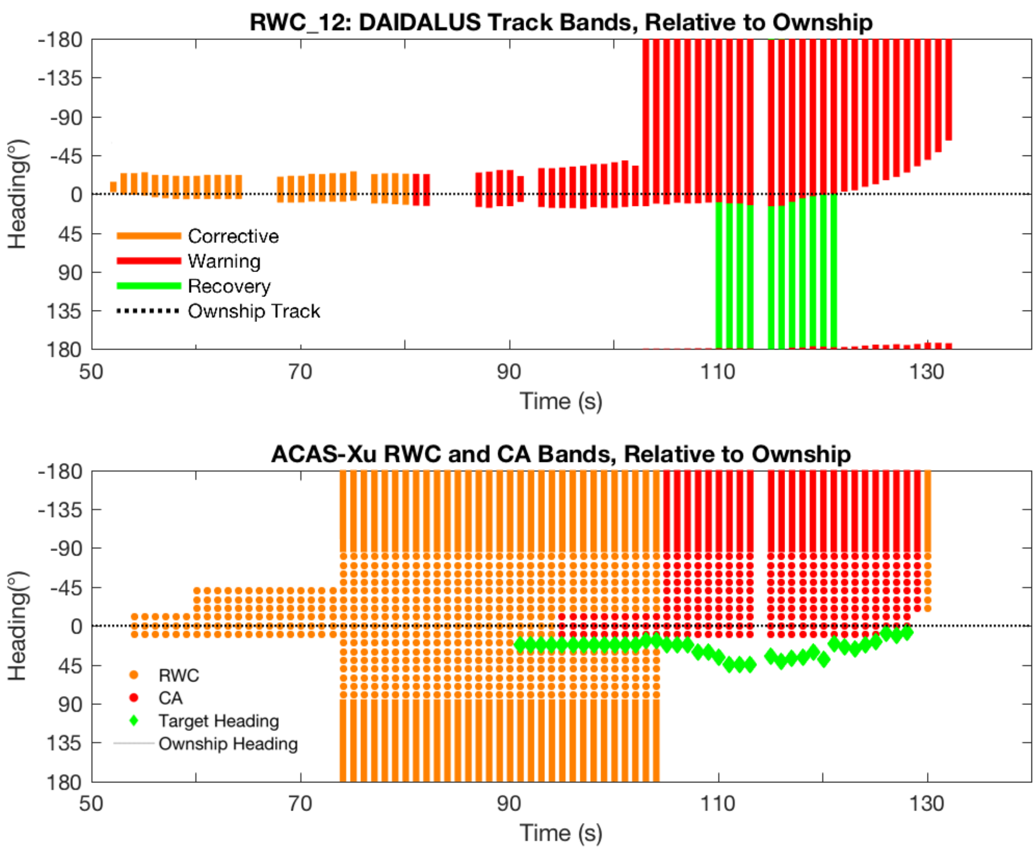


Figure B4. RWC-12 DAIDALUS and ACAS-Xu Guidance Bands

## RWC-15

Figure B5 shows maneuver guidance and Regain-WC guidance for scenario RWC-15. RWC-15 is a mitigated scenario with Intruder enclosing on Ownship from $45°$ North. It can be seen that both DAIDALUS and ACAS-Xu produce suggestive bands cautioning against both Northerly and Southerly turns as the scenario progresses.

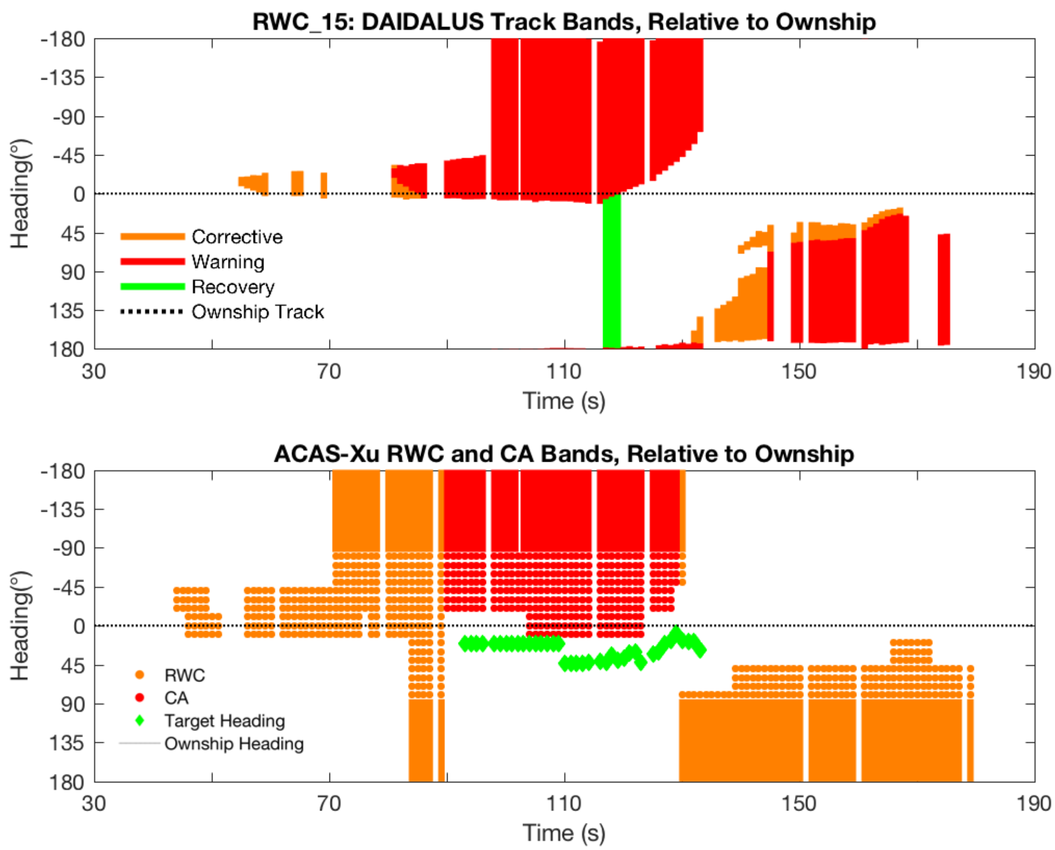


Figure B5. RWC-15 DAIDALUS and ACAS-Xu Guidance Bands

## RWC-18

Figure B6 shows maneuver guidance and Regain-WC guidance for scenario RWC-18. RWC-18 is a mitigated scenario with Intruder enclosing on Ownship from $90°$ North. ACAS-Xu's directive guidance headings occur with the same Southerly sense as DAIDALUS recovery bands but with insufficient strength to put them outside of DAIDALUS warning bands for a few alerts. Differences between ACAS-Xu CA headings and DAIDALUS bands are minimal, diverging by 5 to 10 degrees. An explanation for this may be ACAS-Xu's directive headings are intended to avoid NMAC while DAIDALUS bands are intended to avoid DWC, a much larger volume.

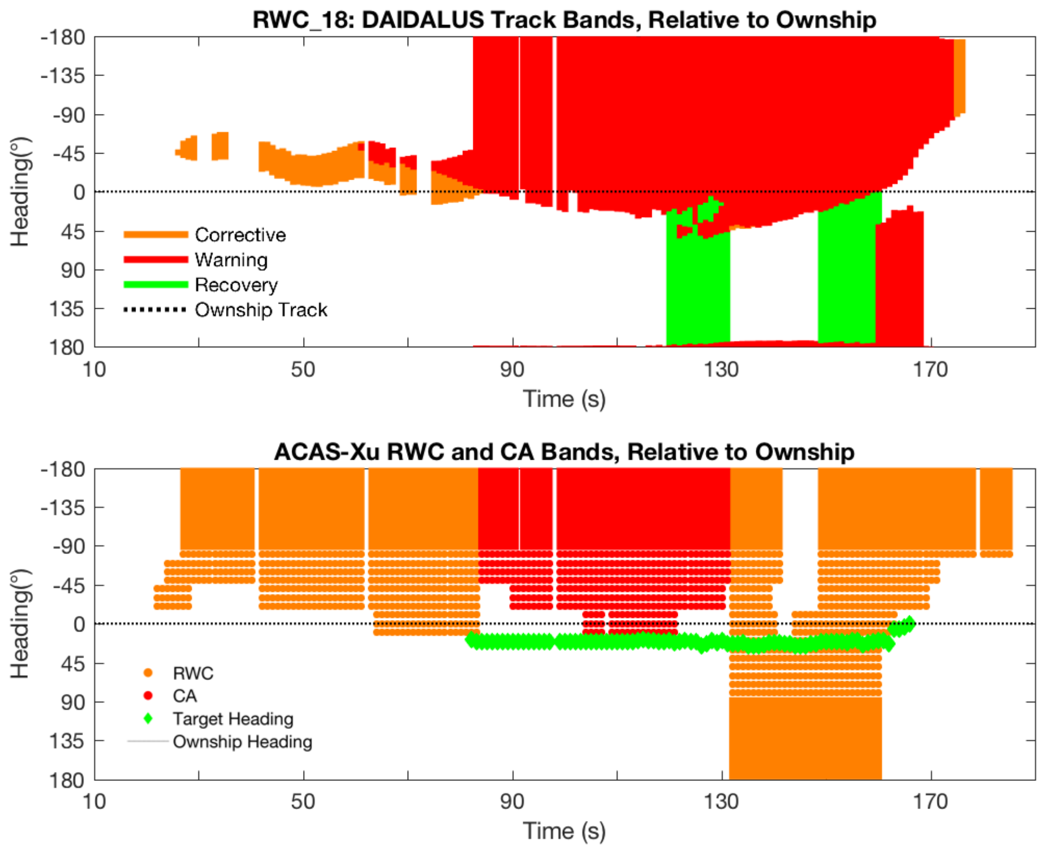


Figure B6. RWC-18 DAIDALUS and ACAS-Xu Guidance Bands

## DA-62

Figure B7 shows maneuver guidance and Regain-WC guidance for scenario DA-62. DA-62 is an unmitigated scenario with a head-on trajectory. Because of this, clear comparisons of ACAS-Xu and DAIDALUS alerting timelines can be made.

ACAS-Xu's RWC guidance begins slightly before DAIDALUS and progresses to cover the same regions. CA guidance occurs later than DAIDALUS but occur over the same regions as well.

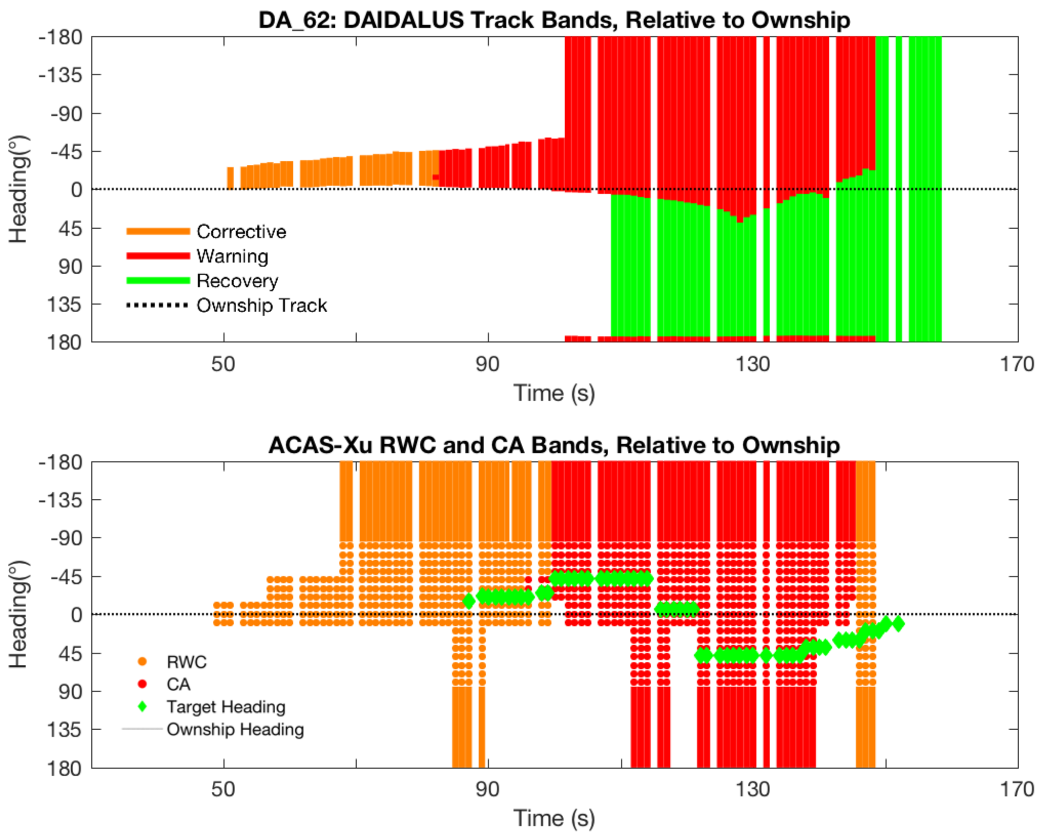


Figure B7. DA-62 DAIDALUS and ACAS-Xu Guidance Bands

A discrepancy between the sense of ACAS-Xu's CA headings and DAIDALUS recovery bands is seen midway through the scenario. This scenario occurs with a slight 0.6 nmi Northern horizontal offset. One hypothesized explanation for this behavior is the relatively large timeline that ACAS-Xu directive guidance occurs on would allow for significant time to divert Ownship trajectory in either direction. In this case, either sense being approximately equal in cost and probability. It is less costly to increase the strength of the maneuver than than inverting its sense so strength is increased as the encounter progresses. A limit is reached where such a turn would no longer be viable or is outside of Ownship performance limits so the maneuver's sense is inverted. Further analysis of this scenario is suggested.

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The Detect and Avoid (DAA) capability of a recent version (Run 3) of the Airborne Collision Avoidance System-Xu (ACAS-Xu) is measured against that of the Detect and AvoID Alerting Logic for Unmanned Systems (DAIDALUS), a reference algorithm for the Phase 1 Minimum Operational Performance Standards (MOPS) for DAA. This comparative analysis of the two systems' alerting and horizontal guidance outcomes is conducted through the lens of the Detect and Avoid mission using flight data of scripted encounters from a recent flight test. Results indicate comparable timelines and outcomes between ACAS-Xu's Remain Well Clear alert and guidance and DAIDALUS's corrective alert and guidance, although ACAS-Xu's guidance appears to be more conservative. ACAS-Xu's Collision Avoidance alert and guidance occurs later than DAIDALUS's warning alert and guidance, and overlaps with DAIDALUS's timeline of maneuver to remain Well Clear. Interesting discrepancies between ACAS-Xu's directive guidance and DAIDALUS's "Regain Well Clear" guidance occur in some scenarios.

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