CHALLENGES IN EUROPEAN AEROSPACE
5TH CEAS AIR & SPACE CONFERENCE
CEAS

Design, Implementation and Evaluation of a Display to Support the Pilot's Ability to Remain Well Clear

Erik Theunissen, Netherlands Defence Academy
Het Nieuwe Diep 8, 1781AC, Den Helder, The Netherlands
E.Theunissen@uav.nl
Brandon Suarez, General Atomics Aeronautical Systems Inc., Poway, CA, United States
Brandon.suarez@ga-asi.com

ABSTRACT

In the development of a Pilot-in-the-Loop (PITL) Detect and Avoid (DAA) capability, the design of a traffic display with alerts and guidance is critical. GA-ASI has developed the Conflict Prediction and Display System (CPDS) and is contributing to ongoing requirements definition activities in the DAA community. Certain decision aids can be used to facilitate the pilot of a Remotely Piloted Aircraft (RPA) remaining Well Clear of other airspace users. Testing and evaluation of CPDS has been performed in both human-in-the-loop simulations and live flight tests. Testing displays designed to support DAA functionality presents unique challenges and stressing scenarios that are not intuitive.

1 INTRODUCTION

For Remotely Piloted Aircraft Systems (RPAS) to meet the intent of ICAO's Annex 2[1], a technical solution is being developed to enable a Detect and Avoid[2] (DAA) capability. A DAA system must be capable of both Traffic Avoidance[3] (i.e. remaining "Well Clear") and Collision Avoidance. It is generally accepted that the Collision Avoidance function should be automated onboard the aircraft to mitigate against datalink intermittency and to provide an additional safety net should an encounter between aircraft progress past the other layers of safety [1].

Both from an operational and from a design perspective there is a need for an objective, quantitative definition of "well clear". The Science and Research Panel (SARP[4]) considered three concepts for the definition of well-clear [2]. All concepts use a spatial threshold as part of the criterion. Two of the concepts use a temporal threshold based on the relative velocity between ownship and intruder. The quantitative definition was tuned to yield a 1.5% probability of a Near Mid Air Collision (NMAC) in case of an unmitigated violation of the well clear boundary. In August 2014, the SARP recommended a quantitative definition of well clear to RTCA SC-228[5].

---

[1] ICAO's Annex 2, commonly known as the Rules of the Air, describe the operational requirements which are adapted in member states (e.g., 14 CFR §91 in the US)
[2] For the purposes of this work, "Sense and Avoid" and "Detect and Avoid" are two terms referring to the same functionality. The authors recognize the definitions published in the ICAO RPAS Manual.
[3] For the purposes of this work, "Traffic Avoidance" and "Self Separation" are two terms referring to the same capability.
[4] The SARP is a U.S. government funded organization established by the Office of the Secretary of Defense (OSD) and designed to bring together SAA community stakeholders to close known research gaps.
[5] RTCA SC-228 is developing Minimum Operational Performance Standards (MOPS) for DAA and RPAS Command and Control (C2) Datalink.

The quantitative definition comprises a spatial and a temporal boundary and is conceptually similar to the alerting threshold used in TCAS II. The desired remote pilot performance in the task of remaining well clear comprises two aspects:

1. Timely detection of all conflicts (future loss of well clear) with the goal of:
    a. Understanding the conflict in case Air Traffic Control (ATC) or the intruder do not resolve it in time
    b. Appropriately performing a manoeuvre (timing and magnitude) that prevents the projected well clear violation.
2. Minimizing unnecessary manoeuvring. This comprises the prevention of:
    a. Situations in which the pilot initiates a manoeuvre to remain well clear whereas the continuation of the current trajectory would not have resulted in a loss of well clear.
    b. Situations in which ownship manoeuvres due to a temporary predicted loss of well clear outside the 85 second threshold used to indicate proximate traffic.
    c. Situations in which the manoeuvre performed by the pilot to remain well clear is far more severe than necessary.

The remote pilot's role, once an alert has been triggered, is to make an assessment of the expected result of not manoeuvring and, in case the pilot judges that a loss of well clear will occur, the pilot has to make a decision on when to manoeuvre and how to manoeuvre in consultation with ATC.
The assessment comprises a (mental) extrapolation of the current situation to certain point(s) in the future and a comparison of this situation with certain known criteria. The ability to achieve the desired performance depends on:

1. The pilot's experience with and training on traffic displays.
2. The presentation of the available information about the current traffic situation (including the trends).
3. The availability of additional information regarding the predicted future situation and separation.
4. The presentation of manoeuvre options/guidance/commands intended to prevent a loss of well clear.

If information is provided that allows the pilot to 'skip' the (required) extrapolation to make the assessment, this reduces the mental effort needed to make a judgement. Depending on other demands on these resources, this can result in:

1. A more effective allocation of mental resources (so better performance on other tasks) and/or
2. lower workload and/or
3. better performance on the current task.

In the context of NASA's ongoing 'UAS Integration in the NAS' Project, three prototype systems to support the pilot in remaining well clear have been evaluated during a range of pilot-in-the-loop simulations and flight tests. The most recent flight test is called Flight Test 3, which started in June 2015. One of the three systems tested is the Conflict Prediction and Display System (CPDS), developed by GA-ASI. The first part of this paper provides an overview of the design rationale in relation to the requirements for a display to support DAA. The second part discusses the goals of the recent flight test for the current implementation of CPDS.

2 CONFLICT SPACE

2.1 Basic data presentation concept

To aid the pilot in avoiding (separation) conflicts, several concepts for the visualization of the results from conflict prediction and resolution functions have been pursued. These concepts differ in the design of the graphical user-interface but also in the level of automation (LOA[6]) applied for decision selection. With a LOA of 2, a conflict prediction function offers a complete set of decision/action alternatives. In case the LOA of the function is increased to 4, the system will only present a single manoeuvre option to the pilot. This is more comparable to a Traffic alert and Collision Avoidance System (TCAS) Resolution Advisory (RA).

An example of a data presentation concept in which this LOA is used is the conflict probe display discussed in [4,5]. The concepts discussed in [4,5] used a spatial-only threshold of the volume of airspace to be avoided. A conflict prediction function uses this threshold to compute *whether*, and if so *where* the boundary defined by the threshold is predicted to be crossed. When performing this computation for a specified range of manoeuvre options, the resulting set of locations define a volume to be avoided. Figure 1 provides an example of the visualization of such a volume.

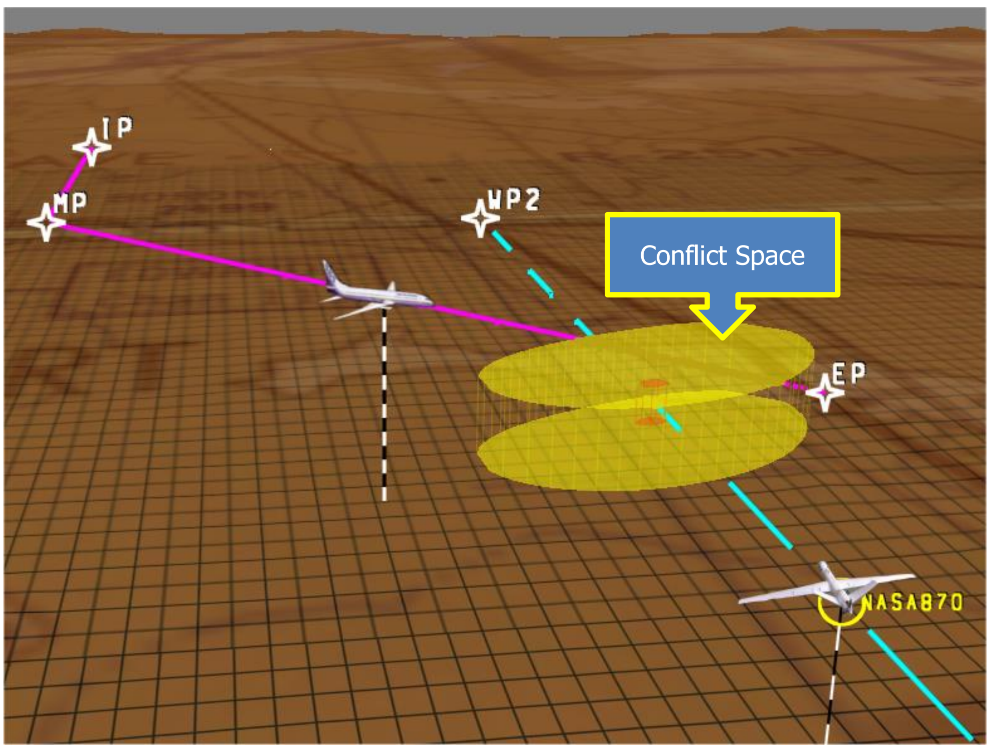

Figure 1: Conflict space that ownship has to avoid in order to remain well clear of the intruder.

[6] In [3], the levels of automation are applied to the four stages of information processing.

To provide the pilot with awareness of the conflict space, it can be projected relative to ownship onto a plan view display[7], e.g. as illustrated in Figure 2.

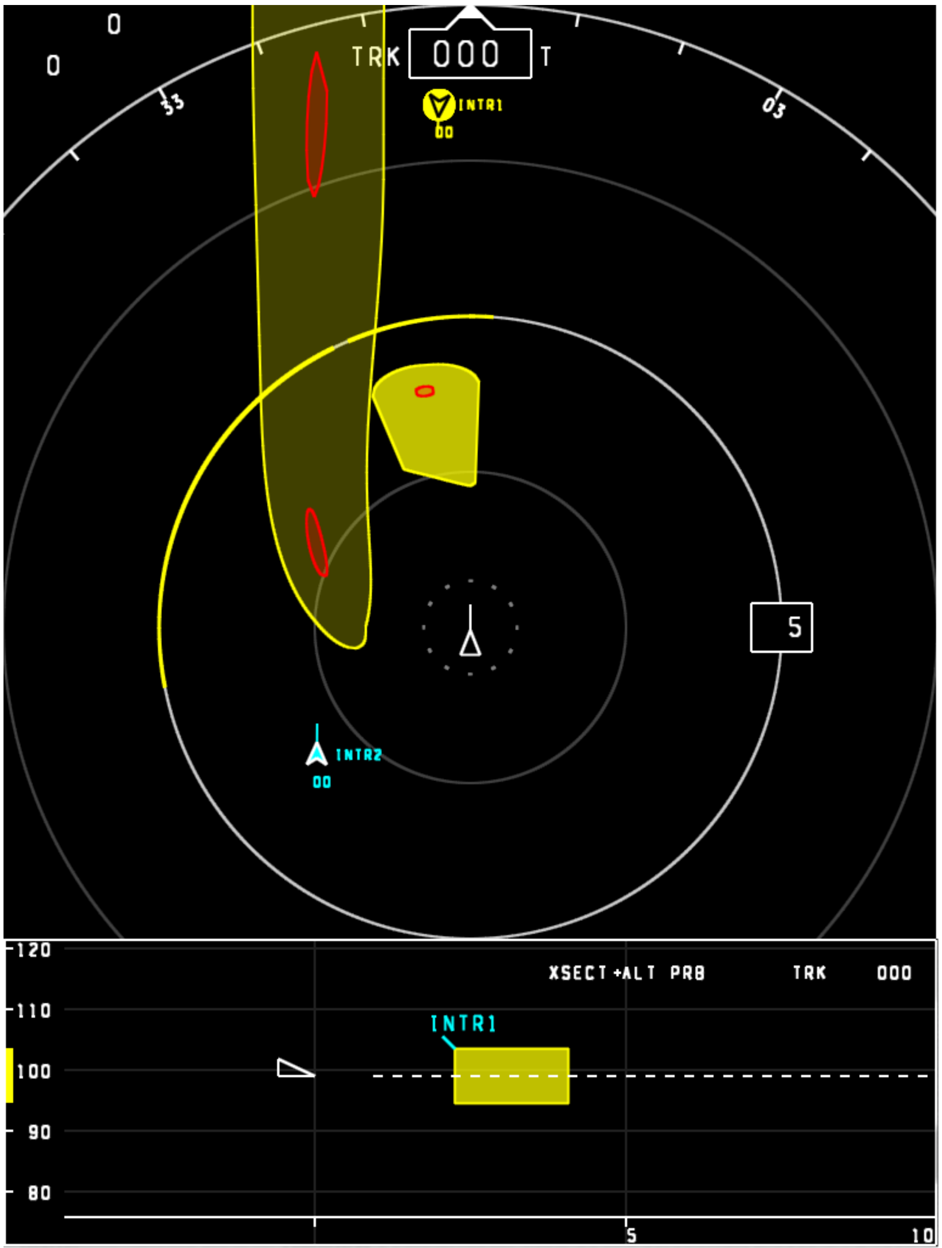

Figure 2. Projection of a horizontal cross section of the conflict space project onto a map and a vertical cross section onto a VPD.

[7] The idea of computing and depicting the predicted conflict space dates back to the HICANS and INCAS projects sponsored by the Office of Naval Research [6,7].

The depiction of the conflict space provides the pilot with awareness of the locations and directions that should be avoided. However, there is no explicit information regarding the time that remains before the boundary is crossed. Besides a continuous numerical or graphical indication of this time for the current track and speed, an indication for the other directions that are predicted to lead to a conflict may be beneficial. In various display concepts this information is provided using colour coded heading and altitude bands [8]. In most of these implementations a three level alerting scheme is used, e.g.:

1. No colour code band: no conflict predicted in this direction in the next X seconds.
2. Yellow (i.e., caution level alert) coloured band: conflict predicted to occur in this direction between the next Y and X seconds.
3. Red (i.e., warning level alert) coloured band: conflict predicted to occur in this direction within Y seconds.

Figure 3 shows the relation between the temporal distance to the conflict space and the colour code used in a heading band. It illustrates the relationship of the predicted conflict space and the heading arc with the colour being dependent on the time it would take ownship to reach the conflict space in that particular direction[8].

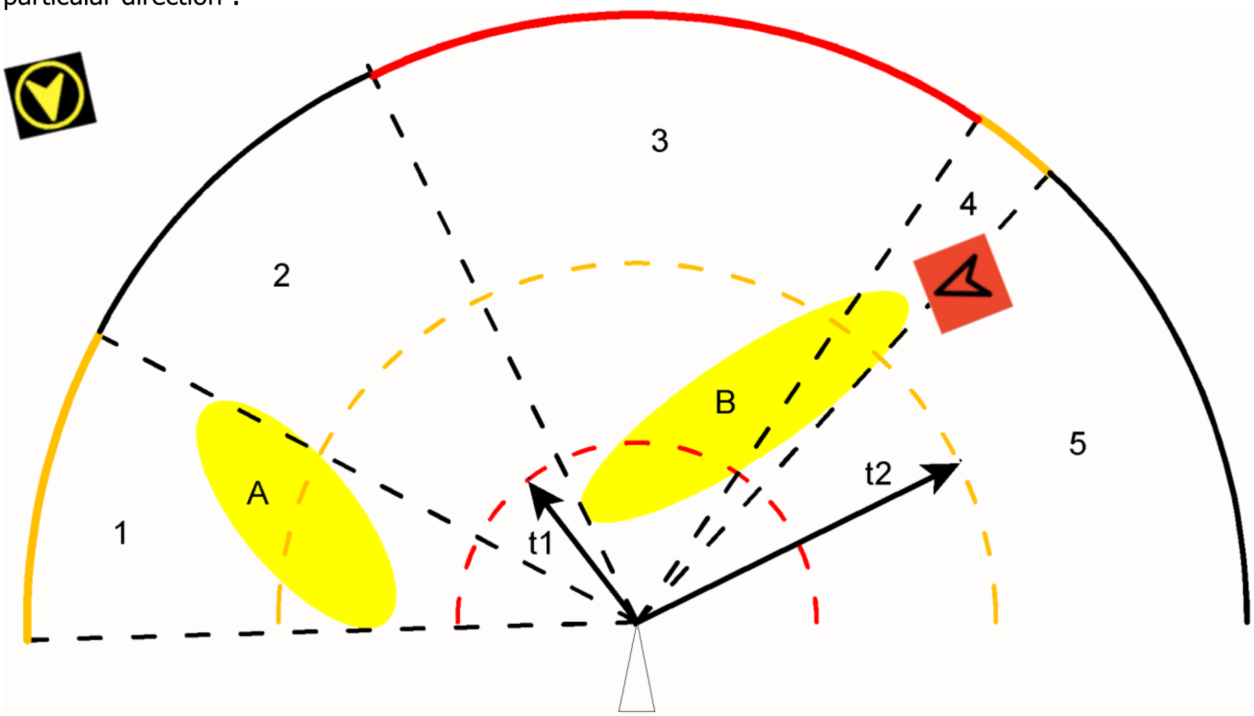

Figure 3: Relation between time to conflict space and heading band alerting concept.

In Figure 3, t1 is the time associated with the warning-level alert (e.g. 25 sec) and t2 with the caution-level alert (e.g. 75 sec). Note that in this example drawing the distance ratios between the yellow and red arc do not represent the 75 to 25 seconds. The arrow next to t1 has a length of Vown * t1. The contour

[8] Instantaneous manoeuvres have to be assumed or assumptions have to be made regarding aircraft dynamics

of probe area B that lies within the red dashed arc can be reached in less than t1 seconds, hence this part of the probe is projected as a red band on the heading arc (sector 3). The part of the area of probe B between the red dashed arc and yellow dashed arc is the area between t1 and t2 seconds, hence this part of the area is 'projected' as a yellow band onto the heading arc (sector 4). The same is true for the area of probe A in sector 1. In sector 2 the area of probe A lies outside the dashed yellow arc, hence no projection onto the heading band is performed. In sector 5 there are no probe areas.

2.2 Impact of Well Clear definition

The current quantitative definition of well clear uses a spatial threshold to protect against low closure-rate encounters and a temporal threshold to ensure sufficient protection for encounters with high closure rates. Like the spatial-only definition, a spatial-temporal definition can also be used to compute the conflict space by varying ownship state, and the resulting conflict space can be presented in the same way. Every manoeuvre that is predicted to avoid the conflict space is a potential option to remain well clear. Based on this and other information, the pilot can select a manoeuvre. Whereas the earlier mentioned studies into conflict probe displays used a spatial-only threshold, the studies discussed in [9,10] addressed the impact of a spatial temporal threshold.

3 CPDS

3.1 Background

In anticipation of future requirements for detect and avoid, GA-ASI started the development of the Conflict Prediction and Display System (CPDS). Based on the results from both published and internal research, it was concluded that CPDS should have the capability to depict the predicted conflict space onto a plan-view traffic display, in combination with temporal cues such as the heading bands.
The initial design of CPDS was started in 2009. The design assumed the use of both a plan view CDTI and a VPD for the depiction of the conflict space. Many design requirements for the CDTI follow from DO-317B [11], but agreement on key aspects such as the definition of well clear was still over the horizon at that time. A key aspect was the use of a modular architecture that supports a stepwise increase in capabilities and refinement. This has enabled GA-ASI to refine and, if needed, update key components of CPDS such as the algorithms that compute the well clear boundary, the self-separation alert thresholds, and the symbology associated with the proposed self-separation alert states.

3.2 DAA Support

CPDS provides the following functionality for DAA support:

1. Self-Separation and Collision Avoidance alerting scheme for traffic symbols
2. Colour coded heading and altitude bands to provide temporal information for directions in which well clear is predicted to be lost
3. Depiction of horizontal and vertical cross sections of the conflict space.

3.3 Self-separation alerting

A change of the traffic symbol style and background (circle, block) informs the pilot that a loss of well clear is predicted to occur within a certain time. The colour informs the pilot about the time until the predicted loss of well clear is going to occur (i.e. for the proposed self-separation alerts the following thresholds apply red<25 sec, >25 yellow<75, and >75 solid <85 sec).
This function aids with conflict detection and provides an indication of severity to ensure the appropriate reaction, but the location where the conflict will occur is not made explicit and the colour coded time

information does not allow for an accurate estimate of remaining time until the actual conflict (except at the transition to yellow and to red and as an upper bound). Thus, the mental effort needed to determine 'whether' a conflict is predicted to occur is reduced because traffic with an alert is predicted to violate the Well Clear Boundary. In the absence of other aids, the pilot still has to perform the mental effort to determine the manoeuvre needed to remain well clear.

3.4 Colour coded heading bands

The headings and altitudes covered by the band inform the pilot about the directions in which a conflict is predicted to occur, the colour coding informs the pilot about the urgency with which the conflict should be resolved. For example, with only a caution-level alert, the remote pilot flying on an IFR clearance, is expected to negotiate a clearance change with ATC.
Compared to the cues provided by the change in symbol attributes, the explicit presentation of the directions in which loss of well clear is predicted to occur changes the task of the pilot from determining a manoeuvre based on an extrapolation of the current situation to selecting a manoeuvre optimized against other constraints. This reduces the mental effort that has to be performed in the context of the assessment and decision making. In terms of LOA this can be classified as implicit LOA 2 support.

3.5 Depiction of horizontal and vertical cross sections of the conflict space

The area covered by the conflict probe inform the pilot about the locations where separation will be below the well clear boundary. Similarly to the heading bands, the explicit presentation of the area where a loss of well clear is predicted to occur changes the task of the pilot from determining a manoeuvre based on an extrapolation of the current situation to selecting a manoeuvre option. This reduces the mental effort that has to be performed in the context of the assessment and decision making. Unlike the two-level colour coding (yellow-red), the explicit depiction of the location provides continuous information about the distance to the conflict. Also, in case a conflict heading arc is caused by multiple traffic, the depiction of the conflict space will make this immediately apparent. In terms of LOA this can be classified as implicit LOA 2 support.

4 TESTING AND EVALUATION

Testing and evaluation of CPDS has been performed using pilot-in-the-loop simulations and live flight tests. The first flight tests with CPDS were performed in August 2012 with only ADS-B (Automatic Dependent Surveillance Broadcast) as a sensor input. These were followed by a second series in August 2013 using an air-air radar as a sensor input. In 2014 CPDS has been used in various projects, including the flight test of a Proof-of-Concept DAA System[9] flight test using ADS-B, an air-air radar, and active surveillance from TCAS as sensor inputs. The most recent flight of a full Prototype DAA System test took place in June 2015 as part of NASA's 'UAS Integration in the NAS' Project.
For this latter flight test, specific goals were to test the system for the following three types of encounters:

1. Well Clear is resolved through an intruder manoeuvre while having a caution-level alert (before the warning-level alert occurs).

[9] The Proof-of-Concept DAA System Flight Tests included collaborative contributions from the Federal Aviation Administration (FAA), the National Aeronautics and Space Association (NASA), Honeywell, and BAE Systems.

2. The intruder triggers a caution-level alert due to a manoeuvre within the 75 -25 seconds to the well clear boundary.
3. Due to an intruder manoeuvre, the self-separation alert state cycles from normal to caution-level to normal.

4.1 Results

The results in this section are those obtained from simulations that were performed for the preparation of the 2015 flight test. The encounters described in this section were flown in June 2015 and the results match with those obtained from the simulations.
Figure 4 shows the predicted distance at CPA (red dots) and the actual separation (yellow dots) with the intruder as a function of time to CPA (horizontal axis) for a situation in which the intruder changed direction approximately 90 seconds before the CPA point was reached. The cyan dots indicate a relative change in ownship track.

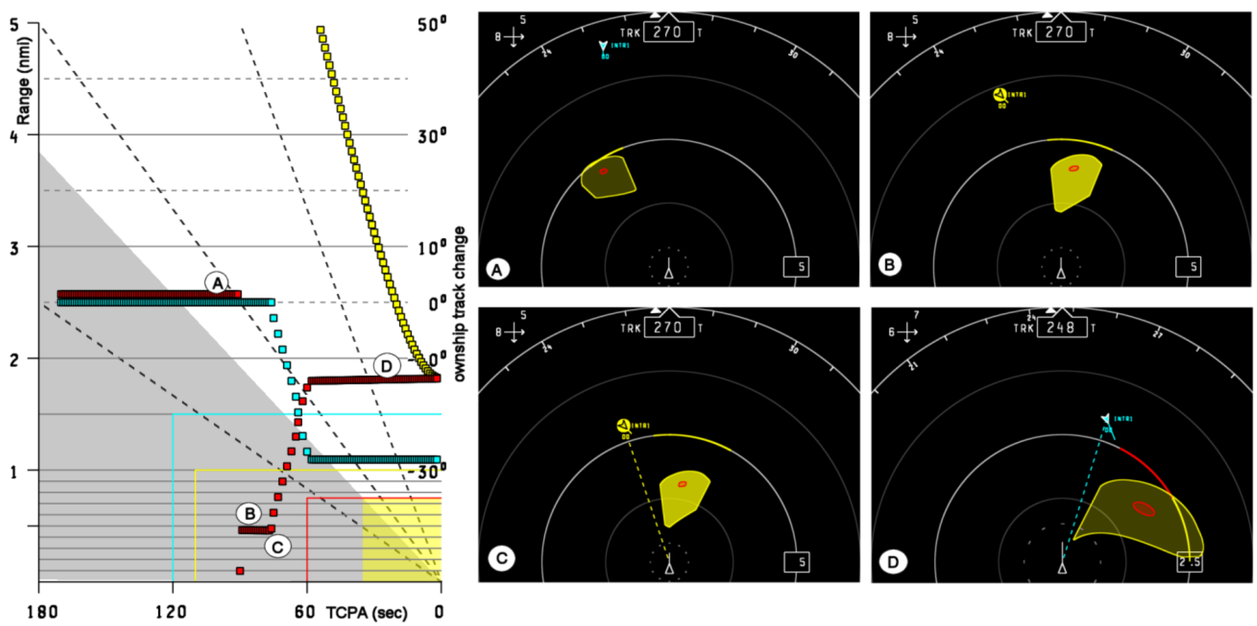

Figure 4: Ownship manoeuvres to remain Well Clear.

Initially, the predicted distance at CPA (red dots) was approximately 2.6 nmi. Briefly after (A) the intruder starts to turn. After the intruder has changed direction, at about 105 seconds before CPA this has decreased to 0.5 nmi (B). The UAS pilot observes this situation for about 15 seconds and decides to manoeuvre (C). The cues provided by CPDS allow the pilot to determine the required change in direction. The cyan dots indicate a change in track of 30 degrees. At about 60 seconds to CPA the UAS has completed its manoeuvre and is predicted to pass the intruder at a distance of about 1.8 nmi, well clear. Around 50 seconds to CPA, the distance to the intruder has decreased to 5 nmi (yellow dots), and during the next minute this distance will further decrease to the predicted 1.8 nmi.
Figure 5 shows the result of a situation in which the intruder manoeuvre prevents a loss of well clear.

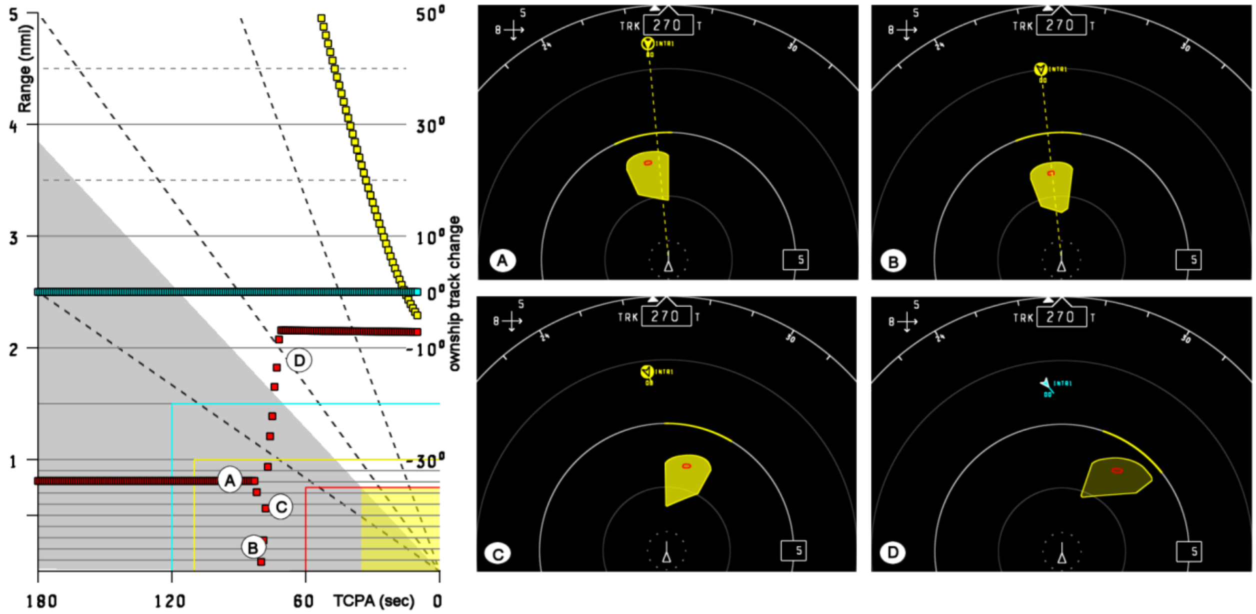

Figure 5: Intruder manoeuvres to remain Well Clear.

The predicted distance at CPA is close to the threshold and enough to trigger the preventive alert status (A), and also the caution-level status. The remote pilot monitors the situation since the current intruder trajectory will cause a loss of Well Clear. At about 80 seconds to CPA, the intruder starts to manoeuvre and initially the predicted distance at CPA decreases (B). However, because the intruder continues its turn, the CPA point crosses ownship track at about 76 seconds to CPA after which the predicted distance at CPA increases (C) to about 2.3 nmi (D). The cyan dots indicate that ownship never changed its track, there was no need since the intruder has resolved the conflict.

Figure 6 shows a similar situation, however in this case initially the predicted distance at CPA is larger and seems no cause for concern. The intruder has the proximate traffic status, indicating that it should be considered in case ownship has to manoeuvre. However, because the intruder manoeuvres within a time to CPA that is below the caution-level alert threshold, the intruder temporarily obtains the caution status. Such a situation should not immediately lead to an action of the remote pilot.

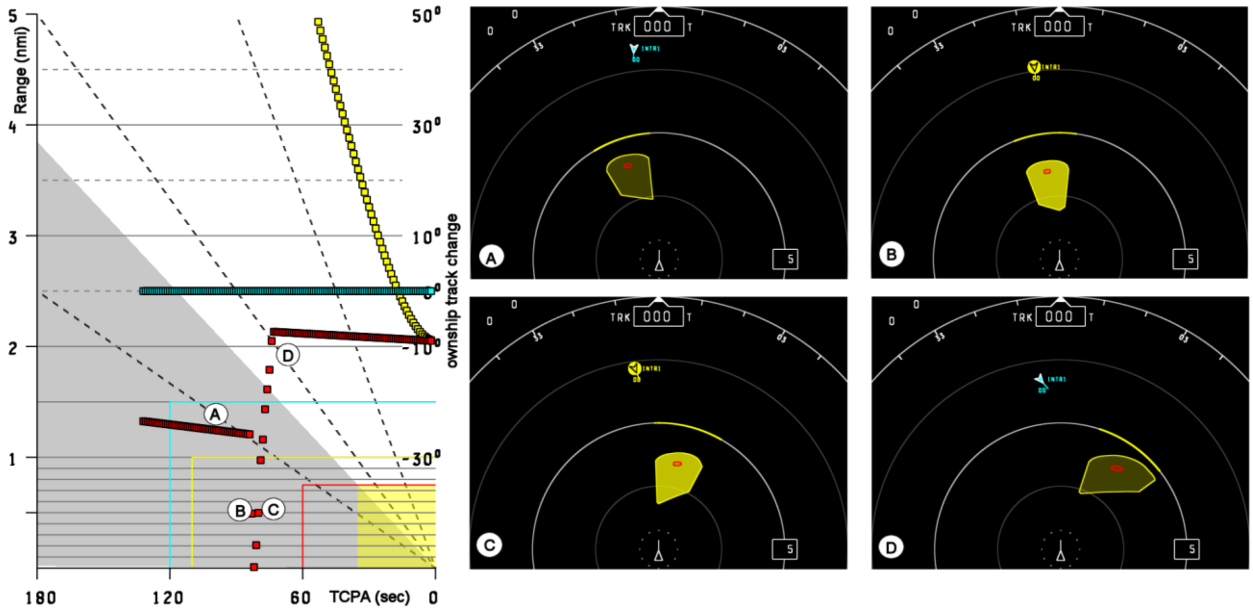

Figure 6: Intruder manoeuvres and temporarily triggers CSSA state.

Between a TCPA of 85 seconds and 75 seconds the remote pilot closely monitors how the location of the conflict space moves from one side of ownship trajectory (B) to the other side (C). In case the conflict space would have remained on ownship trajectory, this would have caused the remote pilot to manoeuvre. However, in this particular case no manoeuvre was necessary since the intruder continues to turn until (D) at which point the alert status has changed back to proximate (D).

4.2 Discussion

In the design, development and implementation of DAA systems that utilize a pilot-in-the-loop operational concept, it is critical to develop alerting schemes and guidance concepts that support the pilots in performing their intended role. This includes understanding how an encounter could progress through the alert levels and the desired reaction from the pilot in each of those transitions. The three encounters described above represent stressing situations due to the dynamic nature of the encounter and intruder manoeuvres. Important test points include:

1. Single transitions through caution-level and warning-level alerts due to range decreasing with a constant projected CPA that will require a manoeuvre to remain well clear
2. Double transitions through caution-level and warning-level alerts with initially decreasing CPA projections, followed by increasing CPA projections due to intruder manoeuvres that do not require a manoeuvre to remain well clear
3. Single transitions through caution-level and warning-level alerts due to a decreasing tau occurring within the alerting time limits, thus providing less time for conflict assessment needed to determine whether a manoeuvre is required to remain well clear

Furthermore, performance-based standards for alerting and guidance should contain test vectors, similar to DO-317B, that ensure interoperability between implementations.

5 SUMMARY AND CONCLUSION

- In 2009, in anticipation of future requirements for detect and avoid, GA-ASI started the development of the Conflict Prediction and Display System (CPDS).
- In 2014 an initial quantitative definition for Well-Clear was established. At present, Minimum Operational Performance Standards (MOPS) for Detect and Avoid (DAA) systems are being developed.
- To be able to adapt the conflict prediction algorithms and user-interface concepts as needed, CPDS was designed as a modular, configurable system.
- Since 2012, CPDS has been successfully used in a series of flight tests.
- Test points should include encounters that trigger transitions through alerts based on the criteria used to specify the alert.
- Simulation results show that the movement of the conflict space due to an intruder manoeuvre provides an important cue for determining how to remain well clear.

6 REFERENCES

1. International Civil Aviation Organization, Document 9854 AN/458 Global Air Traffic Management Operational Concept, 2005.
2. Cook, S., Brooks, D., Cole, R., Hackenburg, D., and Raska, V. (2015). "Defining Well Clear for Unmanned Aircraft Systems", AIAA-2015-0481, AIAA SciTech, Orlando, FL.
3. Parasuraman, R., Sheridan, T.B., and Wickens, C.D. 'A Model for Types and Levels of Human Interaction with Automation'. IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans 30/3 (2000):286–97.
4. Tadema, J., & Theunissen, E. (2008). A concept for UAV Operator Involvement in Airborne Conflict Detection and Resolution. Proceedings of the 27th Digital Avionics Systems Conference, pages 4C1.1-4C1.12, St. Paul, Minnesota. IEEE catalog number 978-1-4244-2208-1/08.
5. Theunissen, E. B. Suarez and K. Kirk (2012). Development, Integration and Testing of a Stand-Alone CDTI with Conflict Probing Support. Proceedings of the AIAA Infotech@Aerospace Conference.
6. Chase, K.H. and B.V. Tiblin (1971). INCAS Integrated Navigation and Collision Avoidance System, Journal of the Institute of Navigation, volume 18, No. 2.
7. Puckett, L. (1983). HICANS - Navigation for High Speed Ships. Journal of the Institute of Navigation, Vol. 30, No. 2, pp. 107-122.
8. Consiglio, M., J. Chamberlain, C. Munoz and K. Hoffler (2012). Concept of Integration for UAS Operations in the NAS. Proceedings of the 28th International Congress of the Aeronautical Sciences (ICAS).
9. Theunissen, E., B. Suarez and M. Uijt de Haag (2013). From Spatial Conflict Probes to Spatial/Temporal Conflict Probes: Why and How Proceedings of the 32nd Digital Avionics Systems Conference, Syracuse, NY.
10. Theunissen, E., B. Suarez and M. Uijt de Haag (2014). The Impact of a Quantitative Specification of a Well Clear Boundary on Pilot Displays for Self Separation. Proceedings of the ICNS, April 8-10, Washington, DC.

11. RTCA (2011). Minimum Operational Performance Standards (MOPS) for Aircraft Surveillance Applications (ASA) System, DO-317B.