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S.B.J. Van Dam

M. Mulder

M.M. (René) van Paassen

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Van Dam, S., Mulder, M., & van Paassen, M. (2009). Towards a Meaningful Presentation of FMS Trajectory Information for Tactical Self-Separation. *2009 International Symposium on Aviation Psychology*, 38-43. https://corescholar.libraries.wright.edu/isap_2009/108

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TOWARDS A MEANINGFUL PRESENTATION OF FMS TRAJECTORY INFORMATION FOR TACTICAL SELF-SEPARATION

S.B.J. Van Dam, M. Mulder, M. M. (René) van Paassen
Delft University of Technology, Faculty of Aerospace Engineering
Kluijverweg 1, 2629HS Delft, The Netherlands

In the context of future airspace management concepts, the flight crew will need tactical navigation support for airborne self-separation. Applying ecological interface design principles, a state-based navigation tool was designed that uses functional information overlays that show how traffic and aircraft performance constrain the horizontal maneuvering. The state-based system has been enhanced with a visualization of intent information from the flight plan trajectory (Van Dam, Paassen, & Mulder, 2007). This paper discusses in detail the exchange of intent information using ADS-B. It presents some promising ideas to show intent in a more meaningful and pilot-intuitive way, particularly focusing on the impact of mode transition from trajectory control mode (Flight Management System) to target state control mode.

Background

In order to give pilots effective support for airborne aircraft self-separation, an Airborne Separation Assistance System (ASAS) support tool was designed to give the flight crew insight into which maneuvers best deal with conflict situations (Van Dam, Mulder, & Paassen, 2008). The design is aimed at showing the reasoning of the automation that deals with the separation problem, and promoting pilot traffic awareness. Applying the Ecological Interface Design principles (Vicente & Rasmussen, 1992), functional information is presented via overlays that show pilots how horizontal maneuvering possibilities are constrained. Maneuver constraints originate from limits to the own aircraft performance (internal constraints), and limits imposed by the environment, i.e., the surrounding traffic (external constraints). The display is usable without the use of explicit maneuver commands. This approach promotes the preservation of travel freedom in a flexible airspace environment, and also facilitates full integration with other navigation support tools.

In the state-based display, the 'eXtended Airborne Trajectory Planner (XATP)(Appleton, Mulder, & Paassen, 2006), the 'State Vector Envelope' (SVE) overlay shows a speed-heading maneuver space that is mapped on the existing Navigation Display (ND), Figure 1. The orange color of the Forbidden Beam Zone (FBZ)-layer informs pilots that the aircraft will enter the Protected Zone (PZ) of an intruder aircraft within the next five minutes. If the FBZ is red, separation will be lost within 3 minutes. The SVE overlay shows the range of feasible aircraft maneuvers in terms of target heading-speed states, thus, separation is maintained by steering the own 'state vector' out of the FBZ. Cooperative conflict resolution is realized by steering out the FBZ in the direction of the closest FBZ boundary, while efficient resolution are realized by staying away from the FBZ origin. A detailed description of the domain analysis, display design and pilot maneuver strategy can be found in (Van Dam et al., 2008). A design for the vertical plane can be found (Heylen, Mulder, Van Dam, & Paassen, 2008). For a general overview and discussion of ecological interfaces applied to vehicle motion applications, consult (Paassen, Amelink, Borst, Van Dam, & Mulder, 2007).

The state-based XATP design predicts aircraft motion by extrapolating the current state (position, speed and heading) of the own aicraft and the surrounding traffic. In realistic traffic situations however, the aicraft trajectory is controlled according the flight plan managed by the Flight Management System (FMS). The state-based display concept was adapted to take into account planned trajectory changes within the prediction horizon of ASAS systems, leading to a preliminary intent-based display (Van Dam et al., 2007). The design assumes availability of the FMS flight plan and Mode Control Panel (MCP) - Flight Control Unit (FCU) target states through the use of Automatic Dependent Surveillance-Broadcast (ADS-B)(RTCA, 2002; Barhydt & Warren, 2002). This paper presents more profound research on how exactly ADS-B technology supports the exchange of intent information. It also analyzes the differences between the state-based display and the proposed preliminary intent display (Van Dam et al., 2007), in particular how these designs shape pilot traffic awareness and affect pilot maneuver strategies. Based on this analysis, FBZ maneuver constraint areas are categorized and a new FBZ color-symbology is detailed with the aim to improve pilot understanding of these areas, particularly when FMS trajectory control mode is disengaged when maneuvering with the MCP/FCU target state control. Finally a proposal for a new intent display is described.

Figure 1: State-based display (XATP)

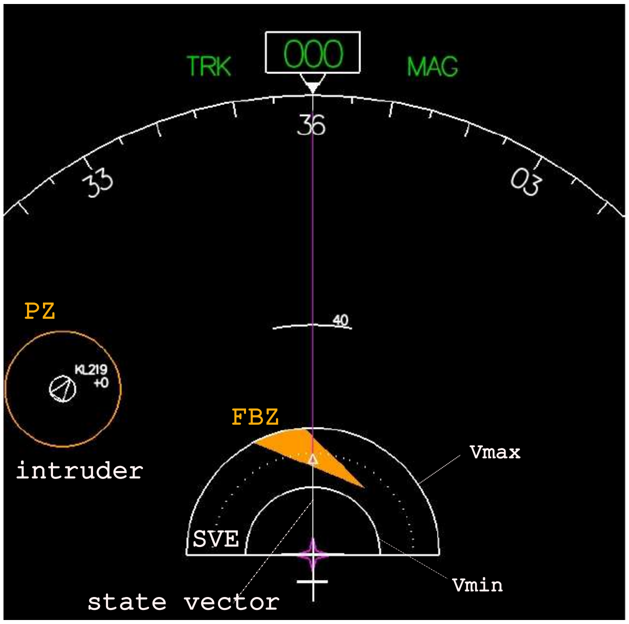
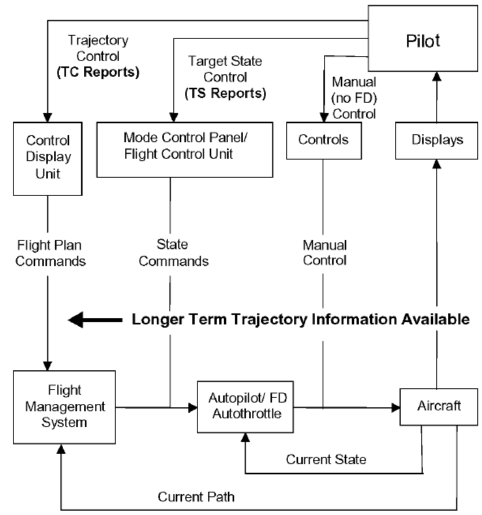


Figure 2: Aircraft control states (Barhydt and Warren, 2002)



ADS-B technology: Trajectory Change (TC) and Target State (TS) Reports

The ADS-B transponders are used to enable airborne data communication between aircraft in each other's vicinity. In addition to current state information the messages can also contain intent information. The transmitting aircraft must ofcourse support FCU-MCP modes to acquire target state commands and FMS-RNAV mode to get the flight plan information of the waypoints where trajectory changes are made. The requirements regarding the message contents are laid down in a RTCA report (Barhydt & Warren, 2002) and is used as a guideline. Without going into further detail it is assumed that the capacity and update rates of the system are sufficient to properly support an intent-based separation assistance tool. There are multiple types of data messages that are sent through ADS-B. Aircraft state reports include actual position and speed information that is used by the no-intent XATP system. For intent messages, two message types exist. First, the Trajectory Change report gives information on the aircraft's FMS flight plan. The Target State report provides information about the aircraft's target state commands, e.g., target heading entered by the pilot in order to make an autopilot controlled turn. Figure 2 presents an overview of aircraft control states (Barhydt & Warren, 2002).

The FMS system is a navigation aid database that contains intent information in the form of waypoints. The information of a waypoint is detailed in a so-called 'Trajectory Change Point'(TCP). Up to four TCPs are defined in one 'TC report'. TC report cycle numbers make it possible to distinguish between TCPs and they define the sequence order of the waypoints for reconstructing the flight trajectory. Figure 1 lists the elements provided in a TC report. Included are waypoint elements such as Time-To-Go (TTG), position, turn radius, track to TCP, track from TCP, and the command/planned flag for different TC types, e.g. a Fly-By turn or a Direct-to-Fix transition. TC reports can only be sent when the FMS is enabled and the aircraft is flying in accordance with the flight path depicted by the FMS. In case the pilot uses the the FCU-MCP to command a autopilot maneuver, the FMS is disabled. From then on all TC reports will have the flag type set on 'Planned' instead of the 'Command' indicating that the listed waypoints are not 'active'. With the FMS disabled, additional TS reports are sent out, containing the MCP target heading. The elements of a TS Report are also given in Table 1. This table is adapted from (Barhydt & Warren, 2002).

With respect to conflict situations in this research it is assumed that pilots fly in FMS mode while the are confronted with a separation problem. After analysis of the situation, the pilot manipulates the MCP to initiate the resolution maneuver. the FMS is automatically disconnected and TS reports representing the heading change will be available from that moment on, while TC reports are also available containing a "planned" typeset flag, informing the ASAS system about the 'FMS-disengaged' status . When the conflict is resolved and both aircraft have passed

Table 1: *Selection of Trajectory Change (TC) and Trajectory State (TS) Report elements*

	Element	TC Content	TS Content	Bits
ID	1	Participant Address	idem	24
	2	Address Qualifier	idem	
TOA	3	Time of Applicability	idem	6
TCR number	4	TCR sequence number	2	
TCR version	5	TCR cycle number	6	
TTG	6	Time To Go	idem	6
Horizontal information	7a	Horizontal data available and TC Type	Target Source Indicator	2
	7b	TC Latitude	Target Heading or Track Angle	16
	7c	TC Longitude	Target Heading or Track Indicator	16
	7d	Turn radius	Horizontal Mode Indicator 8	
	7e	Track to TCP	-	8
	7f	Track from TCP	-	8
	7g	Horizontal command/planned flag	-	1
Vertical information	8a	Vertical data available and TC Type	Target Source Indicator	2
	8b	TC Altitude	Target Altitude	12
	8c	TC Altitude Type	Target Altitude Type	2
	8d	Vertical Command/Planned Flag	Vertical Mode Indicator	1

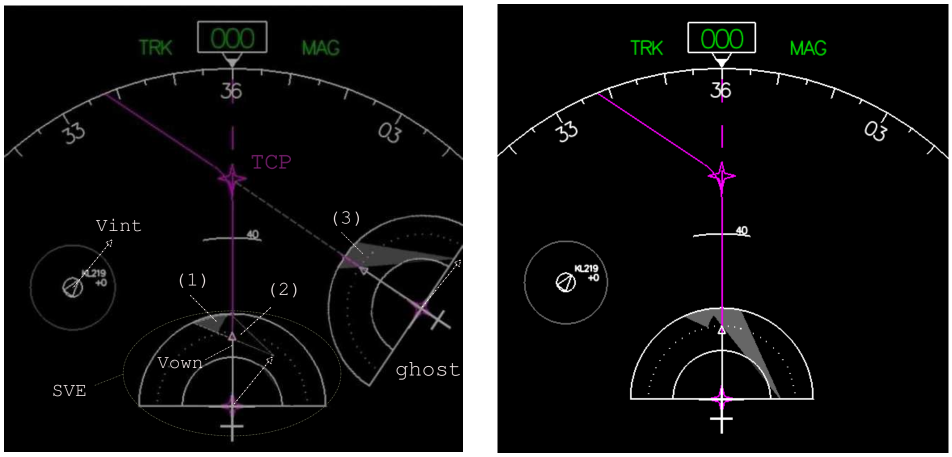
each other, the pilot will initiate the path recovery maneuver by flying a Direct-to to the closest TCP waypoint on the FMS flight path. The FMS is updated and activated again while the TS reports are suspended. At present, the design of the intent display will focus on the scenario where the pilot identifies a conflict situation along the flight plan and manipulates the MCP settings to resolve a conflict situation, hereby disengaging the FMS.

Comparing the state-based and intent-based display

Figure 1 and Figure 3 show an example conflict situation as presented on the ‘state-based display’ and the ‘intent-based display’ respectively. Based on the state-based display pilots assume separation is lost within three to five minutes if no maneuver is performed. With the intent display, the current state vector lies outside the FBZ’s. Therefore the FBZ is in grey color. No loss of separation will happen if both aircraft continue according the FMS flight plan. In this case, the intent display clearly enhances conflict awareness. Figure 3(a) shows how the intent display is the result of mapping two SVE’s on each other. The main SVE shows the constraint area indicated by (1) and visualizes maneuvers that would lose separation before the TCP is passed by. This time is labeled t_{TCP}. The other part of the FBZ indicated by (2) represents all states that would result in a loss of separation when the TCP is already passed by. Since the aircraft turns away at the TCP, this conflict is resolved and area (2) is therefore not shown on the intent display. The borderline between area (1) and (2) is part of a circle with the FBZ origin as it’s center and is referred to as ‘break-circle’ (Van Dam et al., 2007). The FBZ on the ghost SVE indicated by (3) is created using a ghost image for the own aircraft that shows the current fictive position and speed vector of the own aircraft as if it were flying already with constant speed and heading of the TCP.

When using the state-based display no information cues are available to determine wether the FMS turn will resolve the conflict situation or not. The intent display does show the pilot that there will not be a conflict situation when flying according the flight plan. On the other hand, pilots flying with the intent display are more likely to be unaware of how the conflict situation would look like when the FMS is disengaged. This lack of insight could lead to dangerous mode change situations where the FMS flight plan is suddenly abandoned by one of the aircraft. In the example situation, the SVE image will jump from the SVE in Figure 3(b) to the SVE in Figure 1.

On the intent display, Figure 3(b), the pilot can see that he is not able to turn to the right. This area does not exist on the state-based display as it is related to intended path after the TCP turn. Thus, this area is in fact conflict-free if one would maneuver before passing by the TCP. Pilots using the intent display are likely to (mis)interpret this area as a instantaneous no-go zone, i.e., they would not consider a maneuver to the right as a valid maneuver option to instantly resolve a problem.



(a) Constructing the intent display (b) First version of intent display

Figure 3: Intent-based XATP display for the example conflict situation with own intent.

Table 2: *Typification quadrant of FBZ maneuver constraint areas*

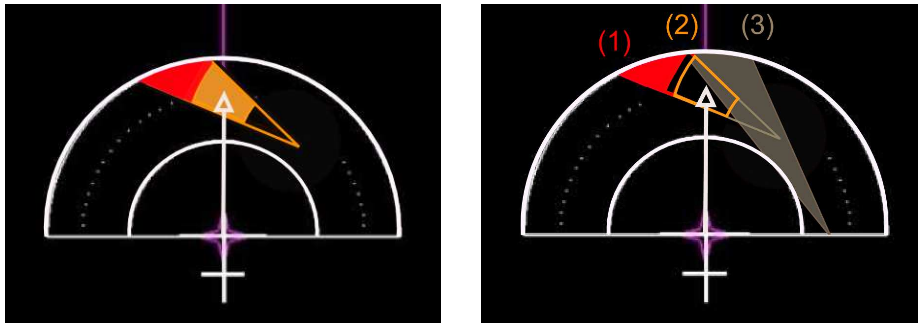
	Before first TCP	**After** first TCP
State-Based	(1) **'pre-SB'**: always conflict	(2) **'post-SB'**: FMS-disabled conflict
current	Yes	No
Intent-Based	(-) not applicable (ghost)	(3) **'post-IB'**: FMS-enabled conflict
current	-	Yes

Different types of FBZ maneuver constraint areas

It is clear that the introduction of FMS intent information result in different types of FBZ maneuver constraint areas. The current display formats create confusion, especially when disengaging the FMS. What does a particular FBZ-area shown inside the SVE actually means to the pilot? Is it possible to steer into this area right now? Will it disappear when the FMS is disabled? Will it's color change? Each display triggers different pilot behavior and conflict awareness.

In order to take away confusion about the interpretation of FBZ's areas, the different kinds of FBZ-areas are typified. Two parameters can be defined to make a distinction. A clear difference exist between areas generated from 'state-based' position and velocity information as opposed to areas generated from intent-based TCP position and velocity information (provided in the TC reports). The former is the most physical constraint where as the latter takes into account planned aircraft behavior from the FMS. A second parameter splits FBZ-areas in areas that result in a maneuver that looses separation 'before' (pre-TCP) and 'after' (post-TCP) the TCP is passed by. These two parameters make up a typification quadrant for FBZ maneuver constraint areas, Table 2.

First, 'State-based pre-TCP' areas (1) are areas created using the actual position, speed and heading to calculate the FBZ, AND showing that part of the FBZ that applies to maneuvers that lose separation before t_{TCP}. This FBZ constraint type is considered the most important constraint type. It is always visible on both state-based and intent-based displays. Second, the 'state-based post-TCP area type (2) is complementary with type (1) in the sense that it captures the state-based conflicts that occur after t_{TCP}. This area is currently not shown on the intent-display. In situations where the FMS is disengaged the display suddenly shows this area. In general, pilots unaware of the location of this type of constraints can not predict if a conflict would be triggered if one of the aircraft would ignore the next TCP and fly straight on. Third, 'Intent-based pre-TCP areas are fictive and not relevant. Fourth, 'Intent-based post-TCP' constraints (3) represent the FBZ-areas created by using intent-based information AND applied to maneuvers that lose separation after t_{TCP}. It is relevant to situations where both aircraft are FMS-enabled. It gives pilots a preview on how the FBZ areas look like from the point of view of the new state vector after the TCP turn (which is



(a) New FBZ color-coding for state-based display (b) New design of the intent display

Figure 4: The new color-coding for FBZ and the new version of the intent display

thus mapped on the current state vector in the SVE). If the current state vector lies inside a 'post-IB' FBZ-area (3), it means separation will be lost after the TCP maneuver is made. Without these constraints shown, pilots would be unable to predict if a conflict would appear after t_{TCP}.

The visualization of urgency

The idea to split up the FBZ shape into a 'pre-TCP' and 'post-TCP' is also usable to enhance, in fact, change the traditional color-coding of the FBZ's. Traditionally, the entire FBZ would be drawn red (or orange), reflecting the urgency of the conflict created by the current state vector. If the intruder's PZ would be intruded within three minutes the FBZ would be entirely red, if within five minutes, orange. If it would take more than five minutes, it would be shown in grey. If the state vector would not lie inside the FBZ, the FBZ would also be filled up in grey if a maneuver moving the state vector inside the region would trigger a conflict (with a predicted loss of separation within 5 minutes). Using the break-circle principle however, one single FBZ can be split up in time-intervals according the urgency color coding. For the example situation, this would results in a state-based display like Figure 4(a). The area representing maneuvers that lead to loss of separation further than 5 minutes away is not filled with any color, but lies by definition inside the FBZ shape. By applying this drawing convention, the grey zones are no longer used. 'Conflict zones' will always be orange or red, also when the current state vector lies outside the FBZ area.

A pilot-suited meaningful visualization of maneuver constraints

With the new insights regarding FBZ constraint area types and 'urgency' color coding, a new display design proposal can be made. The display is aimed at supporting the way pilots deal with a conflict problem when flying in FMS mode, interpreting the situation, and then go to MCP-mode to resolve the problem. The comments below are directly applicable to areas (1), (2) and (3) indicated on the display figures in Figure 3(a) and Figure 4(b).

First of all, *pilots need to be able to identify beyond any doubt if separation will be lost or not at all times.* This can be achieved by only filling areas with color or grey when a conflict exists. In both FMS-enabled and disabled mode, FBZ type (1) should be visible and given most importance. Therefore these constraint areas are brightly coloured in red and/or orange, Figure 4(a). If the FMS is engaged, FBZ type (2) areas do not apply and should not be filled. FBZ type (3) areas do apply to the current trajectory prediction and should be visible on the display. If the pilot switches to AP mode, the FMS is disengaged and FBZ type (2) should be brightly visible in the same way as FBZ type (1) constraints while FBZ type (3) should not be filled. Secondly pilots, when identifying a conflict situation in FMS mode, *should be aware which areas are instantly constraining the aircraft maneuver options* when disengaging the FMS, i.e., pilots should be aware that FBZ type (2) will appear and FBZ type (3) will disappear. Creating awareness about the type (3) constraint can be achieved by always showing intent-based constraints in grey. Grey areas are only shown when the FMS is enabled and inform pilot about intent-based (post-TCP) conflicts. Pilots will learn to take into account grey when predicting conflicts along the FMS trajectory, and will learn to ignore grey when they need to instantly come up with a conflict resolution maneuver. Informing pilots about the location of type (2) constraints, while in FMS-mode, creates awareness about the maneuver constraints when the FMS is disengaged. This awareness can be achieved by clearly depicting the FBZ contour. Type (2) areas are always the unfilled FBZ areas next to the colored type (1) area, see final design in Figure 4(b).

Concluding remarks

Based on FMS Trajectory Change Point information, the typical constraint representation of a conflict, the FBZ, is split up. This leads to a higher number of FBZ shapes on the display, Figure 3(b). Given the different nature of some of this areas, the original intent display proposal in (Van Dam et al., 2007) creates confusion, especially when disabling the FMS. A typification quadrant was set up to define the different types of FBZ-areas, Figure 2. Based on on the differences between each type, a more straightforward FBZ symbology is proposed so that pilots can clearly understand the meaning of each FBZ-area's shown on the display. It allows pilots to quickly perceive how their maneuver space is constraint when flying FMS enabled as well as FMS disabled, Figure 4(b).

The situation example in this paper has been chosen fairly simple in order to address a complex problem domain in an understandable way. The ideas expressed in this paper are however expandable to more complex situations, including multi-conflict scenario's, situations with intruder TCP point, situations with more than one TCP point. In the future, the interception of FMS trajectory after recovering from the conflict resolution maneuver will be treated. Even more display design can be enhanced by using target heading information of the Target State reports when switched to MCP target state commands (Van Dam et al., 2007). A pilot experiment will be set up were the display will be evaluated online using more complex multi-conflict situations.

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