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Analysis of DAA Alerting and Guidance using reconstructed trajectories that resulted in (N)MACs

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ABSTRACT

In this paper it is analyzed how the alerting and guidance provided by a Detect and Avoid system meeting the minimum operational performance requirements specified in RTCA DO-365 could have contributed to the prevention of 8 (N)MACs that occurred between 1972 and 2015.

Keywords: Detect and Avoid; See and Avoid; (Near) Mid-Air Collision; Guidance; Alerting

1 Introduction

Detect and Avoid (DAA) is intended as an electronic means of avoiding conflicting traffic to meet the intentions of the See-and-Avoid requirement. In May 2017 RTCA published DO-365, the Minimum Operational Performance Standards (MOPS) for UAS Detect and Avoid Systems [1]. Four months later the Federal Aviation Administration (FAA) published Technical Standard Order (TSO) C-211 for DAA Systems [2] referencing [1] for the required minimum performance standards. Following the 2018 National Aeronautics and Space Administration (NASA) No-Chase Certificates of Waiver or Authorization (COA) flight [3], the UAS pilot-in-command commented: '*I think we are better equipped to do this mission than any of the manned airplanes that are out there in the National Airspace*' [4].

A DAA system may also support pilots of manned aircraft flying under Visual Flight Rules (VFR). The study presented in this paper analyzed 8 encounters between aircraft in which See-and-Avoid failed. To determine whether a DAA system might have contributed to preventing the (Near) Mid Air Collision, the information a DAA system would have provided to the pilots up to two minutes preceding (N)MAC is analyzed.

2 Background

A fundamental element of a DAA system is the use of a quantified volume of airspace around ownship to keep clear of other aircraft, the so-called DAA Well Clear (DWC) volume. In [1], the DWC volume is defined as a temporal and spatial boundary relative to ownship position. DAA alerting and guidance requirements are specified in relation to a prediction of losing DWC. In a non-maneuvering encounter, the pilot will be provided with a so-called Corrective[1] Alert approximately 75 seconds before a predicted loss of DWC. If the time until a predicted loss of DWC decreases below approximately 25 seconds, a Warning[2] Alert is declared.

A DAA display provides the pilot with alerting and guidance information. On the Cockpit Display of Traffic Information (CDTI), color coded guidance bands indicate all directions in which an alert is predicted (Fig. 1). In the absence of alerts, the indication of directions (Fig. 2) on the CDTI and altitudes (Fig. 3) on the Vertical Profile Display (VPD) in which an alert would be declared, contributes to pilot awareness of conflicts that would result from a maneuver of ownship.

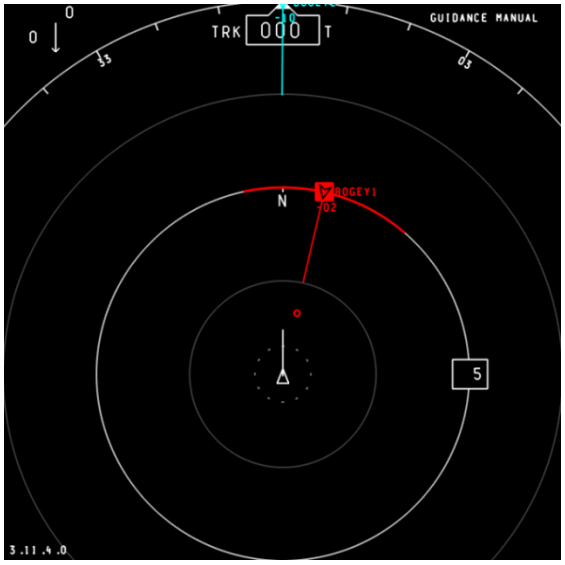


Figure 1. CDTI showing Warning Alert and heading guidance (red = headings to avoid)

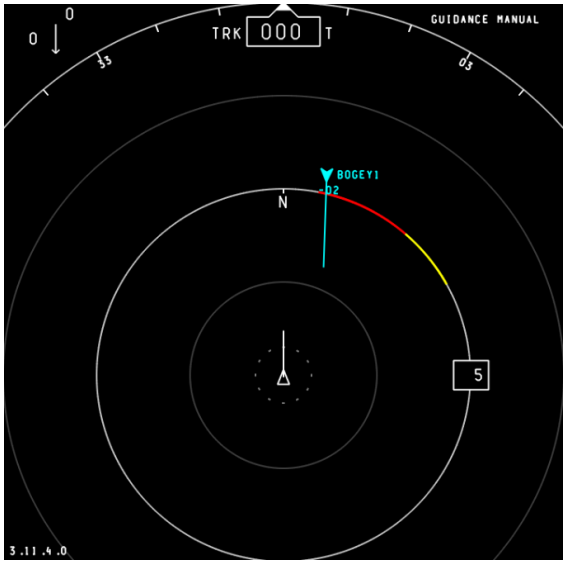


Figure 2. CDTI depicting peripheral heading guidance

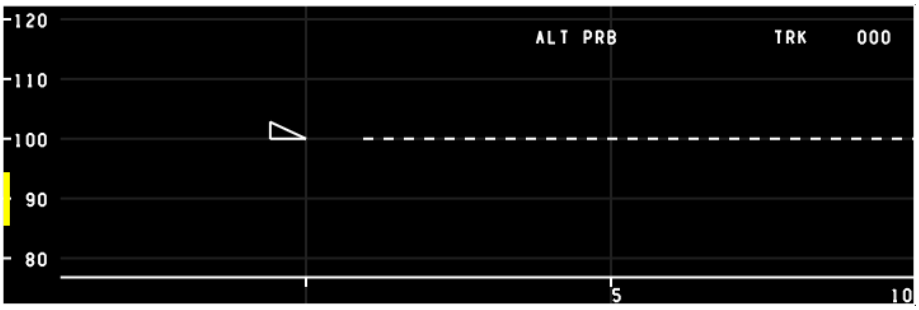


Figure 3. VPD with altitude tape indicating altitudes that would result in a DAA Corrective alert

[1] In the Operational Services and Environment Description (OSED) of [1] the pilot action after a Corrective Alert is described as follows: 'The pilot uses training, judgment, and display of traffic to assess the threat and the need to maneuver. If the PIC can't maneuver in response to ATC Traffic Advisory, the PIC will inform ATC'.

[2] In [1] the associated pilot action is specified as: 'The DAA warning alert is intended to inform the PIC that immediate action is required to maintain DWC. The warning alert necessitates immediate awareness of the PIC and a prompt ownship maneuver'.

To illustrate how, unlike other types of guidance data presentation, DAA peripheral guidance contributes to situation awareness, the following subsection discusses three types of guidance data presentation.

2.1 Different types of guidance information

Various types of guidance information are present in the flightdeck. A flight-director (FD) display shows guidance commands. The algorithm behind a flight director display is such that the desired state is obtained when the needles are in the center location. It is an error-zeroing presentation that does not convey actual physically interpretable information, i.e. the pilot does not know what the magnitude of the tracking error is if the deflection of a needle is non-zero. In contrast, on a Traffic Alert and Collision Avoidance System (TCAS) guidance display, red bands indicate vertical speeds that are to be avoided and a green band indicates the commanded range of vertical speed. As such, a TCAS display provides physically interpretable guidance information. The Remain Well Clear (RWC) guidance concept as specified in DO-365 differs from both of these two. It is neither an error-zeroing steering command nor an explicit commanded reference state (e.g. heading, altitude or vertical speed). It does not indicate a particular direction or altitude towards which the pilot has to maneuver. In contrast, it shows all directions and altitudes that are predicted to result in a loss of Well Clear. Within SC-228 this caused the committee to coin/adopt the term 'suggestive guidance'. In some research projects that pioneered this type of guidance for DAA (several years before SC-228 was established) the term 'conflict bands' was used to refer to the color-coded headings and altitudes that are predicted to cause a loss of separation [5]. Conceptually this type of guidance information is similar to the information provided by a plan-view Terrain Awareness and Warning System (TAWS) display and a weather radar display. The pilot can see the directions in which a hazard is predicted, also in case the current aircraft path is assessed as to avoid these hazards.

The fundamental difference between FD and TCAS guidance on one hand and DAA guidance on the other hand is, that in the former case the maneuver direction is determined by the automation whereas in the latter case the pilot makes the maneuver decision based on an understanding of the directions to avoid. Furthermore, DAA guidance bands may be present in the absence of a DAA alert. In DO-365 this is referred to as Peripheral guidance information.

Table 1 provides an overview of the three different types of guidance data presentation.

Table 1. Properties of three different types of guidance presentation

Type of guidance presentation	Type of data presented	Decision allocation	Control strategy
Error-zeroing display	No direct physically interpretable reference	System determines magnitude of error	Based on the goal of zeroing the error
Commanded reference state, with margins	Physically interpretable reference, e.g. heading, altitude or vertical speed	System determines reference state	Based on the goal of the aircraft achieving the reference state
States to avoid	Physically interpretable references, e.g. heading, altitude or vertical speed	Pilot chooses a reference state	Based on the goal of the aircraft achieving the reference state

The mental effort needed to predict future separation increases with the dimensions in which an extrapolation is not trivial[3]. By automating this prediction and presenting the outcome, detection of potential future hazards becomes independent of the complexity of the extrapolation process. The situation awareness provided through the depiction of heading and altitudes that would result in a DAA alert enables the pilot to answer the 'what if' maneuver question and thus can be classified as level 3 situation awareness. A limitation of the presentation of this data in two separate dimensions, i.e. on the CDTI and the altimeter, is that peripheral guidance is only available if the conflict exists in the other dimension.

2.2 Operational use of DAA alerting and guidance information

The Operational Scenario and Environment Description (OSED) of DO-365 assumes that the pilot will make a maneuver decision using the information provided by the DAA display in combination with information about other potential constraints (including those that follow from the right of way rules). The basis for the research described in this paper was the question to what extent such a DAA display could have been of potential help in (Near) Mid-Air Collisions (N)MACs in which at least one aircraft was operating under VFR.

3 Approach

To answer this question, a survey into (N)MACs was performed. A total of 8 were selected for further analysis[4].

Table 2. (N)MACs analyzed for the study described in this paper

Location / type	Date	Aircraft involved	Sources
San Diego / Midair	August 16, 2015	Sabreliner, Cessna 172M	NTSB Investigator-in-Charge presentation [6]
Moncks Corner / Midair	July 7, 2015	F-16CM, Cessna 150M (VFR)	NTSB Investigator-in-Charge presentation [7]
Lelystad / near midair	August 1, 2015	DO-228-100 (VFR), Tecnam P92 Echo Super (VFR)	Dutch Safety Board [8]
Hudson River / Midair	August 8, 2009	Piper PA-32 (VFR), Eurocopter AS350 (VFR)	NTSB/AAR-10/05 [9]
Front Royal / near midair	April 26, 1972	Boeing 720B, Convair 240 (VFR)	NTSB-AAR-72-30 [10]
Memphis / Midair	May 18, 1978	Falcon Jet (IFR), Cessna 150M (VFR)	NTSB-AAR-78-14 [11]
Greenwood / Midair	Sept. 11, 1992	Piper PA-32 (VFR), Mitsubishi MU-2B (VFR)	NTSB/AAR-93/05 [12]
Etten-Leur / Midair	December 22, 1999	F-16, Piper PA28	Dutch Safety Board Report 1999142 [13]

[3] An example of a trivial extrapolation is a head-on encounter at co-altitude. In contrast, a crossing encounter with different velocities and ownship/traffic climbing or descending makes the mental extrapolation more challenging

[4] The limit of 8 was determined by time constraints for the study.

3.1 Method

The aircraft trajectories preceding the (N)MACs were simulated, and the data from the simulated aircraft states was used to drive the DAA system. To be able to have the autoflight system of the simulator replicate the trajectories preceding the (N)MAC, flightplans for the aircraft involved had to be specified using 3-D waypoints and a reference velocity at each waypoint. Trajectories were reconstructed from data in the various reports. Although there certainly will be some discrepancy between the actual and the simulated trajectory, the differences will be smaller than the margins outside which a DAA system would have not provided alerting and guidance. Figure 4 illustrates how a series of radar plots were used to define a trajectory line that would be used to specify two waypoints defining that part of the trajectory.

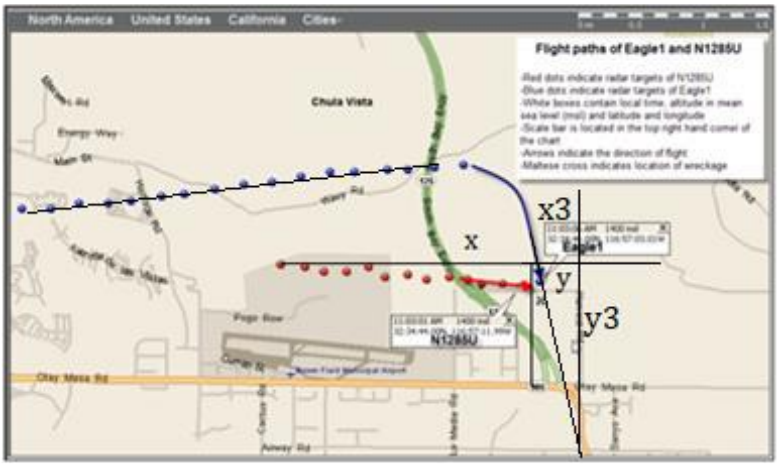


Figure 4. Example of how published radar plots were used to reconstruct trajectories for the simulation

Three types of geometries were present:

1. Geometry in which the conflict existed for a considerable time but was never noticed
2. Geometry in which aircraft were in safe proximity with low relative velocity but a blunder turn caused the (N)MAC
3. Geometry in which aircraft would pass at safe separation but a blunder turn caused the (N)MAC

Criteria used for the analysis comprised:

1. When would DAA peripheral[5] guidance bands have been presented relative to the time of a maneuver that preceded the (N)MAC?
2. When would a DAA Corrective Alert have been declared relative to time of (N)MAC?
3. When would a DAA Warning Alert have been declared relative to time of (N)MAC?

For each of the reconstructed trajectories, simulation of the flight along these trajectories was performed. Alerting times and situation awareness cues were identified using the DAA system in the simulation environment with the autopilot steering both aircraft.

Besides this analysis, the UAV Ground Control System (GCS) simulator[6] at the Netherlands Defence Academy (NLDA) in Den Helder was connected with a research flightdeck at the Technical University of Berlin. Both simulators were equipped with the same (simulated) DAA system. This provided the possibility to view the encounters as seen from either of the two aircraft, and also explore maneuvering options.

[5] Safety metrics that only consider the time of alert relative to the CPA do not reveal the full potential of a DAA display. The situation awareness conveyed by peripheral guidance bands is a defense against maneuvers that otherwise would cause loss of DWC at very low TCPA.

[6] The GCS simulator only provides a simulated sensor view. To perceive the situation as seen from the flightdeck and out-of-the-windshield view is needed, which was available in the setup at TU Berlin.

3.2 Analysis of the data

To determine when a DAA system would have provided the pilot with information that certain maneuvers would lead to alerts and whether, and if so when, a DAA system would have provided an alert, the following three tools were used:

1. Depiction of predicted Distance at CPA as a function of Time to CPA (TCPA-DCPA) charts[7]
2. Guidance band time-histories
3. Snap-shots of the DAA display

The following section provides examples on how these tools were used to analyze the situations preceding the (N)MACs.

4 Examples

In this section, the use of TCPA-DCPA charts for the horizontal- and TCPA-VCPA for the vertical dimension, guidance band time-histories and snapshots of the DAA display are used to illustrate how the analysis of the situations preceding the 8 (N)MACs was performed.

4.1 Monks Corner

The TCPA-DCPA chart in Fig. 5 shows how the predicted separation remained a little over 1 NM until TCPA was about 25 seconds. The TCPA-VCPA chart in Fig. 6 shows that vertical separation was decreasing. Given the small TCPA at which predicted DCPA decreases below the alert threshold, there would have been no Corrective Alert and the Warning Alert would have been provided at a very late moment. It is questionable whether an alert this late could have helped the pilots[8] prevent the (N)MAC. However, given the fact that at a TCPA of 100 [s] the vertical separation was already within 450 ft, peripheral guidance bands would have been present on the DAA display. The snapshot of the CDTI that was taken at a TCPA of 85 [s] shows the yellow heading guidance to the left of ownship track that the F-16 pilot would have seen. As TCPA decreases, the color of the heading guidance band changes to red. This situation is depicted in Fig. 8. Based on these situation awareness cues, it is hypothesized that the availability of a DAA display in the F-16 would likely have prevented the pilot from deciding to turn left.

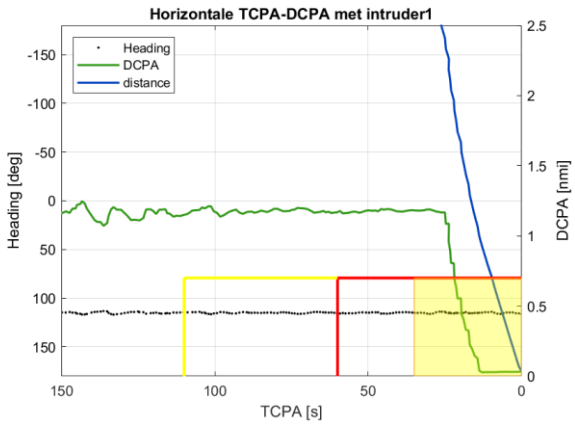


Figure 5. TCPA-DCPA chart for reconstructed Moncks Corner trajectories.

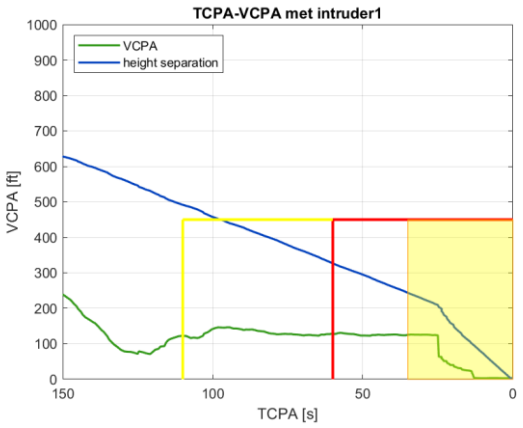


Figure 6. TCPA-VCPA chart for reconstructed Moncks Corner trajectories.

[7] For low closure-rate the TCPA-DCPA chart has limitations, see [14].

[8] A DAA display on board the Cessna 150M would have declared a Warning Alert at approximately the same moment.

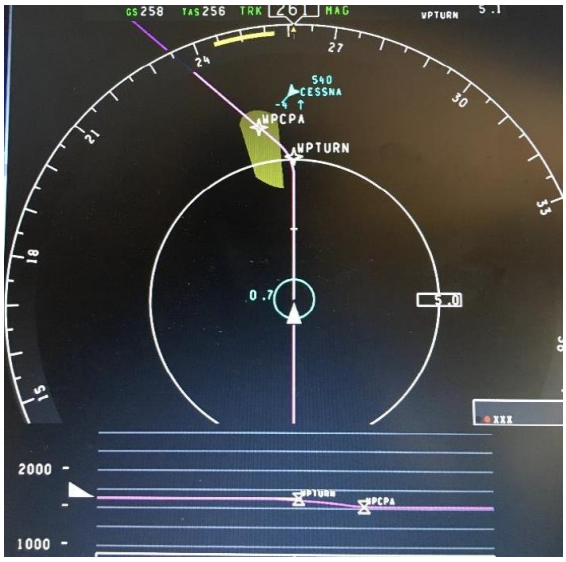


Figure 7. DAA display for F-16, Moncks Corner, TCPA 85

Figure 8. DAA display for F-16, Moncks Corner, TCPA 40

The snapshots in Figure 7 and 8 give an indication of the DAA information the pilot would have been provided with. The key is the location of the guidance bands relative to ownship track. In the next example, a time-history of these guidance bands is used as an alternative to a sequence of snapshots.

4.2 Etten Leur

The TCPA-DCPA chart for the Etten-Leur midair (Fig. 9) is similar to the TCPA-DCPA chart for the Moncks Corner midair (Fig. 5). At a very low TCPA, the maneuver of the F-16 causes predicted DCPA to decrease below the Warning Alert threshold.

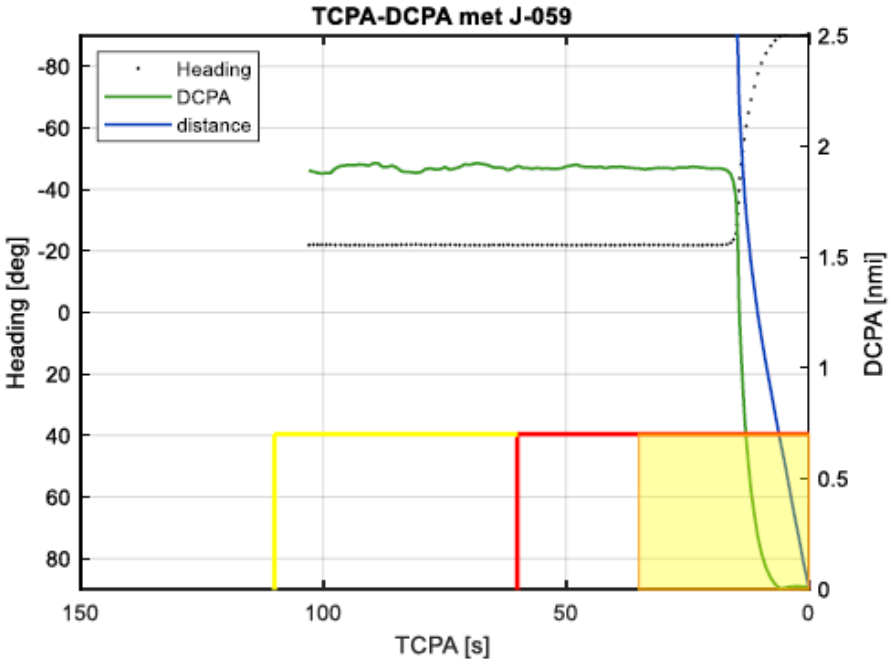


Figure 9. TCPA-DCPA chart for reconstructed Etten-Leur trajectories.

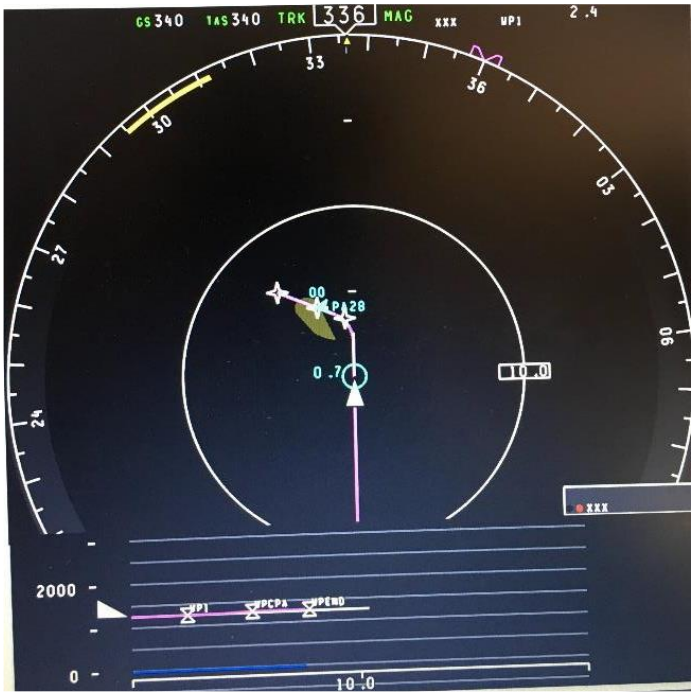


Figure 10. DAA display for F-16, Etten-Leur, TCPA 40.

Figure 10 shows what a DAA display in the F-16 would have depicted just before the left turn.

Figure 11 shows the time-history of the guidance band. On the horizonal axis, t=0 represents the first moment a peripheral guidance band is depicted. As can be seen, around t=90 the peripheral guidance band is completely red and extends from about 25 to 50 degrees to the left of ownship track. Around this time, the F-16 pilot turns left. Similar to the midair at Moncks Corner, it is hypothesized that the availability of a DAA display in the F-16 would likely have prevented the pilot from deciding to turn left.

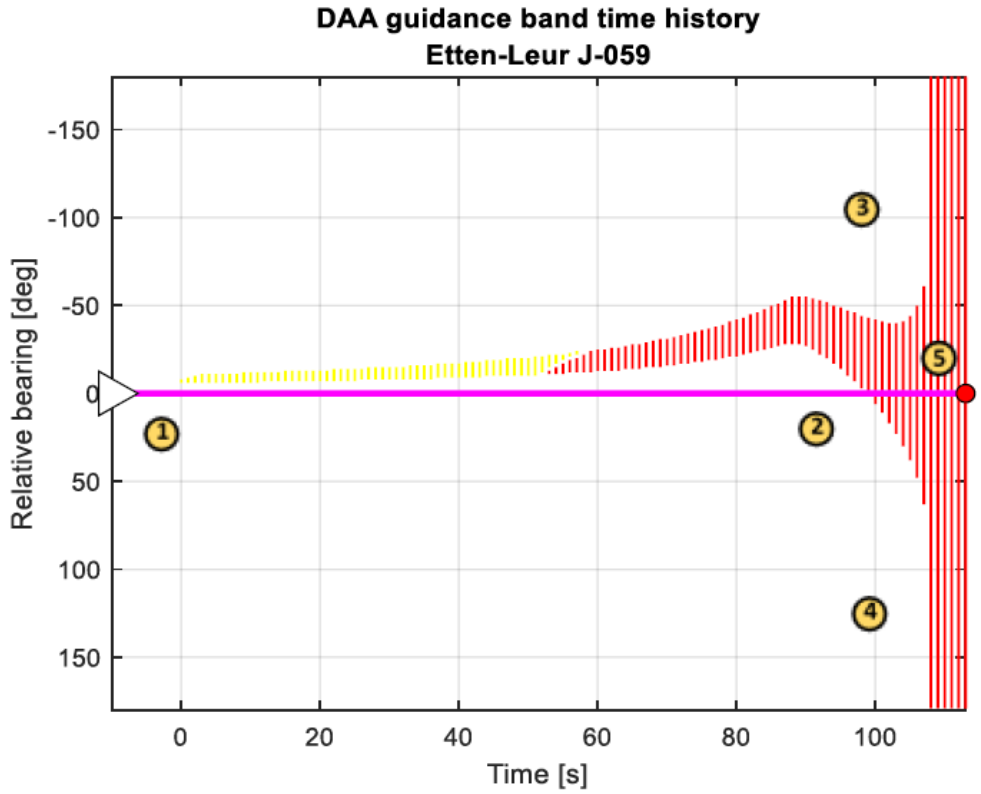


Figure 11. Guidance band time-history for DAA display on board F-16 preceding Etten-Leur (N)MAC

Figure 12 shows the guidance band time-history for a DAA display on board the Piper PA28.

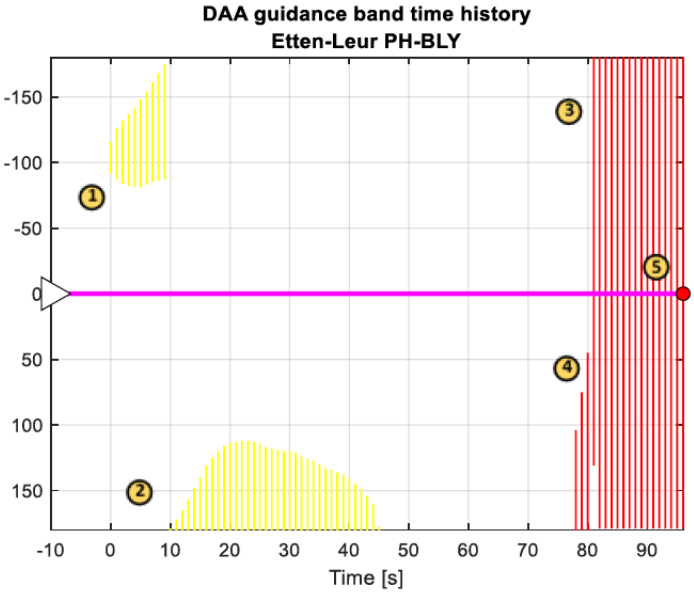


Figure 12. Guidance band time-history for DAA display on baord Piper PA28 preceding Etten-Leur MAC

From this time-history it can be concluded that before the Warning Alert (that was declared only briefly before the MAC), no other cues were available to the pilot of the Piper PA28.

Figure 13. ND showing that a turn to the right will result in an alert

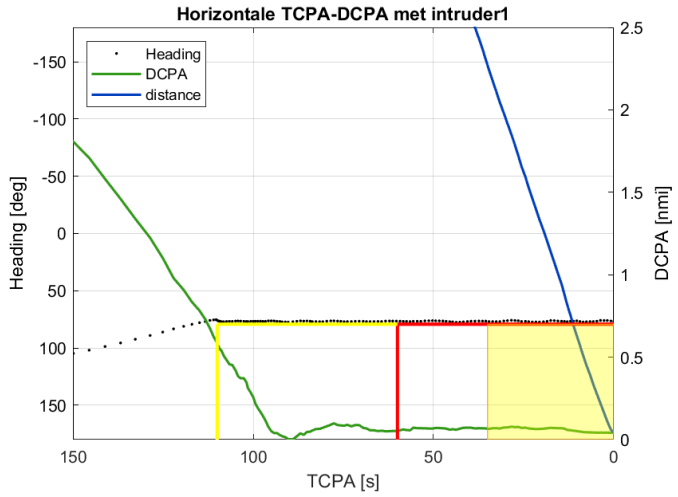
4.3 San Diego

As pointed out, for low closure-rates a TCPA-DCPA chart has limitations. Screen captures and guidance band time-histories still provide sufficient information to analyze the potential contribution of a DAA display.

Figure 13 shows what a DAA display in the Sabreliner would have depicted before the turn to the right was made that resulted in the MAC near San Diego on August 16, 2015. Close to current ownship track the heading band is already yellow, and after 20 degrees changes to red.

4.4 Timely alert example – Lelystad

The previous three examples all comprised geometries in which a turn at low CPA suddenly created a collision hazard. In these situations, DAA alerts would have come late and it is uncertain how much such an alert could have contributed to preventing the MAC. The contribution of a DAA display to prevent such situations is the situation awareness provided by the peripheral guidance. The TCPA-DCPA chart in Figure 14 illustrates a situation in which a collision geometry existed at a longer time before the closest point of approach. In such a geometry, guidance bands appear at the same time as the Corrective Alert.



In this situation, a Corrective Alert would have been declared at about 110 seconds before CPA. This would have provided the pilots with time to assess the situation and take action to prevent the predicted loss of Well Clear. Around the time of the alert, a yellow guidance band would have been displayed that intersected ownship track.

Figure 14. Lelystad

5 Results and Discussion

Table 3 summarizes the results of the analysis of all 8 (N)MACs.

Table 3. Summary of the results of the analysis

Location / type	Aircraft	Peripheral before maneuver[s]	Corrective Alert [s] before (N)MAC	Warning Alert [s] before (N)MAC	Trajectory
San Diego / Midair	Cessna 172	None	None	**<15**	Steady course
	Sabreliner	**15**	None	**<15**	Overtake with right turn
Moncks Corner / Midair	Cessna 150	None	None	**<15**	Steady course
	F-16	**83**	None	**<15**	Crossing behind with left turn
Lelystad / near midair	Do-228	None	>100	60	Steady course, speed decr.
	Tecnam P92	**10**	>100	60	Steady course
Hudson River / Midair	Piper	None	None	**<30**	
	Eurocopter	None	None	**<30**	turns and climbs
Front Royal / near midair	Boeing 720	None	>100	60	Steady course
	Convair 340	None	>100	60	Steady course
Memphis / Midair	Falcon jet	**73**	None	**40**	Crossing, course correction
	Cessna 150	**>45**	None	**40**	Crossing, course correction
Greenwood / Midair	PA32	None	None	**<35**	Steady course
	MU2	**9**	None	**<35**	Right turn and climb
Etten-Leur / Midair	PA28	None	None	**<15**	Steady course
	F-16	**90**	None	**<15**	Turns left

Two of the analyzed (N)MACs (Lelystad and Front Royal) could likely have been prevented because the Corrective Alert would have been triggered more than a minute before CPA was reached.

Another four of the analyzed MACs (San Diego, Moncks Corner, Memphis and Etten-Leur) could likely have been prevented because the pilot of the aircraft that caused the sudden decrease in predicted separation would have been presented with yellow/red guidance bands in the direction of the turn.

As pointed out, DAA peripheral guidance bands provide no preview on threats that result from a blended[9] maneuver. For both the Hudson River midair and the Greenwood midair, the Warning alert would have been declared only briefly before CPA and before this alert any peripheral guidance bands would have shown up very (too?) late.

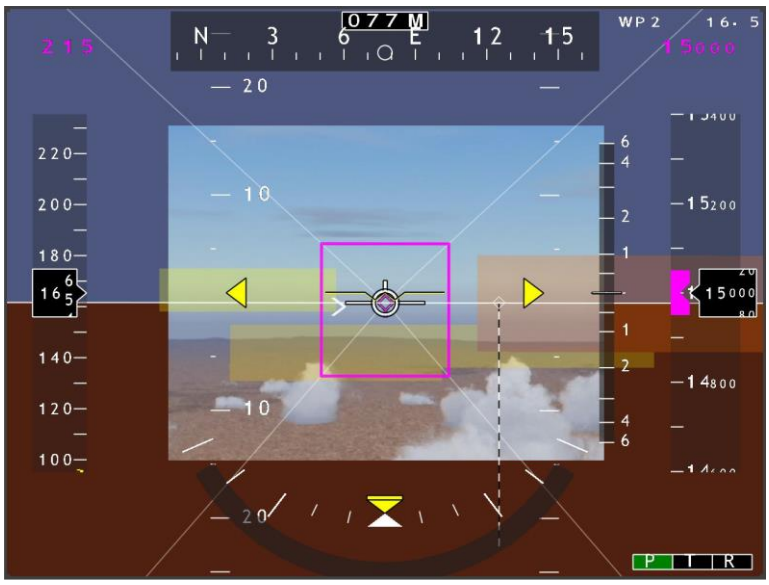


Figure 15. Conflict space depiction in a forward-looking display [5]

A forward-looking DAA display that is based on two-dimensional conflict probing is one potential solution to provide preview on the impact of blended maneuvers. An example of such a display format (Fig. 15) was implemented and evaluated in 2008 [5].

6 Perspective from the flightdeck

Figure 16. Research flightdeck at TU Berlin.

To replicate the situation as seen from the flightdeck, the UAV GCS simulator at NLDA was connected to a research flightdeck at TU Berlin. Tests were performed to measure latency and the ability to re-create (N)MAC geometries, and it was concluded that even with two asynchronous simulations it would be possible to bring the simulated positions within (N)MAC distance. Figure 16 shows a view from the research flightdeck of TU Berlin during the turn into the Cessna 150M (Moncks Corner). The technical feasibility was demonstrated and this capability proved very useful to illustrate the contribution of a DAA display using simulated (N)MAC geometries.

[9] In a blended maneuver the aircraft changes direction in both the horizontal and vertical dimension.

7 Summary and conclusions

For 8 (N)MACS, the information that would have been provided by a DO-365 compliant DAA display was analyzed.

For 2 out of the 8 analyzed situations, the Corrective alert would likely have caused the pilots to assess the cause of the alert and take appropriate action.

For another 4 out of the 8 analyzed situations, the presentation of headings and altitudes that would lead to a loss of Well Clear, would have significantly reduced the likelihood of a pilot turning into the direction that caused the (N)MAC.

8 Acknowledgements

The authors would like to thank prof.dr.ir. Uijt de Haag from TU Berlin for his support and Sam Kim from NASA Armstrong for his review and comments.

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