Faculty of Aerospace Engineering

Ecological Altitude Display Design for Tactical Air Traffic Control

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Delft University of Technology

Challenge the future

Ecological Altitude Display Design for Tactical Air Traffic Control

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at Delft University of Technology

K. Capiot

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The undersigned hereby certify that they have read and recommend to the Faculty of Aerospace Engineering for acceptance a thesis entitled **"Ecological Altitude Display Design for Tactical Air Traffic Control"** by **K. Capiot** in partial fulfillment of the requirements for the degree of **Master of Science**.

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Part I

Paper

Ecological Altitude Display Design for Tactical Air Traffic Control

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Abstract—**The solution space for conflicts between aircraft consists of velocity, heading and altitude changes. In the current design of the air traffic controller workspace the instantaneous values for velocity, heading and altitude can all be found in the aircraft labels on the radar, however the heading and velocity can also be derived from the direction and speed of the aircraft on the radar display. Since the radar is a top view of the traffic situation, no means of deriving the altitude other than the aircraft labels can be found. Previous attempts to present the altitude domain in the radar display showed room for improvement. These display designs have been analysed and information gathered from them is used to create a new ecological user interface. The aim of this interface is to improve the support in conflict detection and resolution for air traffic controllers by representing the situation in the altitude domain. A preliminary feasibility test was performed from which it can be concluded that the altitude display has potential to improve safety in air traffic control and to reduce the complexity within the sector, but that some more attention should be put on making sure the aircraft leave the sector within the constraints linked to their exit waypoint. The subjective data from the questionnaire at the end of the feasibility test showed that the users felt that generally the display was easy to use.**

I. INTRODUCTION

The main responsibility of an air traffic controller is to make sure no loss of separation occurs. A loss of separation takes place when the distance between two aircraft is less than five nautical miles and 1,000 feet in the horizontal and vertical plane, respectively [1]. In order to avoid a loss of separation, aircraft can change their heading, speed and altitude. The heading and velocity of an aircraft can be derived from the direction and speed of the aircraft on the radar display, by means of the history dots, or directly from the aircraft label [2]. However, no way of deriving the altitude other than the aircraft label is currently present on the radar display. The air traffic controller thus has to combine the information from the aircraft labels in order to create a mental picture of the airspace in the vertical domain.

The aim of this research is to represent the vertical domain in a more intuitive way and link it to the information seen on the plan view display (PVD).

For the speed-heading domain, the solution space diagram (SSD), developed at Delft University of Technology, shows all possible speed-heading combinations that would not result in a conflict. However, the altitude domain is still not available in this display, the full solution space is not directly available to the air traffic controller.

From previous research [3–5] it can be found that there are two different design options available to integrate the altitude domain in the air traffic controller workspace. The first option is to integrate the altitude display into the plan view display, while the second option is to integrate the altitude domain on a separate display that is used side by side with the plan view display.

The altitude-extended solution space diagram [3] is an example of the first design option, where the altitude domain is integrated into the radar display. It is an extension on the solution space diagram, explained in Section II, where parts of the conflict zones are cut-off based on the climbing or descending performance of the aircraft. The actual information about this performance is lost, making the information shown unclear to the user. Some recommendations for this display included to make the altitude change command easier, since it took on average 15 user inputs to clear an aircraft towards its exit conditions. A suggestion for this included to use direct manipulation on an altitude tape. Another recommendation was to change the display in such a way that it supports for buffers, like maintaining a separation of 10 flight levels in order to cope with unexpected events. A suggestion is to incorporate the information about traffic 10 flight levels above or below the target flight level [3].

Another display that implemented the altitude domain in the radar display is the integrated and interactive solution space diagram (iSSD) [4]. The iSSD adds the altitude heading diagram to the altitude-extended SSD. This extension gives an overview of the blocked altitude-heading pairs. The main problem related to this display design is that the information takes much space to display, potentially blocking the information shown on the plan view display [4]. Also the information with respect to the climbing and descending performance of the aircraft gets lost in the representation.

An example of the separate display design option is the vertical situation display. The design in this display is a trajectory-based design rather than a state based-design. This also leads to the main disadvantage of this display: it relies on the fact that all aircraft have full 4D trajectory capabilities, which is currently not available [5].

In the new design presented in this paper, the SSD, presented on the PVD, will be the main interface for the air traffic controller, but with the addition of a separate display showing the vertical situation. The main challenges linked to this display design option are to ensure the coupling between the displays is done correctly and the display does not distract the users, but rather supports them.

The paper is structured as follows. The first section deals with the previous displays designs, followed by a work domain analysis of these displays in Section III. Then in Section IV the concept design is introduced, followed by an analysis of the anticipate work flow in Section V. The evaluation study is introduced in Section VI, with the results presented in Section VII.

II. Previous work

This section discusses the SSD display as well as previous efforts to integrate the altitude domain in it. The designs discussed here will be analysed further in Section III. The information of this section is also important for the newly designed interface, which will be discussed in Section IV.

A. Original Solution Space Diagram

The original solution space diagram was designed for the purpose of self separation [6, 7]. Figure 1 presents a traffic situation for which the solution space diagram will be explained.

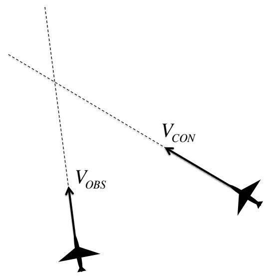


Fig. 1: Traffic situation

In the figure two aircraft can be seen: a controlled aircraft with a velocity of V_{con} and an observed aircraft with a velocity vector V_{obs}.

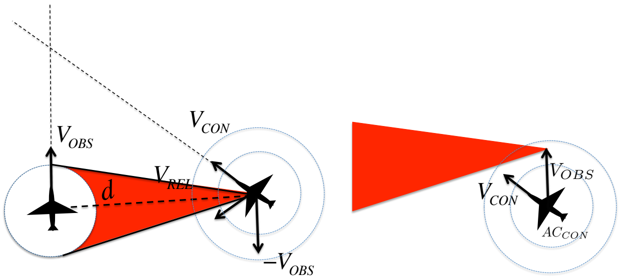


Fig. 2: Construction of solution space diagram

The left side of Figure 2 shows the projection of the protected zone of the observed aircraft on the controlled aircraft. If the relative velocity of the two aircraft would be inside this red cone, the aircraft would be in conflict.

In order to make the SSD, the velocities that are blocked should be given in function of the speed and heading of the controlled aircraft. This can be done by shifting the protected zone with the velocity of the observed aircraft, as can be seen on the right side of Figure 2.

Doing this for all the aircraft in the sector, results in the full SSD. The SSD is limited to the minimum and maximum indicated airspeed of the aircraft, thus cutting off the triangles at those values. These values can be seen in Figure 2 by the outer and inner circles around the controlled aircraft. The controlled aircraft will not be in any conflict as long as its velocity vector is not inside any of the triangles.

B. Altitude-extended Solution Space Diagram

The altitude-extended solution space diagram [3] was the first effort to implement the altitude dimension in the SSD. The forbidden zones on the SSD can be filtered based on the altitude. An observed aircraft that is flying at flight level (FL) 320 is not relevant for a controlled aircraft at FL 270. However, if the observed aircraft is cleared to descend to FL 260 this aircraft can become important, based on the reaction of the pilot. The two most extreme reactions would be a fast reaction, represented by no delay and a fast descent, and a slow reaction, which includes a delay up to one minutes followed by a slow descent. These kind of reactions can be seen in Figure 3.

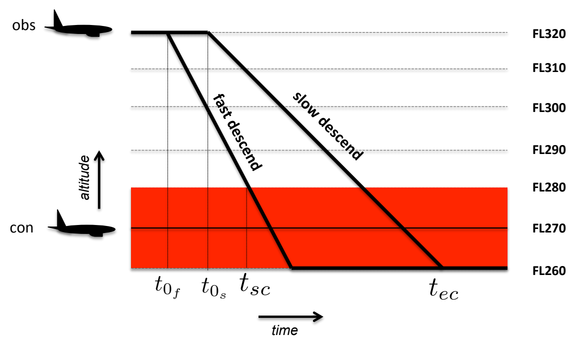


Fig. 3: Extreme conditions pilot response adapted from [3]

The earliest an aircraft will start descending, is represented by t_{0_f}, while the time with delay is given by t_{0_s}. The earliest the aircraft can be in conflict is when the fast descending aircraft enters the vertical protected zone of the controlled aircraft. This time is given by t_{sc} in Figure 3. The latest point of potential conflict takes place when the slow descending aircraft leaves the protected altitudes of the controlled aircraft, presented by t_{ec} in Figure 3. A conflict can thus only occur if the aircraft are in horizontal conflict between t_{sc} and t_{ec}.

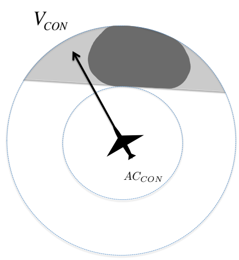


Fig. 4: Example altitude-extended SSD

The result is a triangle with cut-off edges. These edges can be cut-off because a conflict in this region would fall outside the climbing or descending profile of the aircraft. An example of this can be seen in Figure 4. The tip is cut-off because the aircraft would have already passed through the protected altitudes of the controlled aircraft, while the other part of the triangle gets cut-off because the controlled aircraft would already have passed the observed aircraft when it enters the protected altitudes.

An experiment with four participants was conducted. The participants either had experience in ATC, experience with the original SSD, or both. Four different scenarios were used during the experiment with two independent variables, the traffic (low and high) and the conflict zones (on and off).

The objective data collected from the experiment showed that the number of loss of separations were lower compared to the same traffic situation when the conflict zones were not available.

However, when the subjective data was analysed, the altitude-extended SSD did not show a better result in high traffic density scenarios. In low traffic density situations the participants indicated it was easy to find the aircraft that were involved in a conflict, however in high traffic situations this was harder when the altitude-extended SSD was available compared to any other scenario. This could be explained by the fact that the tasks of identifying a conflict and determining which aircraft are involved in a conflict were confused in high traffic scenarios [3].

C. Integrated and Interactive Solution Space Diagram

The integrated and interactive solution space diagram (iSSD) [4] integrates the altitude display on the standard SSD display [4]. It consists of two different parts, the speed-heading diagram (SHD) which is the same as the altitude-extended solution space diagram, and the altitude-heading diagram (AHD), which gives an overview of blocked altitude-heading pairs. In Figure 5 the subdivision between the displays is indicated by the brown circle ①. The current state of the selected aircraft on the AHD is indicated by the green dot ② in Figure 5. The red bands in the AHD ③ represent which headings would be blocked if the selected aircraft would descend to that altitude. The angle α thus represents the blocked headings if the aircraft would descend to the current selected altitude indicated by the black circle ⑤. This also can be seen in the SHD which represents the situation for a descent to the selected altitude. If however the selected altitude would be 20 flight levels higher than the black circle, the blocked headings would be represented by β. Finally ④ is a conflict zone on the SHD, which is the same as a conflict zone on the altitude-extended SSD.

Figure 6 shows the zoom function integrated on the iSSD when hovering over a certain altitude ring. In this figure the rings represent the different altitudes, while the SHD would be shown in the inner white area.

A human-in-the-loop experiment was conducted to test the workings of the display. For the experiment a mix of participants that have a lot of experience and almost no experience

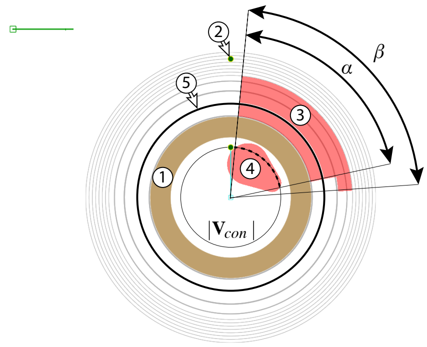


Fig. 5: iSSD example [4]

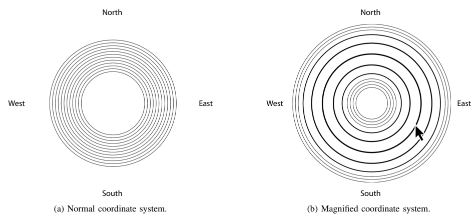


Fig. 6: Zoom function iSSD [4]

with air traffic control was used. The difference between both groups of participants could be seen in how they used the display.

Participants with less experience in air traffic control indicated to find the display useful, while the more experienced air traffic controllers did not really use the information on the display. The results also showed that the iSSD made the less experienced participants aware of relevant traffic when given a clearance and that the display reduced their workload.

Participants with more air traffic control experience resorted more to the information on the PVD, while indicating that the iSSD increased their workload.

One of the main problems with the iSSD is that it takes up space and thus sometimes obscures the information on the PVD. A suggestion to improve this is to make sure the information on the PVD is always visible on top of the iSSD with enough contrast.

D. Vertical Separation Display

The Vertical Separation Display (VSD), designed by Klomp et al. (2011) used a different design option compared to the other two displays that have been discussed. The VSD was developed as a seperate display that should be used side by side with the plan view display (PVD) [5].

The design of Klomp consisted of 3 display elements. The PVD, VSD and the Time-Space Diagram (TSD). The design is based on trajectories that can be manipulated. The TSD shows the along-track distance versus the planned time of arrival. It shows constraints on the speed, as well as conflicts that will occur with different speed settings. It also shows the traffic sequence and the wake-vortex separation.

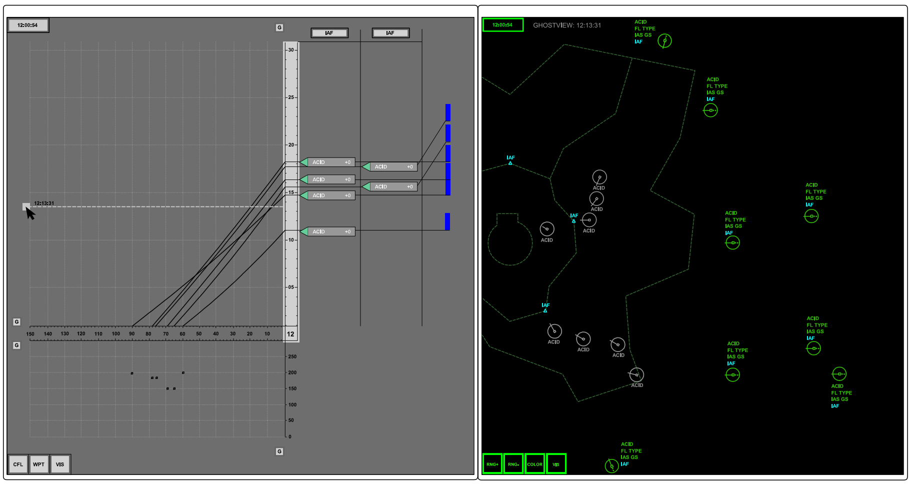


Fig. 7: VSD (lower part, left side separated by axis), TSD (upper part, left side separated by axis) and PVD (right side) when no aircraft is selected [5]

The VSD is based on 4D trajectory management rather than tactical air traffic control. Since the VSD uses 4D trajectories, the time domain is an important factor in the design. The VSD represents the altitude over the along track distance for an aircraft. Figure 7 shows the situation of the VSD when no aircraft has been selected. It can be seen that the aircraft are represented on their current altitudes. Figure 8 shows the situation when an aircraft has been selected. When the white line on the VSD passes through a conflict zone, represented by the red coloured boxes, the aircraft will be in a conflict at some point in time. A conflict can be solved by changing the velocity, trajectory or the altitude.

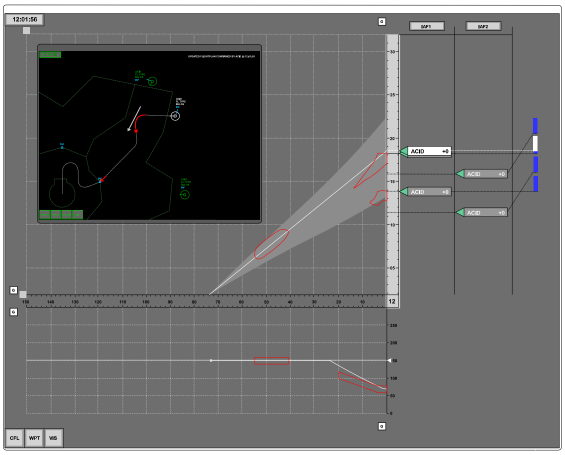


Fig. 8: VSD, TSD and PVD when an aircraft is selected [5]

One important tool that this display system has to offer is the ability to see the future position of aircraft by means of the ghost aircraft tool. An example of the usage of this tool can be seen in Figure 9. However this design feature is not as useful for the newly designed display due to the fact that the problem is state-based rather than a fixed 4D trajectory.

An experiment was conducted in order to validate the workings of the display. From this experiment some promising results could be seen. No loss of separation occurred during the experiment and a positive trend towards a better situation awareness for the air traffic controllers was noticed, however this trend was not significant. Further the feedback of the participants of the experience was the strongest point of this display design. In general the feedback indicated a positive experience with the display design.

The main disadvantage of the VSD is that it relies on a mature state of four-dimensional operations. In this scenario it is expected that all aircraft have full 4D capabilities, which is not yet the case in current state of air traffic.

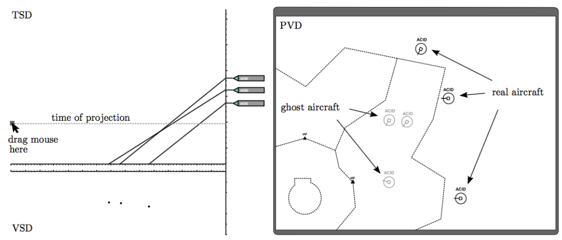


Fig. 9: Ghost aircraft function [5]

III. Work Domain Analysis Previous Designs

In this section a work domain analysis of the previous designs will be done in order to find what aspects of the work these displays do support the most.

The primary tool for a work domain analysis is the abstraction hierarchy. The abstraction hierarchy consists of five levels containing information about the work domain that is being modelled. These layers are: functional purpose, abstract function, generalized function, physical function and physical form. The link between the different levels represent the means-ends relationships. [9].

Figure 10 shows the abstraction hierarchy for the ATC work domain. It shows the three top layers and indicates where the different previous designs focus on. This analysis is supported by an study of the different display designs.

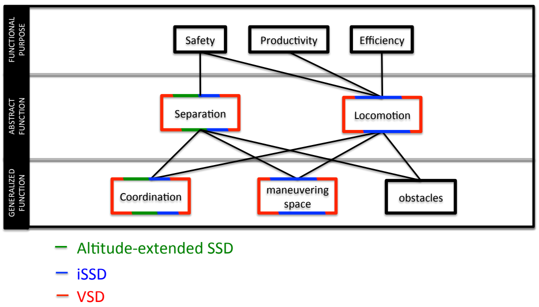


Fig. 10: Abstraction hierarchy ATC work domain

Figure 11 shows the part-whole decomposition of the ATC work domain. The colours used to represent the support from the different display systems is the same as the one used in Figure 10.

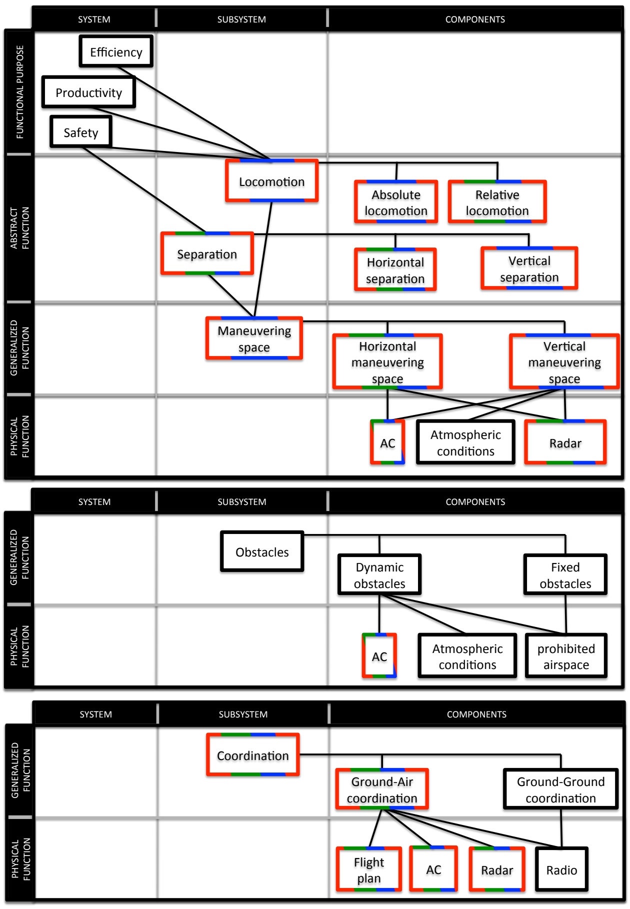


Fig. 11: Part-whole decomposition ATC work domain

1) Altitude-extended SSD: The altitude-extended solution space diagram focuses on the aspect of separation and coordination. The separation is supported mainly in the horizontal domain, where the speed-heading pairs that would lead to a conflict are made visible in the SSD. Some support also exists for the altitude domain by means of the filtering, but the overview is limited since the user has to check these altitudes in order to see the changes to the SSD.

The coordination is also a focus points of the altitude-extended SSD, although for the experiment no radio communication was supported. The coordination in the experiment consisted mainly of ground-air coordination that is simulated by committing commands after which the aircraft executes them.

From this design the climbing and descending profile of an aircraft is one of the most important aspects to implement in the new design, but the presentation of the data should show these expected performance limitations.

2) Integrated and interactive SSD: Since the iSSD is an extension on the altitude-extended SSD, the features that were present in the altitude-extended SSD are also present in the iSSD. The separation in the horizontal domain is the same as in the altitude-extended SSD, since it is presented in exactly the same way. The visualization of the vertical separation is improved, by the addition of the AHD, since this directly gives the overview of the situation on other altitudes.

In the iSSD an effort to improve the understanding of the locomotion of the aircraft can be seen. The absolute locomotion is given by means of the line indicating the current path the aircraft is following when it is selected. An improved understanding of the relative locomotion can be found in the addition of the AHD and by showing the states of other aircraft in the display.

The coordination on the iSSD is also represented similarly to the situation for the altitude-extended SSD. The controller can change the states of the aircraft on the screen and then commit them by pressing enter. No voice communication is present during the experiment.

With the iSSD the user gains an overview of the vertical situation in the sector. This results in a better understanding of the maneuvering space for the aircraft.

In this design it can be seen that the altitude-heading combination can result in a cluttering of the display, for a new design it might thus be useful to look for a different state to combine with the altitude. Extending the original SSD with an additional display element is however a good idea as it makes sure that the data seen on the SSD is more clear to the user.

3) Vertical Separation Display: The vertical separation display focuses on the separation by introducing the conflict zones in both the VSD and TSD. These indicate how far ahead a conflict would take place and gives an overview of the solution space in order to solve this problem.

The locomotion is given by the path of the aircraft on the PVD. Also the ghost aircraft helps the user with the locomotion of the aircraft. This tool can be used to have an overview of the absolute and relative locomotion.

In this display set-up the coordination is represented by the manipulation of the 4D trajectories. The user can change the altitude, even with the option to give an intermediate altitude change, change the speed of the aircraft as well as change the trajectory of the aircraft.

The maneuvering space is supported by the conflict areas on the display as well as the usage of the ghost aircraft tool. These together give the user a good overview of both the horizontal and vertical maneuvering space.

The ghost aircraft function turned out to be a useful integration for this 4D trajectory based problem. Some way of making a future conflict visible on the PVD should be implemented. Further is the visualization of the climb or descent in the display very important for the new design.

IV. Proposed Concept

This section will introduce a newly designed user interface that aims at improving the conflict detection and resolution for air traffic controllers. The design consists of the original SSD display, combined with a newly designed altitude display.

Since both displays will be used side by side, one of the most important aspects of the design is the coupling between them, as will be discussed later in this section.

First the design of the new altitude display will be presented, then the linking between both displays will be explained in detail and finally an overview of the calculations for the constraints is given.

A. Display Design

For the design of the display, two different states had to be considered: the state with no aircraft selected and the state where a certain aircraft has been selected.

The design of the display focuses on area control, where aircraft are climbing, descending and flying through a sector. These aircraft should exit the sector at a predefined waypoint, making the distance to the sector border a valid representation for the horizontal axis. The vertical axis represents the different flight levels, in steps of ten. a representation of this axis system can be found in Figure 12.

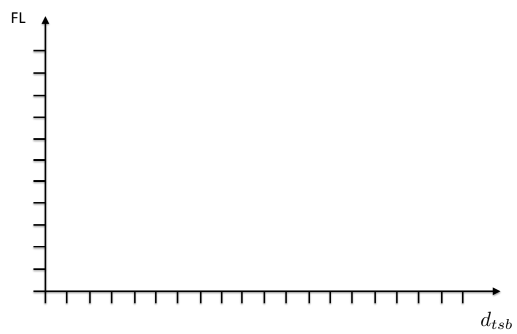


Fig. 12: axis system altitude display

But now, why is the design option of the separate display chosen over the integrated altitude domain representation? The reason can be found in some of the display design principles [8].

First the principle of pictorial realism [8] states that the representation of a variable in a display should match the mental model linked to this variable. Since the objective is to present the user the information of the vertical domain, it is important that the concept of altitude is kept. A higher altitude should be presented higher on the display, while a lower altitude should be shown lower on the display. If the altitude is chosen as one of the axis in the display system, only one axis is available for the representation of the two-dimensional horizontal locomotion. The representation of the distance to sector border matches the principle of pictorial realism, since a smaller distance between the aircraft and the sector border is represented by a smaller distance between the aircraft and the origin of the x-axis.

The principle of the moving part [8] states that the movements on the display should match those in the real world system. In the current axis system this does support the altitude domain, however the two-dimensional movement in the horizontal plane is not represented according to the matching movement in the real-world system.

The principle of minimizing the information access cost [8] is supported by this display system, since the user knows the information of the vertical domain can be found on the second display, one does not need to search for this information.

The proximity compatibility principle [8] deals with the fact that if more than one piece of information must be obtained to conduct a task the sources for this information should be in close proximity to each other. The sources of information however should not be so close to each other that they overlap and the information is obstructed. When putting the information on a separate display, but keeping this display in close proximity to the plan view display, the proximity compatibility principle is respected, because no overlap of the information sources will occur.

The principle of consistency [8] can be found in the coupling between the two displays. The colours in both displays are used to represent the same information.

Since the design option of a separate display has been chosen, it is important that the coupling between the displays is not lost. When a user has to switch between displays, there is a mental reset time, it takes time for a user to understand the context of a new scene [10]. A high level of visual momentum will support the user when switching between displays. The methods used to ensure a high level of visual momentum in the display system will be discussed later in this section.

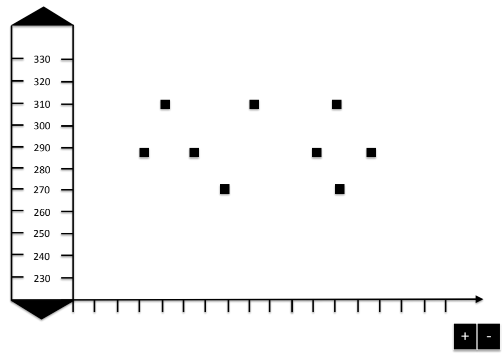


Fig. 13: Altitude display overview state

Figure 13 shows the state of the display when no aircraft has been selected. This display state give the user a general overview of the aircraft with their altitude and distance to sector border. The main disadvantage of this representation is that all sense of direction of the aircraft is lost. On the display all aircraft are moving in a single direction (to the left), while in reality the aircraft are flying in different directions to different sector border.

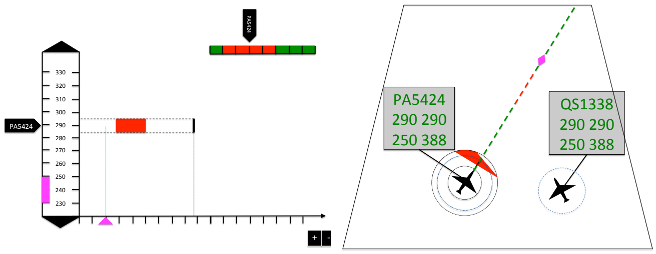


Fig. 14: Solution space diagram and altitude display with conflict

Figure 14 presents a schematic overview of the situation where two aircraft are in conflict. When an aircraft is selected, the current direction the aircraft is indicated by a line coloured in green and red. The red parts indicate where a conflict would take place on the current altitude, velocity and heading. The red segments are equivalent to the red conflict zones shown on the altitude display on the current altitude of the selected aircraft.

Another feature that is added to this line representing the current direction, is an indication of the point where an aircraft should have started its descent in order to reach the altitude limitations linked to its exit waypoint. This indication is shown in Figure 14 by the magenta diamond on the PVD. This constraint is also visualized in the altitude display with the magenta triangle on the distance to sector border axis. Further is the altitude constraint of the exit waypoint visualized on the flight level axis by the magenta bar.

On the altitude display a velocity tape was added. This velocity tape indicates the ranges of the indicated airspeed that result in a conflict on the current altitude with a red colour, while safe airspeeds are indicated in green.

Two options to change the view of the altitude display have been implemented, on the one side the view of the flight level axis can be changed by clicking on the triangles at both ends of the fight level axis. The other option to change the view is by zooming in or out on the distance to sector border axis using the '+' and '-' buttons presented next to this axis.

On the altitude display, the speed and altitude both can be changed by means of dragging their respective labels. When dragging the velocity label into a green area on the velocity strip and committing this change, the aircraft will accelerate or decelerate, and no longer be in conflict. When dragging the altitude label, a preview of the climbing or descending performance of the aircraft can be seen. an example of this can be seen in Figure 15. When these preview lines do not cross any blocked areas, the aircraft will not be in any conflict during the descent or climb.

Finally the overlay button in the upper left corner of the display is used to activate an overlay that shows the altitudes that would be blocked. These blocked altitudes are based on

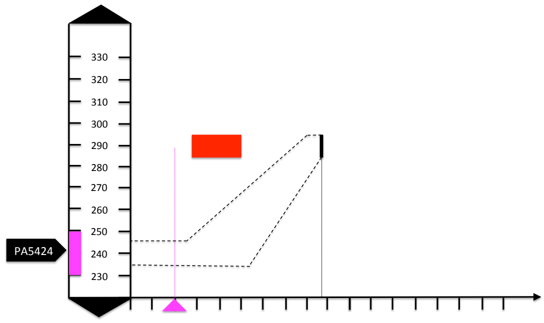


Fig. 15: Altitude display altitude label dragged

the flight direction of the aircraft and the air traffic regulations that are given for that direction. An example of this overlay can be seen in Figure 16.

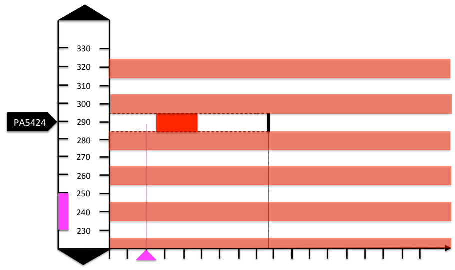


Fig. 16: Altitude display example with blocked altitudes active

When the overlay is activate another button pops up. If this button is activate the user can only drag the altitude labels onto the altitudes that are not blocked.

Figure 17 shows the display state in different traffic situations.

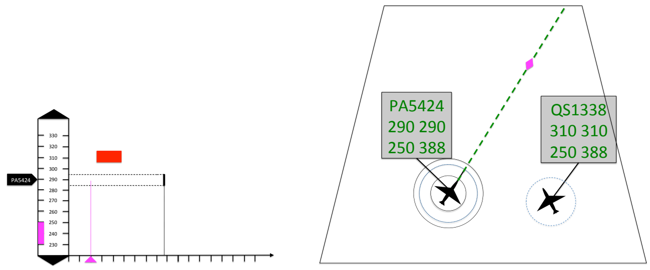
Figure 17a shows the state of both the SSD and the altitude display when an aircraft is selected that would be in conflict with an other aircraft if they would be flying on the same altitude. In this case the conflict zone will be displayed on the altitude of the observed aircraft, FL 310 here.

Figure 17b shows the situation where the observed aircraft is at a higher altitude than the controlled aircraft and has been given an altitude change command to descend to an altitude below that of the controlled aircraft. In this case the full altitude range from the current altitude to the target altitude is blocked on the altitude display. This is done for safety purposes due to the uncertainties linked to the descending and climbing of aircraft.

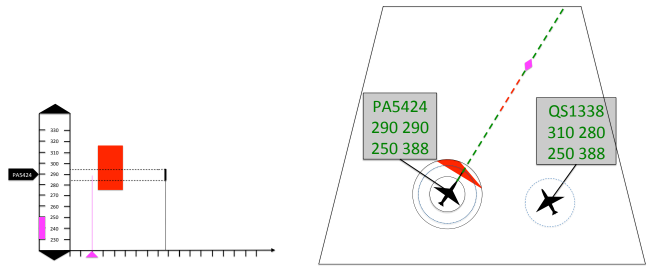
Figure 17c shows the situation where the observed aircraft is overtaking the controlled aircraft. In this case the relative velocity between both aircraft is low, thus resulting in a long conflict time. This can also be seen by the conflict zone, which will be larger compared to the situation in Figure 17a.

B. *Display Coupling*

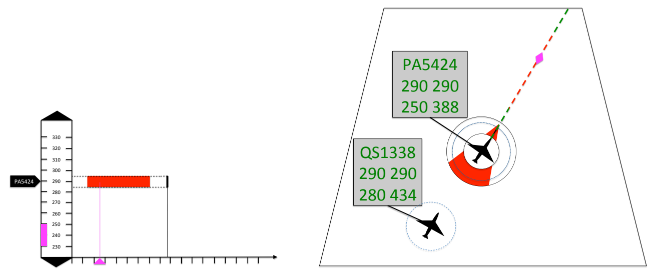
In a design with multiple displays it is of most importance that the user does not get lost, then one has a clear view on the relationship between the different display elements, knows the



(a) Situation: two aircraft on different altitude with conflict zone on higher altitude



(b) Situation: aircraft from higher altitude descending to lower altitude



(c) Situation: aircraft overtaking selected aircraft

Fig. 17: Display state for different situations

current location within the system and knows where to look next [10].

Important to ensuring that users do not get get lost, is to support them in the analysis of the global properties. Users are guided by visual cues such as colour, shape and location. In this display system colours are used across the display elements to represent the same kind of information. When an aircraft is on its course towards its waypoint, both the aircraft on the PVD and the square on the overview of the altitude display will turn green. Other examples of this can be seen in the fact that on both displays a magenta colour is used for information that is related to commands (i.e., the preview lines for an altitude change on the altitude display, the preview line for a speed or heading change on the SSD) and the red colour on both displays that represent a blocked area where a conflict will take place (i.e., the conflict areas on the altitude display and the blocked speed-heading pairs on the SSD).

Perceptual landmarks [10] are used to give the user a point of reference to link the different elements of a display system together, and thus increase the visual momentum in the system. Examples of this can be found in the integration of the conflict zone in the line representing the current direction of the aircraft on the PVD. These conflict zones can be seen on both the PVD and the altitude display. Another example is the integration of the magenta triangle and diamond on the altitude display and PVD, respectively. They represent the same information on both displays and thus give a relative frame of reference in the displays.

Display overlap [10] is used to integrate information across displays. When hovering over a constraint, the aircraft causing this constraint is highlighted on the PVD. Similarly, when no aircraft has been selected, hovering over an aircraft blip on the altitude display highlights the corresponding aircraft on the PVD.

Also the coupling between the two different states of the altitude display is important for the design. The most important consideration in this perspective is that the layout of the display does not change when an aircraft is selected. Since the axis system does not change, the position of the aircraft that is selected does not change on the display.

Finally within the PVD another coupling can be found. If a controller clicks on a waypoint, all aircraft that have this waypoint as exit condition will be highlighted, giving an overview of the global state of the display.

C. *Conflict Zones Calculations*

The conflict zones are calculated in the time domain, later converted into the distance domain and thus the distance from the sector border. Currently this does not take into account the difference in true airspeed on different flight levels. It uses the true airspeed of the aircraft on the current flight level rather than the flight level of the observed aircraft.

To convert the time to loss of separation to the distance domain for the controlled aircraft, the time should be multiplied by the velocity of the controlled aircraft:

$$d_{LoS} = t_{LoS} \cdot V_{con} \tag{1}$$

The distance to the sector border when the loss of separation occurs can be computed:

$$d_{tsb_{conf}} = d_{tsb_{con}} - d_{LoS} \tag{2}$$

The variables used are defined in Figure 18, where the subscripted s represents the start of the loss of separation and the subscripted e represents the end of the conflict.

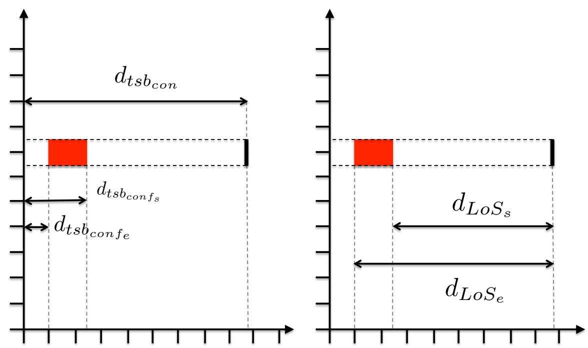


Fig. 18: variables used in calculations

The time to closest point of approach can be computed:

$$t_{CPA} = \frac{-d \cdot (V_1 - V_2)}{|V_1 - V_2|^2} \tag{3}$$

When the time to closest point of approach is calculated, it can be converted to the distance at this point in time:

$$d_{CPA}\left(P(t), Q(t)\right) = |P(t_{CPA} - Q(t_{CPA})| \tag{4}$$

If the d_{CPA} is smaller than five nautical miles, a loss of separation will occur at some point in time. The start and end time for this loss of separation can be found by solving the equations above for a distance of five nautical miles.

The program of the display solves this equation using a numerical integration.

V. Anticipated Work Flow

In this section the way the display is intended to help the user in controlling traffic will be discussed. The analysis consists of a work domain analysis, with the help of the abstraction hierarchy and the part-whole decomposition, and a control task analysis with the help of the decision ladder.

A. Work domain Analysis

Looking back at the abstraction hierarchy from Section III, It can be seen that the focus areas of the altitude display are similar to those of the previous designs. The horizontal separation is shown on the SSD, while the altitude display shows the vertical separation.

The absolute locomotion is represented by both the current path of the selected aircraft and the climb/descend envelope, while the relative locomotion is given by the conflict zones on both the SSD and altitude display.

When looking at the maneuvering space in more detail, it can be seen that the horizontal and vertical maneuvering space are both present in the display. The horizontal maneuvering space can be derived from the speed-heading pairs that do not result in a conflict, while the vertical maneuvering space is presented by the conflict areas on the altitude display. The climb/descend envelope further helps to understand the vertical maneuvering space of the aircraft.

The coordination is again limited to the ground-air coordination, since no radio communication is present in the experiment. The only communication between different air traffic controllers that is present in the display are the rules of the airspace, as given by the constraints on the different exit waypoints.

B. Control Task Analysis

The control task analysis gives an overview of the support of the display using the decision ladder as a tool, shown in Figure 19. The support provided by the altitude display combined with the SSD will be discussed below:

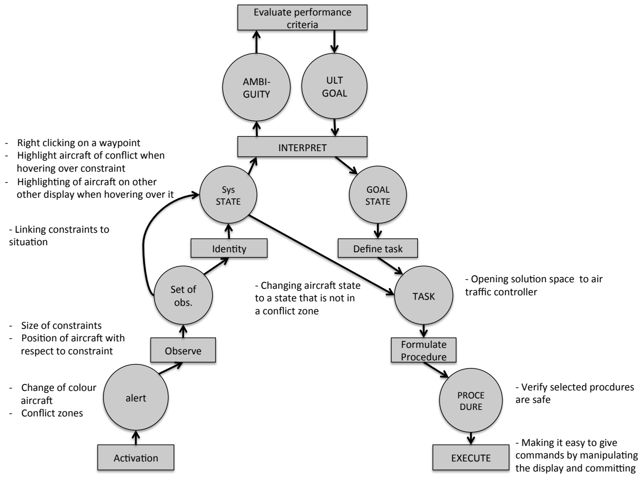


Fig. 19: Decision ladder altitude display

1) Support for 'alert': The air traffic controller can be alerted of a future conflict in a number of different ways. The most obvious alert is the moment an aircraft turns into a orange colour, or even a red color. This indicates that a conflict will take place within the next 120 or 60 seconds, respectively. When an aircraft will get into a conflict within the next 60 seconds, the controller does not only get alerted by the change in colour, but also an alert sound will be triggered.
Other support for 'alert' can be seen in the altitude display and the SSD by means of the constraints when an aircraft has been selected. If the current state of the aircraft is in a conflict zone, a loss of separation will occur somewhere in the future.
2) Support for 'observe': The observe state is supported by the constraints. A large constraint (see Figure 17c) on the altitude display indicates a conflict that will take place over a long period of time. When the selected aircraft symbol is closer to a conflict zone, this indicates a conflict in the near future.
3) Support from 'observe' to 'system': The displays make sure that a direct link can be made from the observe state to the system state. It ensures that the information seen in the form of constraints gives an overview of the current state of the aircraft.
4) Support for 'system': The altitude display and SSD try to give support to the system state with the means-ends links. Some examples of this include right-clicking on a waypoint which highlights all the aircraft that have to travel to that waypoint, highlighting of the aircraft in conflict when hovering over the constraint, etc.
Further the linking between the two displays is given clearly by highlighting the corresponding aircraft when it is highlighted in one display.
5) Support from 'system' to 'task': This is supported by redirecting a single aircraft in such a way that the combination of states is outside the conflict regions. On the SSD this is done by making sure the speed-heading combination is not within a conflict area. In the altitude display, by changing the altitude in such a way that the conflict regions are not crossing the aircraft's vertical performance.

6) Support for 'task': The task is defined as rerouting aircraft. The displays support in this by opening the full solution space to the air traffic controller.
7) Support for the 'procedure': The display supports the user to verify whether the procedures that have been selected are safe and do not result in conflicts.
8) Support for the 'execution': The display helps here by making it easy to give a command manipulating the state directly on the display and committing this afterwards.

VI. Evaluation Study

A small-scale human-in-the-loop study has been conducted in order to evaluate how this display is used in realistic traffic scenarios.

The experiment was conducted with help of scenarios used in a different experiment [11]. One reason for this is that these scenarios are a realistic representation of the air traffic within an ACC sector. Another reason is that in the experiment, where these scenarios were used, the traffic was controlled using the current state-of-the-art tools. By using the same sector and scenarios this would present the opportunity to compare the data gathered from both experiments.

For further reference in this paper, the experiment conducted with the state-of-the-art tools will be called EX0, while the experiment with the altitude display will be named EX1.

A. Experiment Setup

The experiment was conducted with the use of two monitors. A big screen monitor on which the SSD was presented and a second smaller screen with the altitude display as can be seen in Figure 20.

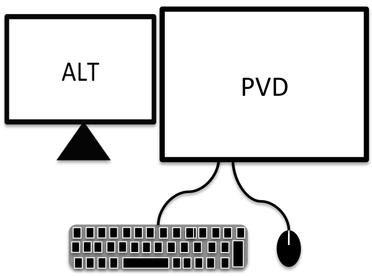


Fig. 20: Experimental setup

The input devices for this set-up included a computer mouse and a keyboard. The only key that was of actual use on the keyboard, however was the "ENTER" key, which was used to commit state changes. The sector that was used during the experiment can be found in Figure 21.

During the experiment data was collected from two different sources: objective data from the actions performed on the display and subjective data from a questionnaire at the end of the experiment.

The data gathered from the actions on the screen consisted of:

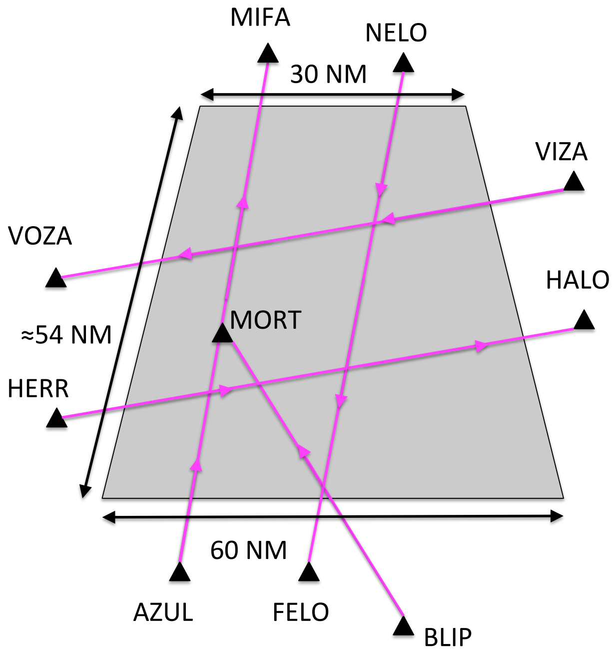


Fig. 21: Sector used in evaluation study

- mouse inputs
- keyboard inputs
- aircraft positions at any point in time
- subjective workload indication

These data are then used to derive more relevant data for the analysis, i.e., whether aircraft reached their exit waypoint within its constraints, whether conflicts occurred, the amount of aircraft inspections and the amount of commands. These are derived because they give an insight in the controller workload, traffic safety and display usage.

Some data cannot fully be compared between both experiments since there are some fundamental differences between them. During EX0, the controllers were required to give a transfer of control which can lead to a slight increase in workload. However, the controller was able to control the aircraft fully when outside the sector, which can reduce the workload of the controller, since only the altitude and speed could be controlled outside the sector during this experiment.

B. Participants and Instructions

The participants all completed an extensive course on air traffic control and were familiar with the previous versions of the SSD. The participants also took part in EX0.

They were instructed to safely guide aircraft to their respective exit waypoints at a certain altitude or altitude range. Traffic could be guided towards the exit waypoint by means of speed, heading and altitude changes. Also a separation of five nautical miles in the horizontal plane, or 1,000 feet in the vertical plane should be kept at all times.

The instructions on the exit altitudes were:

- Traffic from AZUL and BLIP towards MIFA should leave the sector between FL70 and FL 100.

- Traffic from NELO to FELO should leave the sector at FL210.
- Traffic towards VOZA should leave the sector at the same flight level as they entered the sector, thus FL140.

C. Scenarios

The experiment consisted of nine training scenarios of about three minutes each, followed by four measurement scenarios of 20 minutes each.

The training scenarios were designed in such a way to gradually increase the participants understanding of the display.

Training scenario 1 was designed to give the participant a general feeling for the display commands. The scenario consisted of a single aircraft that should be guided to the right exit point.

In training scenario 2 a crossing aircraft that has to be guided towards a different waypoint was introduced. This helped the participant in getting used to the constraints on the altitude display, as well as on the SSD.

Training scenario 3 introduced two aircraft going towards the same waypoint. This scenario helped in getting familiar to the merging procedure.

Training scenario 4 introduced more realistic traffic with different types of aircraft with different exit waypoints.

In training scenario 5 the traffic volume has been increased to get the participant a better feeling for the display in a high traffic situation.

Finally training scenarios 6 to 9 are some final training scenarios to get used to the display with realistic scenarios.

The measurement scenarios used in this experiment are identical to the ones used by Somers (2017). Below in Table I an overview of the measurement scenario characteristics can be found.

Scenario 1 was designed with a high traffic density with a mix of the different aircraft types: heavy (H), medium (M) and light (L). A large amount of aircraft are coming from the streams from BLIP and AZUL merging towards their exit waypoint MIFA. Also aircraft that are overtaking each other are implemented into this scenario.

In Scenario 2 the low traffic density consisted of one aircraft type. Also the amount of aircraft coming from the merging streams was limited making this part of the task quite a bit easier. No overtaking or deviating aircraft were introduced in this scenario.

The parameters of Scenario 3 are similar to those of Scenario 1, but the traffic flows were structured differently.

Scenario 4 is a low traffic density scenario with a mix of all aircraft types. In this scenario a surprise element was added with respect to the other scenarios by means of an aircraft which is not part of any of the traffic streams.

TABLE I: Measurement scenario characteristics (adapted from [11])

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Traffic Level	High	Low	High	Low
Traffic Mix	L/M/H	M	L/M/H	L/M/H
Merges	lots	few	lots	few
Overtakes	yes	no	yes	no
Deviating a/c	no	no	no	yes

D. Simulator Settings

All aircraft behave in the same way. A random delay between no delay and one minute has been given to an altitude command to simulate a slow or fast response to the given command. The delay can easily be changed to a lower value in future experiments. Also a random value between the minimum and maximum value was chosen, in order to simulate that different pilots chose a different climb rate.

The maximum delay of one minute is on the high side and might need to be adjusted for future experiments. For this initial experiment however it does help in a clear visualization of the delay for the climbing or descending performance.

Changing the velocity on the altitude display can be done in steps of one knots, while the velocity on the SSD can only be changed in steps of ten knots. This design choice was made because the representation of the blocked velocities on the velocity strip does show possible solutions in between two consecutive velocities within ten units from each other. If this same design choice would be used on the SSD this would make it a lot harder to control the velocity on this display.

Some differences with the simulator setting in EX0 could be seen: The aircraft in this experiment cannot be controlled outside the sector with the SSD, but can with the altitude display. The biggest difference between both experiments is of course the way the commands are given. Where in EX0 the commands were given with the command display, here the commands were given by direct manipulation.

In the simulation some simplifications were made with respect to the real world:

- No wind
- Change in climb/descend performance every 100 flight levels
- No radio communication
- No prohibited areas

These simplifications decrease the workload for the air traffic controller. In order to increase the complexity of the experiment, the simulator is run at double speed rather than real-time.

VII. Results

In this section the results from the evaluation will be discussed. First the outcomes of the analysis of the data obtained during the simulation will be presented and later the subjective data gathered from the questionnaire.

A. Data Results

The data that are gathered for each scenario consists of the amount of aircraft that have reached their exit waypoint, which of these have reached the waypoint within the constraints that are given to it, how many aircraft have been in the sector over the full duration of the scenario, which of these aircraft are still in the sector and which of the aircraft are outside the sector but have not yet reached their exit waypoint. Also the number of conflicts, the number of aircraft inspection (both the total and those on the altitude display), the different commands that have been given and on which display they were given. Also the number of left clicks on the altitude display which are used to manipulate data on the display and the right clicks on the altitude display that are used to deselect the aircraft are analysed.

The goal is that every aircraft that leaves the sector also reaches its intended waypoint, within the constraints given for that waypoint.

1) Scenario 1: Table II shows the data gathered in Scenario one. The values represented between brackets indicate the data from EX0.

TABLE II: Data scenario one

	P1	P2	P3
reached waypoint	20 (21)	21 (21)	20 (21)
reached constraint	18 (21)	21 (21)	20 (21)
total in sector	28 (28)	28 (28)	28 (28)
still in sector	8 (6)	5 (6)	8 (6)
outside sector to waypoint	0 (1)	2 (1)	0 (1)
conflicts	0 (1)	1 (2)	0 (0)
total inspections	135 (186)	168 (133)	65 (162)
AD inspections	0	0	0
altitude commands	44 (44)	25 (26)	27 (32)
altitude label dragged	53	27	29
speed commands AD	9	0	3
speed commands SSD	0	4	0
total speed commands	9 (7)	4 (6)	3 (3)
track commands	21 (56)	8 (29)	18 (34)
combined commands	2	4	2
AD left clicks	63	29	36
AD right clicks	0	1	0
workload	86 (71)	46 (73)	56 (71)

The most important difference that can be seen between both experiments is that during EX1 less conflicts took place.

During the experiment there were no AD (altitude display) inspection. This shows that the selection of aircraft took place on the PVD rather than the altitude display. After the selection on the PVD the user could manipulate the data on the altitude display, as can be seen from the commands given on the altitude display.

Figure 22 gives an overview of the situation in the sector. The figure on the right represents the raw data of the aircraft that reached their waypoint, those that reached the waypoint within the altitude constraints and those that are still on their way to the waypoint, but are outside the sector already. The figure on the left visualizes this data in a different perspective, it shows the total amount of aircraft that have been inside the sector and shows how this is composed in terms of the other values.

Figure 23 shows the same data, but instead for EX0. What can be seen here is that for Participant one the percentage of aircraft that did reach the waypoint within its altitude constraints is higher compared to the direct manipulation display.

Figure 24 shows the distribution of the aircraft towards MIFA over their respective altitudes when reaching the waypoint. The data shows that during EX1, aircraft were spread out over the different altitudes within the constraints, while during EX0 the aircraft were all concentrated on FL 70. When a column does not reach the norm, this indicates that an aircraft

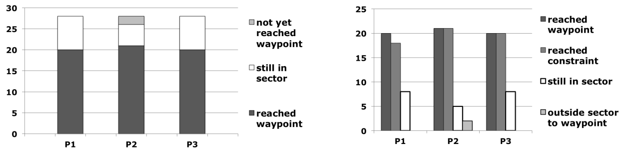


Fig. 22: Simulation results waypoint EX1

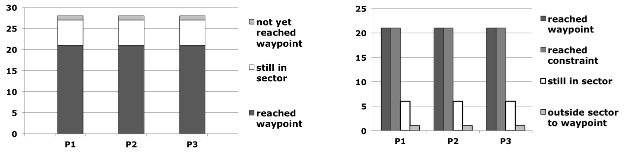


Fig. 23: Simulation results waypoint EX0

did not reach the waypoint within the altitude constraints. An example of this can be seen for Participant one in EX1.

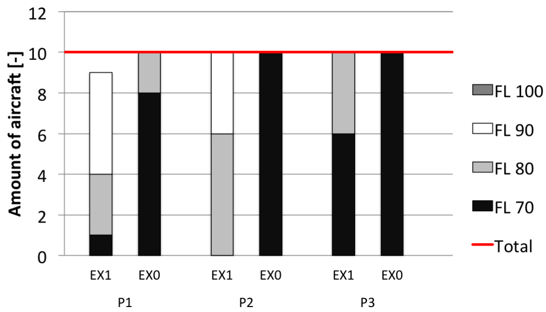


Fig. 24: Aircraft to MIFA altitude distribution

Figure 25 gives a graphical overview of the distribution of the different commands. The column on the left always represents data from EX1 and the right column represents the data from EX0. For Scenario one it can be seen that the amount of command in EX0 seems to be larger than in EX1. The main difference is the amount of track commands.

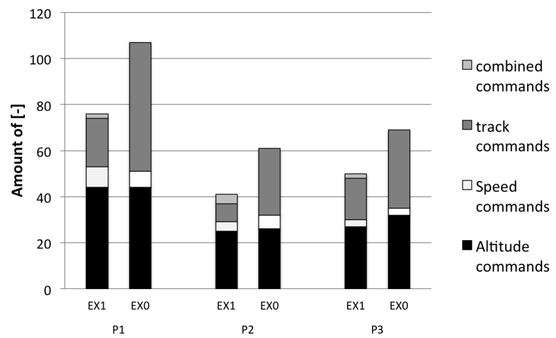


Fig. 25: Command distribution Scenario one

Also the complexity of the sector at every moment in time is analysed. The complexity of the solution space for a given aircraft can be found using the SSD: a more filled SSD gives a higher complexity to solve a conflict.

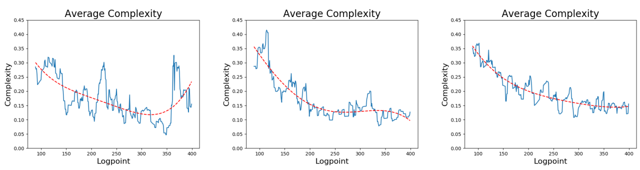
Figure 26 shows the complexity for the experiment with the altitude display available, while Figure 27 shows the data for

EX0. The red line in the figure is a polynomial fit of the fourth order used to represent the general trend of the data.

The complexity metric used to analyse this experiment is based on the occupied area of the SSD [12]. The larger the area that is unsafe to reroute an aircraft in, the more complex the scenario is at that moment. A higher complexity is correlated with a higher workload for the user [13]. The parameters for the complexity metric in this experiment have been chosen as an observation angle of 180 degrees and a cut-off time of 600 seconds.

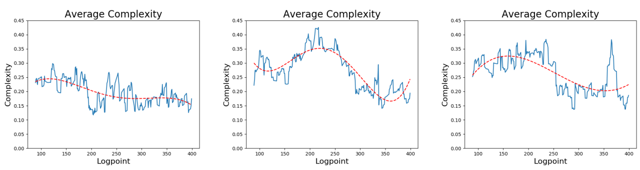
Comparing the two situations, it can be seen that the complexity for Scenario one is generally lower in EX1. The trend of the complexity is similar for Participants two and three, starting at a high complexity and progressing to a lower complexity over time. For Participant one, the complexity first goes down but ends with a higher complexity. This higher complexity at the end can be explained by the fact that Participant one had to divert two aircraft in order to avoid a conflict.

This difference between Participant one and the other Participants can also be seen with their indicated workload in Table II. Participant one indicated a higher workload compared to the other participants.



(a) P1 (b) P2 (c) P3

Fig. 26: Experiment with altitude display



(a) P1 (b) P2 (c) P3

Fig. 27: Experiment with state-of-the-art tools

In Figure 28, the curved lines inside the circled area indicate the diverted aircraft's trajectories at the end of the simulation. This manoeuvre was done in order to make sure that the left aircraft reaches the waypoint without getting into conflict with the right aircraft.

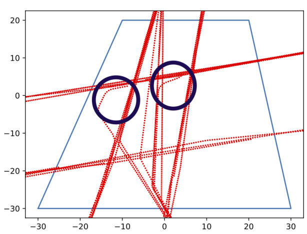


Fig. 28: Scenario one Participant one

TABLE III: Data Scenario two

	P1	P2	P3
reached waypoint	17 (18)	17 (18)	16 (18)
reached constraint	17 (18)	17 (18)	16 (18)
total in sector	22 (22)	22 (22)	22 (22)
still in sector	4 (4)	4 (4)	5 (4)
outside sector to waypoint	1 (0)	1 (0)	1 (0)
conflicts	0 (1)	0 (0)	0 (0)
total inspections	85 (115)	148 (106)	50 (105)
AD inspections	0	25	2
altitude commands	32 (36)	19 (24)	22 (21)
altitude label dragged	34	19	22
speed commands AD	2	0	1
speed commands SSD	0	2	0
total speed commands	2 (1)	2 (3)	1 (1)
track commands	13 (56)	12 (24)	12 (25)
combined commands	0	1	0
AD left clicks	37	69	29
AD right clicks	0	29	1
Workload	30 (20)	25 (13)	40 (33)

2) Scenario 2: Table III shows the collected data from Scenario two. What can be seen here is that the workload here is lower compared to Scenario one

The amount of SSD inspections is higher for Participant two compared to EX0, but lower for both other participants.

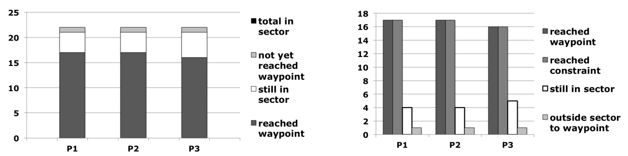


Fig. 29: Simulation results waypoint EX1

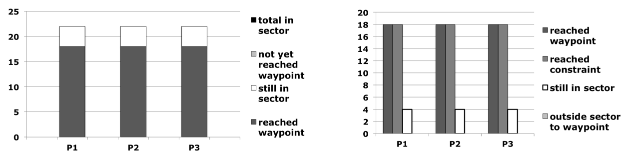


Fig. 30: Simulation results waypoint EX0

Figure 29 visualizes the data concerning the aircraft inside the sector during EX1. Figure 30 shows the same results for EX0. What can be seen is that the aircraft that are still in the sector and that have not yet reached their waypoint is higher in EX1.

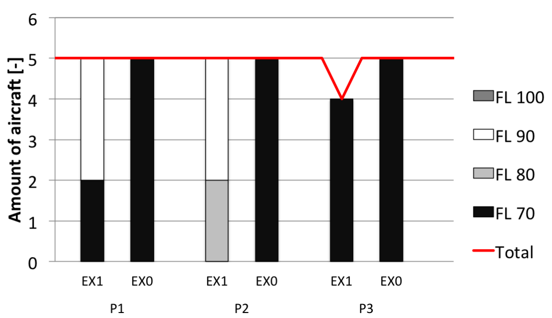


Fig. 31: Aircraft to MIFA altitude distribution

Figure 31 shows the distribution over the different altitudes for the aircraft that have reached MIFA. What can be seen again is that in EX0 all aircraft are controlled to FL70, while in EX1 the aircraft are most of the time controlled to two different altitudes within the constraints.

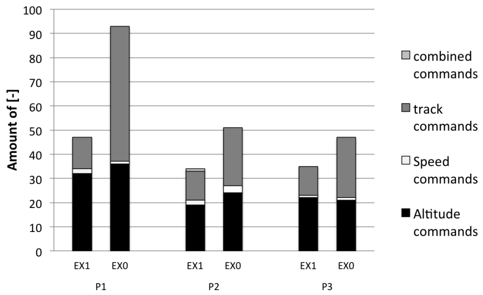
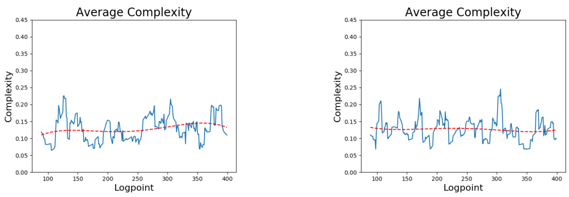


Fig. 32: Commands distribution Scenario two

Figure 32 shows the distribution of the commands over Scenario two. It can be seen that with the new display design, the amount of commands given are generally lower compared to EX0. Again the largest difference can be found in the amount of heading commands.



(a) Direct manipulation

(b) State-of-the-art

Fig. 33: Average complexity Scenario two

Figure 33 shows the average complexity during the experiments for Scenario two. Since most complexity figures are similar in this scenario, only the data for Participant one are shown. Comparing this to the complexity in Scenario one it can be seen that the general trend is that the complexity is lower. This can also be seen in the workload ratings given by the participants. The difference in workload ratings between EX0 and EX1 cannot be seen in the complexity figures, since these are similar in both experiments.

3) Scenario 3: Table IV shows the data gathered from Scenario three.

In general the amount of SSD inspections is lower in EX1. This does however not generally result in a lower workload. Participant two is the only participant that indicated a lower workload compared to EX0. Participant two is also the only participant with more SSD inspections during EX1.

Figure 34 shows the amount of aircraft that are leaving the sector. Figure 35 shows the same data for EX0. What can be seen again is that the aircraft that reach the waypoint also reach this within the constraints more consistently during EX0.

Figure 36 shows the end altitudes of the aircraft going to MIFA. Again it is shown that in EX0 more aircraft tend to be on FL 70 when reaching MIFA, while the aircraft in EX1 tend to be more spread out over the different flight levels.

Figure 37 shows the distribution of the different commands given during both experiments. Again it can be seen that the

TABLE IV: Data Scenario three

	P1	P2	P3
reached waypoint	21 (21)	21 (20)	20 (20)
reached constraint	21 (21)	21 (20)	19 (20)
total in sector	29 (29)	29 (29)	29 (29)
still in sector	7 (7)	7 (7)	7 (7)
outside sector to waypoint	1 (1)	1 (2)	2 (2)
conflicts	0 (0)	0 (0)	0 (0)
total inspections	132 (165)	149 (143)	74 (174)
AD inspections	0	6	0
altitude commands	55 (51)	28 (28)	35 (35)
altitude label dragged	57	29	35
speed commands AD	18	0	11
speed commands SSD	1	20	0
total speed commands	19 (12)	20 (9)	11 (9)
track commands	16 (51)	6 (39)	17 (32)
combined commands	1	7	2
AD left clicks	78	34	48
AD right clicks	0	4	0
Workload	60 (53)	36 (46)	66 (59)

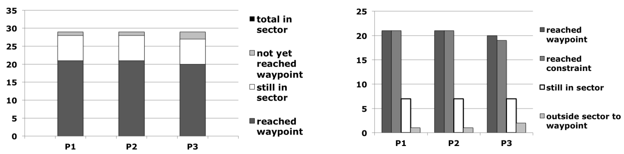


Fig. 34: Simulation results waypoint EX1

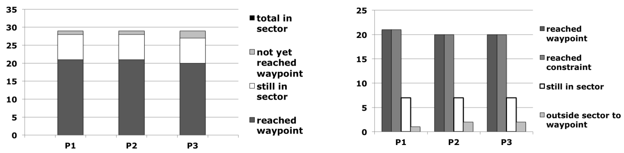


Fig. 35: Simulation results waypoint EX0

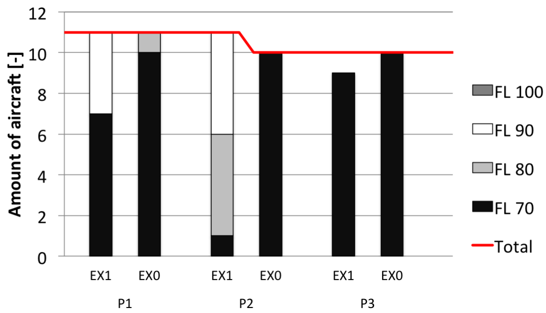


Fig. 36: Aircraft to MIFA altitude distribution

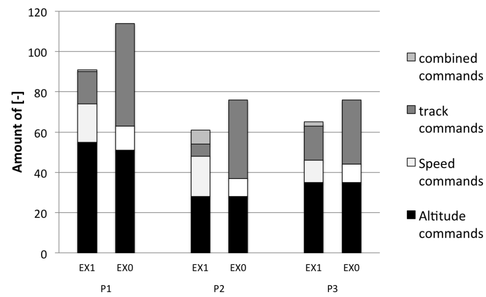
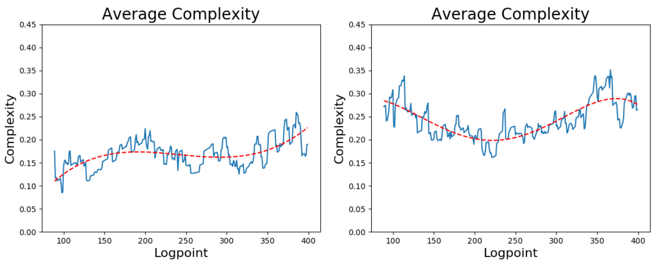


Fig. 37: Command distribution Scenario three

total amount of commands during EX0 is higher compared to EX1. The biggest difference can again be seen in the amount of heading commands.



(a) Direct manipulation (b) State-of-the-art

Fig. 38: Average complexity Scenario three

Figure 38 shows the most interesting result from the complexity analysis for Scenario three. It shows the complexity measured for Participant two. It can be seen that the complexity trend is lower in EX1. This is also supported by the fact that Participant two indicated a lower workload in this case.

4) Scenario four: Table V shows the data gathered from Scenario four.

TABLE V: Data Scenario four

	P1	P2	P3
reached waypoint	16 (16)	16 (16)	16 (16)
reached constraint	16 (16)	14 (16)	16 (16)
total in sector	22 (23)	22 (22)	22 (23)
still in sector	6 (6)	6 (6)	6 (6)
outside sector to waypoint	0 (1)	0 (0)	0 (1)
conflicts	0 (2)	1 (1)	0 (0)
total inspections	96 (101)	108 (90)	57 (128)
AD inspections	0	7	0
altitude commands	34 (29)	22 (19)	21 (24)
altitude label dragged	37	23	21
speed commands AD	7	3	4
speed commands SSD	0	3	0
total speed commands	7 (6)	6 (7)	4 (3)
track commands	21 (47)	8 (21)	9 (19)
combined commands	1	4	4
AD left clicks	46	34	27
AD right clicks	0	9	0
Workload	22 (17)	25 (30)	40 (57)

In this scenario it can be seen that the amount of SSD inspections are closer to each other for both experiments, except for Participant three, who in general always had less inspections during EX1.

Also the amount of conflicts was lower for participant one. During EX0, this scenario resulted in two conflicts for participant one, where for EX1 no conflicts were detected. Participant two had one conflict in both experiments.

Figures 39 and 40 show the results for the aircraft that reached the waypoints for the different experiments. It can be seen that the results for the aircraft that reach the waypoint within the constraints is again more consistent during EX0.

In Figure 41 it can be seen that also in Scenario four the participants chose to distribute the aircraft over multiple flight levels during E1. In E2 again all aircraft reached MIFA at FL 70.

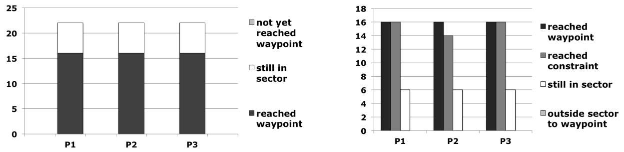


Fig. 39: Simulation results waypoint EX1

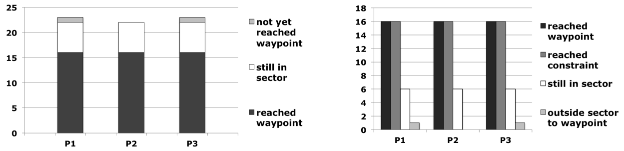


Fig. 40: Simulation results waypoint EX0

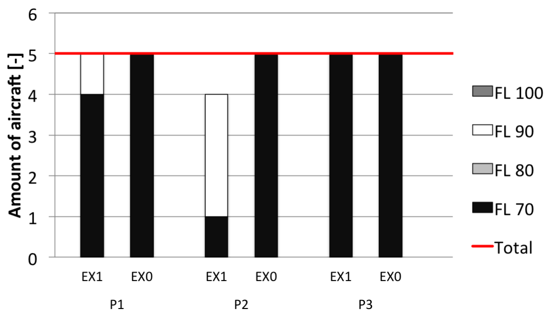


Fig. 41: Aircraft to MIFA altitude distribution

Figure 42 show the distribution of the commands during both experiments. It can be seen that the results are consistent with the other scenarios. The total commands in EX0 is higher than when the altitude display is available.

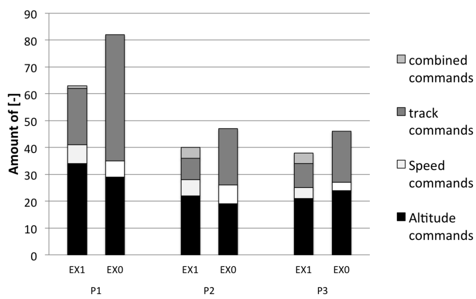


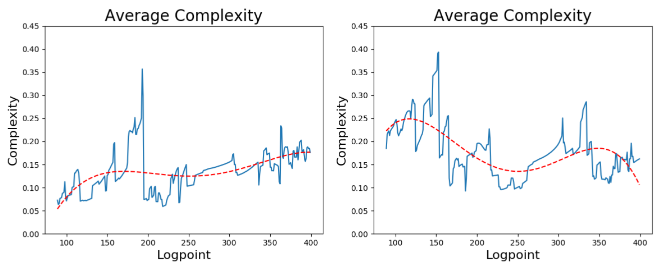
Fig. 42: Command distribution Scenario four

The most interesting graphs for complexity can again be seen for Participant two. The complexity seems lower in the case where the altitude display is available. This is only accompanied by a small decrease in workload.

B. Questionnaire Results

An important question to ask the participants of the experiment is whether or not they understand the information shown on the display. The response on this question was positive, ranging from fully understand to mostly understand, as seen Figure 44.

Question 2 asked the participants whether they found the representation of the altitude display intuitive or not. Most



(a) Direct manipulation (b) State-of-the-art

Fig. 43: Average complexity Scenario four

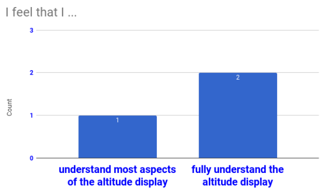


Fig. 44: Responses to Question one

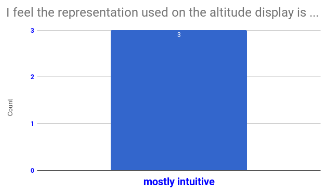


Fig. 45: Responses to Question two

aspects of the display were intuitive according to the participants. From feedback it could be seen that the along track distance axis made the participant lose track of the direction of the aircraft, however the participant thus required the PVD in order to gain the full understanding of the airspace.

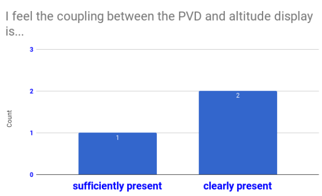


Fig. 46: Responses to Question three

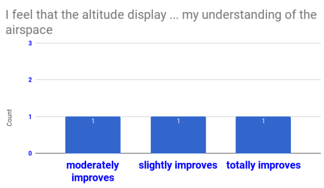


Fig. 47: Responses to Question four

When looking into the coupling between the PVD and the altitude display, it can be seen that all participants thought there was sufficient to clear coupling present. From the remarks it showed that participants liked the blocked altitudes and that hovering over them indicated to which aircraft this blocked altitude belonged.

In question four, where the participants were asked to give their feedback on how the altitude display affected their understanding of the airspace, the responses were slightly different between participants as can be seen in Figure 47. All responses indicated a positive contribution to the understanding of the airspace, but how much it improved was different for each participant. The remarks on this included that the intended constraints on the waypoint really helped a lot, since this meant that these should not be memorized, but that this might also be dangerous when the controller has no access to the altitude display. Further the representation when no aircraft was selected, gives no useful information. The preview of the climb/descend performance helped in the judgement of the participants.

When analysing the response to question five, it can be clearly seen that the main display is still the PVD, as most of the time the participants' attention goes to this display, but the altitude display was used to give the aircraft its altitude change commands, as well as a way to double check if everything goes according to plan.

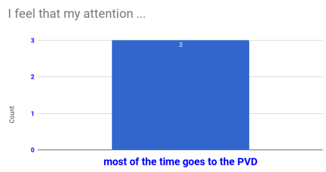


Fig. 48: Responses to Question five

Fig. 49: Responses to Question six

Participants reported the altitude display did not distract them. One participant felt the altitude display did distract sometimes. Another participant felt that the altitude display did sometimes distract during the training phase, but he later learned to use the altitude display in a different way. Since the participants indicated that the overview display did not give them any useful information, this can be the source of confusion for the participant.

The altitude display was for a large part used to proactively search and solve conflicts, however one participant indicated an equal reactive usage of the display. One of the participants also included a remark that he felt more proactive compared to a situation without the altitude display support. This proactiveness could be caused by the fact that the altitude display gives the user a better overview of the traffic situation, thus making it easier to proactively search for and solve conflicts.

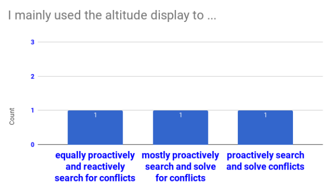


Fig. 50: Responses to Question seven

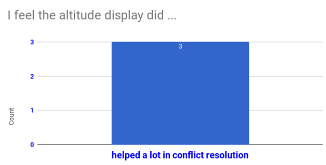


Fig. 51: Responses to Question eight

In conflict resolution, all participants felt that the display helped them a lot. One participant explained that the altitude display helped him to separate the aircraft in altitude without having to worry about the triangles on the SSD, since it can be seen that no conflict would arise.

The magenta triangle on the distance to sector border axis indicating the moment a descent should be taking place already to make sure the altitude constraint on the waypoint are met, did not in every case seem to be useful. For two participants it sometimes helped them to meet the altitude constraint, but the other participant indicated they were not really using this feature because they were giving the altitude commands as early as possible.

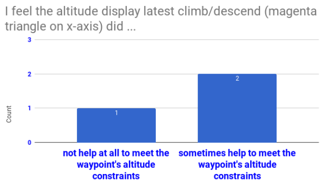


Fig. 52: Responses to Question nine

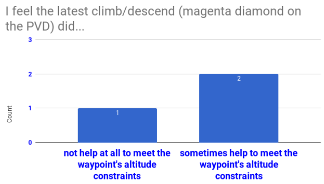


Fig. 53: Responses to Question ten

The responses to the magenta diamond on the PVD were the same as the ones to the magenta triangle on the distance to sector border axis, as can be seen in Figure 53. It sometimes helped except for the participant who gave the altitude commands as early as possible.

As can be seen in Figure 54, all the participants completely trusted the information shown by the altitude display. From the remarks it can be found that the participants say that there was never any wrong information shown by the altitude display.

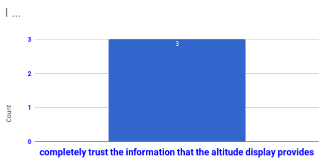


Fig. 54: Responses to Question eleven

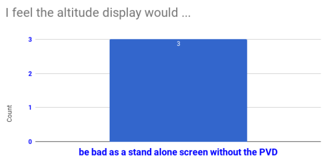


Fig. 55: Responses to Question twelve

The participants agreed on the fact that the altitude display would not work as a stand-alone display. The PVD is thus needed in combination with the altitude display for the full understanding of the airspace.

When asking the participants about their control strategies, the responses included some different strategies.

Participant 1 learned about the different streams and their characteristics, constraints and how they would occasionally lead to conflicts. He then figured out a strategy to prevent the conflicts from taking place. As an example he first let the traffic flying to FELO climb to FL 120 in order to avoid a conflict with the VOZA stream. When the aircraft has passed the VOZA steam, he would then let it climb further to its final flight level.

Participant 2 changed his control strategy for the merging stream towards MIFA. Where before he would merge the streams and keep all aircraft on FL 70, now he would separate the streams by guiding the aircraft from BLIP to flight level 90 and the ones from AZUL on FL 70 or 80, thus always ensuring of a vertical separation.

He suggested for a future experiment to make the constraint on MIFA a hard constraint at FL 70 instead of a altitude range of FL70 - FL100 like now, in order to see how the traffic would be controlled in this case.

Participant 3 indicated his strategy was to use the SSD as an overview and the altitude display more as a check and a help on the climb/descent performance.

Suggestions from the participants included to remove the speed tape from the altitude display. One of the participants indicated that he did not used this feature. Another participant indicated he would like it more if the select/deselect feature was more consistent between both display. They would also like to see combined heading/speed and altitude commands. Finally an instruction log indicating what commands were given to what aircraft was suggested.

Other remarks included that on the SSD the display can become cluttered with aircraft labels. This would make it harder to select the right aircraft or give them a speed/heading command. Another remark that was given was that it is not good that the speed tape on the altitude display is not consistent with the speed commands on the SSD. In the SSD the speed can be controlled by units of ten, while on the altitude display this can be done by the unit.

VIII. Discussion

In the evaluation it could be seen that all participants use the PVD as their main display and see the altitude display as a useful addition to improve their insight in the vertical performance of the aircraft.

This display system shows a potential for implementation within the current ATC work domain. However, still some inconsistencies within the display design should be fixed before this would be possible. The manipulation of the velocity should be consistent between the two displays. Also a problem occurred with the conflict zones on the SSD when an aircraft was descending and passing through an altitude where it would be in conflict with another aircraft. Also the fact that the conflict area is calculated using the true airspeed at the current altitude of the selected aircraft rather than the altitude of the observed aircraft. This is a flaw because the conflict would only occur when the selected aircraft would be on the altitude of the observed aircraft.

When comparing the data of aircraft that reached their waypoint within the waypoint constraint, it can be seen that here overall the state-of-the-art-tools gave more consistent results. This means some more tools should be added to the newly designed display system to support the controller in this task. However the amount of conflicts that occurred during the experiment with the new display system was lower compared to the state-of-the-art tools, indicating a potential to improve safety.

On the number of commands that had to be given during the scenario, it can be seen that generally the new display system required less heading changes. This could be explained due to the fact that merging the aircraft may be easier with the altitude display at hand.

IX. Conclusions and Recommendations

A new addition to the solution space diagram has been introduced: the altitude display. For the design of this display, previous attempts to introduce the altitude domain into the

SSD were analysed with the help of a work domain analysis. The altitude display has been designed as a co-planar addition to the SSD, thus making the linking between the display one of the most important aspects.

The altitude display shows the constraints for an aircraft in the altitude plane for the current direction and speed it is flying at.

A small human-in-the-loop evaluation was conducted. From this study it followed that the altitude display worked mostly as intended. Some improvements can be made to the representation when no aircraft are selected, since the current representation loses the sense of direction. The altitude display should always be used in combination with the SSD, since this display is currently still considered the main display while the altitude display gives the user support in the altitude domain.

The addition of the altitude display did seem to lead to less conflicts, however at a cost of some accuracy when it comes to leading aircraft to their respective waypoint within the altitude constraints that were determined. This indicates that there is potential for the altitude display, but maybe some more emphasis should be put on the altitude constraints. Possibly a list sorting the aircraft by time left to let them reach the waypoint constraint can be shown to support the air traffic controller in this. This list would give the user an overview of the aircraft that still would require an altitude command in order to reach their constraint and would help the user to prioritize the altitude changes for these aircraft.

A more elaborate study should be conducted in order to verify the workings of the altitude display. For this experiment it might be an option to make merging streams with a hard altitude constraint on the destination waypoint in order to analyse how users use the display in this situation. This would make the scenario a bit more challenging and yield better insight how controllers will use the altitude display for this kind of merging tasks.

Further research can be conducted on the question whether the altitude display might be a good choice to use in the training of air traffic controller novices, since it could learn students more about aircraft limitations and different pilot responses.

The simulator reality could be improved by the implementation of wind, radio communication and prohibited areas. The implementation of wind would result in a change of the conflict areas on the altitude display, as well a change in the climbing and descending performance of the aircraft. Radio communication will result in a much higher workload for the user, which might have an effect on the usage of the altitude display. Prohibited areas would result in a more complex airspace, but the altitude display might also be useful in the visualisation of these.

Finally the climb or descend rate only gets updated every 100 FL. In reality, however this is a continuous change with altitude. Decreasing this update interval would make the performance envelope more realistic. Another option might be to implement the climb and descent performances using BADA. This will increase the accuracy of the simulator and will narrow the solution space down slightly, but this change is not believed to be major.

References

[1] ICAO, ”Doc 4444: Air traffic Management, ” International Civil Aviation Organisation, 2016.

[2] L. Pfeiffert, N.H. Müller, P. Rosenthal ”A Survey of Visual and Interactive Methods for Air Traffic Control Data,” Technische Universitat Chemnitz, 2015.

[3] J. Lodder, “Altitude-extended Solution Space Diagram for Air Traffic Controllers,” M.Sc. Thesis, Faculty of Aerospace Engineering, Delft University of Technology, 2011.

[4] B. Beernink, “Towards an Integrated Ecological Plan View Display for Air Traffic Controllers,” M.Sc. Thesis, Faculty of Aerospace Engineering, Delft University of Technology, 2014.

[5] R.E. Klomp, “Redesign of an Inbound Planning Interface for Air Traffic Control,” M.Sc. Thesis, Faculty of Aerospace Engineering, Delft University of Technology, 2011.

[6] S.B.J Van Dam, M.Mulder and M.M. van Paassen, ”Ecological Interface Design of a Tactical Airborne Separation Assistance Tool,” Faculty of Aerospace Engineering, Delft University of Technology, 2008.

[7] G.A. Mercado Velasco, M.Mulder and M. van Paassen, “Analysis of Air Traffic Controller Workload Reduction Based on the Solution Space for the Merging Task,” Faculty of Aerospace Engineering, Delft University of Technology, 2010.

[8] C.D. Wickens, S.E. Gordon and Y.Liu, ”An Introduction to Human Factors Engineering,” Addison Wesley Longman, New York, 1997.

[9] A.M. Bisantz, C.M. Burns ”Applications of Cognitive Work Analysis,” Taylor & Francis Group, LLC, Boca Raton, 2009.

[10] D.D. Woods, ”Visual Momentum: A Concept to Improve the Cognitive Coupling of Person and Computer,” International Journal of Man-Machine Studies, The Ohio State University, 1984.

[11] V.L.J. Somers ”Design and Evaluation of a 3D Solution Space Metric for Air Traffic Control Workload,” M.Sc. Thesis, Faculty of Aerospace Engineering, Delft University of Technology, 2017.

[12] S.M.B. Abdul Rahman, M.M. van Paassen and M. Mulder, ”Using the Solution Space Diagram in Measuring the Effect of Sector Complexity During Merging Scenarios,” Proceeding of AIAA Guidance, Navigation, and Control Conference, Portland, Oregon, 08 - 11 August 2011. No. AIAA 2011-6693.

[13] P. Hermes, M. Mulder, M. M. van Paassen, J. H. L. Boering and H. Huisman, ”Solution Space Based Analysis of the Difficulty of Aircraft Merging Tasks,” November-December 2009. Journal of Aircraft. Vol. 46, No.6.

Part II

Appendices

Appendix A

Experimental briefing

Dear participant,

Thank you for taking the time to participate in this experiment testing the workings of a newly designed ecological altitude display for tactical air traffic control.

The experiment will start with 9 training scenarios aimed at getting familiar with the display and the different aspects of it.

After the training scenarios, the experiment will continue with 4 scenarios, taking 20 minutes each.

At the end of each scenario a workload assessment will pop up asking a rating between 0% and 100%. These should be filled in as accurate as possible.

A-1 Sector

The sector that will be used in the experiment can be found in Figure A-1.

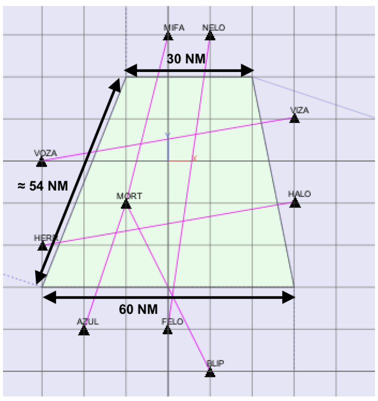


Figure A-1: Sector used in experiment

The size of the sector has been represented in Figure A-1. Every square of the grid represents 10 by 10 nautical miles, thus giving the sector border lengths shown in Figure A-1.

The rules of the sector are given as following:

- Inbound traffic going from both AZUL and BLIP towards waypoint MIFA should be merged and leave the sector between FL 70 and FL 100.
- Outbound traffic going to FELO from NELO should leave the sector at FL 200.
- Flights towards HALO should be leave at FL 210.
- Flights towards VOZA should leave the sector at FL 140, which is the same altitude as they enter the sector at.

A-2 Control Task

During the experiment, your task as air traffic controller is to guide the aircraft to their intended waypoint.

While doing so, keep in mind to:

- respect the waypoint's altitude constraints.
- respect the horizontal and vertical separation of 5 NM and 1000 ft respectively.

Since the aircraft in the simulation do not have a programmed flight plan, the aircraft will stay on their current course when no new commands are given.

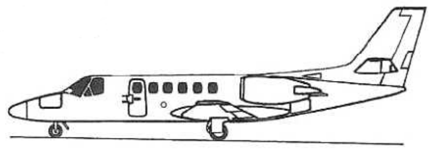
A-3 Aircraft

In the scenarios, 3 different aircraft types can be distinguished: light (L), medium (M) and heavy (H). Each type will have different specifications, which can be found in the overview below.

Note that the rate of climb and descent are given in a range, in the simulation a random value between these ranges will be used every time an altitude change command has been issued.

The minimum value of each interval will be used to draw the slow climb or descend lines, while the maximum value of the interval will be used to draw the fastest climb or descend lines.

Table A-1: Light Aircraft



Label: L

Performance

IAS MIN	180 kts	IAS MAX	250 kts
ROC (FL 0 - 100)	1930 - 3040 fpm	ROD (FL 0 - 100)	1370 - 3430 fpm
ROC (FL 100 - 200)	1970 - 2780 fpm	ROD (FL 100 - 200)	3430 - 3770 fpm
ROC (FL 200 - 300)	940 - 1970 fpm	ROD (FL 200 -300)	2240 - 3900 fpm
ROC (FL 300 - 400)	240 - 940 fpm	ROD (FL 300 - 400)	2340 - 2800 fpm

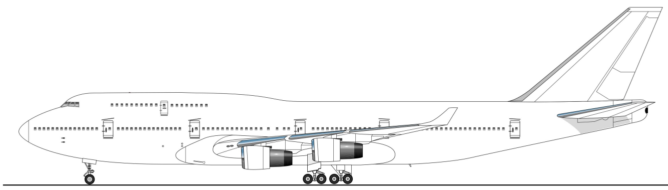
Table A-2: Medium Aircraft

Label: M

Performance

IAS MIN	200 kts	IAS MAX	290 kts
ROC (FL 0 - 100)	2170 - 3130 fpm	ROD (FL 0 - 100)	1340 - 1750 fpm
ROC (FL 100 - 200)	1790 - 2740 fpm	ROD (FL 100 - 200)	1750 - 2220 fpm
ROC (FL 200 - 300)	1180 - 1790 fpm	ROD (FL 200 -300)	2220 - 3270 fpm
ROC (FL 300 - 400)	360 - 1270 fpm	ROD (FL 300 - 400)	2890 - 3180 fpm

Table A-3: Heavy Aircraft



Label: H

Performance

IAS MIN	230 kts	IAS MAX	350 kts
ROC (FL 0 - 100)	1830 - 2720 fpm	ROD (FL 0 - 100)	1160 - 1430 fpm
ROC (FL 100 - 200)	1900 - 2610 fpm	ROD (FL 100 - 200)	1430 - 2080 fpm
ROC (FL 200 - 300)	1440 - 1900 fpm	ROD (FL 200 -300)	2080 - 2330 fpm
ROC (FL 300 - 400)	220 - 1440 fpm	ROD (FL 300 - 400)	2330 - 3480 fpm

A-4 Displays Available

During the experiment two different displays are used. The Plan View Display (PVD) and the Altitude Display (AD).

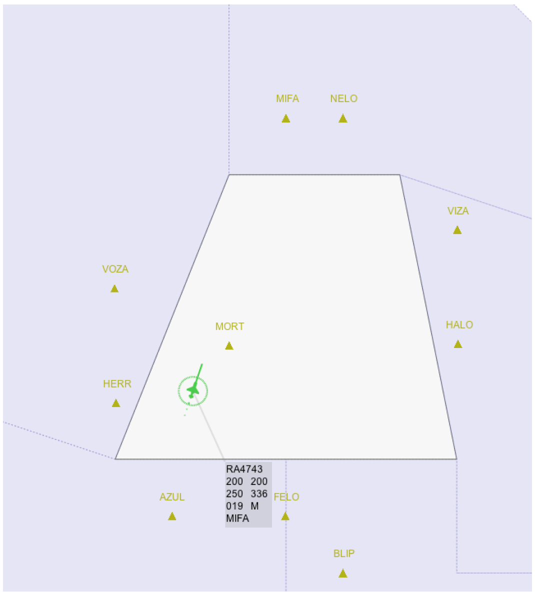


Figure A-2: sector with aircraft

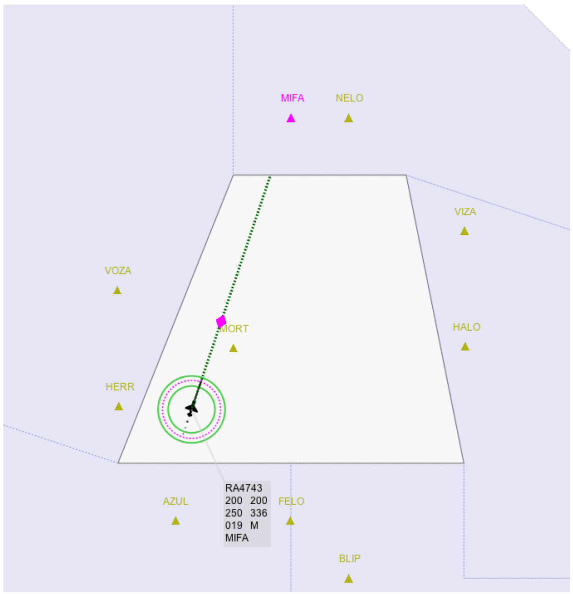


Figure A-3: aircraft selected in sector

Figure A-2 shows the sector when no aircraft has been selected. In this case the information of every aircraft is available in the aircraft label. Figure A-4 shows what information is found on the aircraft label.

Aircraft ID	
Current FL	Target FL
IAS	TAS
Heading	Type (L/M/H)
Destination Waypoint	

Figure A-4: Aircraft label

Figure A-3 shows the PVD when an aircraft is selected. The waypoint MIFA has an altitude constraint, in this case the aircraft should reach the waypoint at an altitude between FL 70 and 100. This constraint can be seen on the altitude display (the magenta line on the flight level axis in Figure A-6). On the PVD, the purple diamond shows when the aircraft should atleast have started it's descend in order to meet this requirement when exiting the sector.

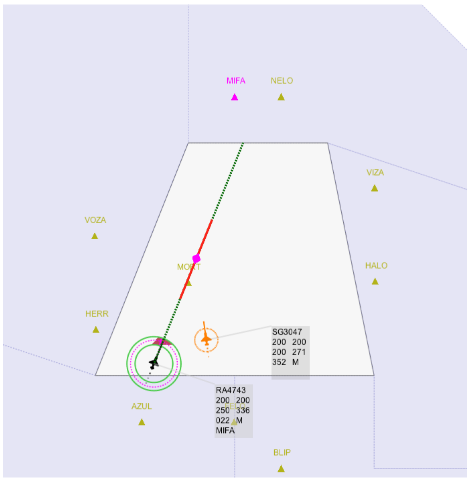


Figure A-5: Conflict view on PVD

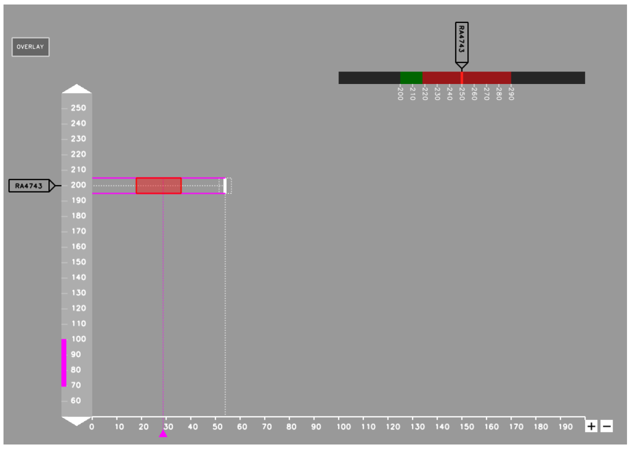


Figure A-6: visualisation of waypoint constraint on altitude display

Figure A-5 shows a selected aircraft that is in conflict with another aircraft. The green line is an extrapolation of the flight direction. The red segment shows the interval on which a loss of separation takes place. This can also be seen when looking at the altitude display shown in Figure A-6 in the red box on the current altitude.

When two aircraft are in conflict, this will show in 3 different stages. When the conflict will take place in less than 120 seconds, the aircraft will become orange, as seen in Figure A-5. The color will change to red if the conflict will take place in less than 60 seconds.

The situation seen in Figure A-5, results in the altitude display show in Figure A-7. The blips shown on the altitude display represent all the aircraft that are in the sector, as well as aircraft that are still approaching the sector. It can be seen that these blips do take over the colors of the aircraft on the PVD, in this case orange, because the aircraft will be in conflict in less than 120 seconds.

The altitude display represents the aircraft in an axis system, where the y-axis represents the flight levels in steps of 10, and the x-axis the distance to the sector border.

The x-axis can be manipulated with the zoom function. When clicking the '+ button' the display will zoom in on the x-axis, when clicking the '- button' the display will zoom out on the x-axis.

On the y-axis the flight level range that is shown can be changed by scrolling up and down. In order to do so, the triangles at the end of the flight level axis should be clicked. The top triangle is used to scroll the range up, while the lower triangle is used to scroll the range down.

When the most right aircraft blip is selected on the altitude display, the display shown in Figure A-8 can be seen. In this display there are a lot more functionalities, but first let's look at what can be seen on this display.

The controlled aircraft is shown with the white rectangle, together with a line to make it easier to read the distance to sector border. The path if the current altitude is kept is shown in magenta. The conflict with the other aircraft is calculated in distance from sector border,

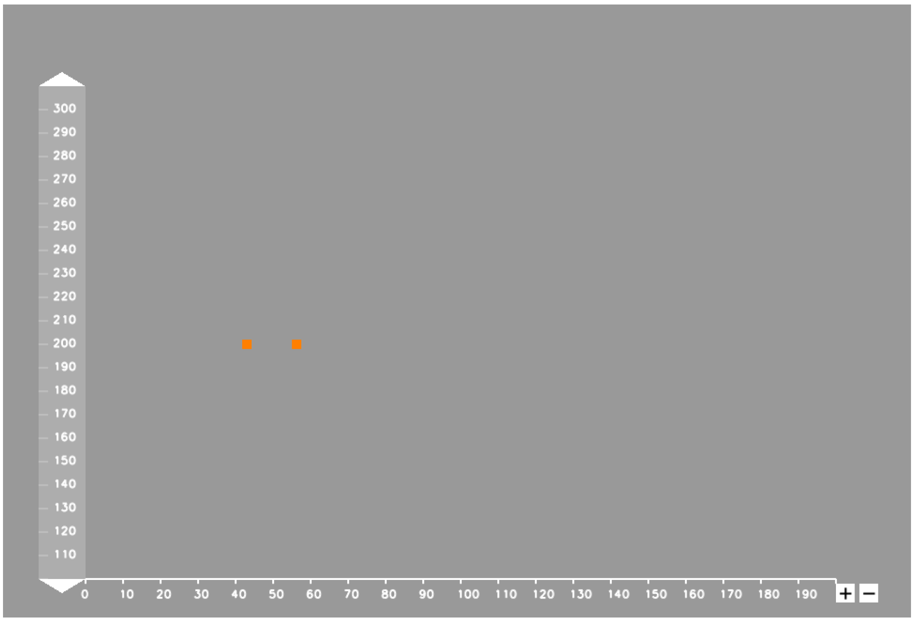


Figure A-7: altitude display no aircraft selected

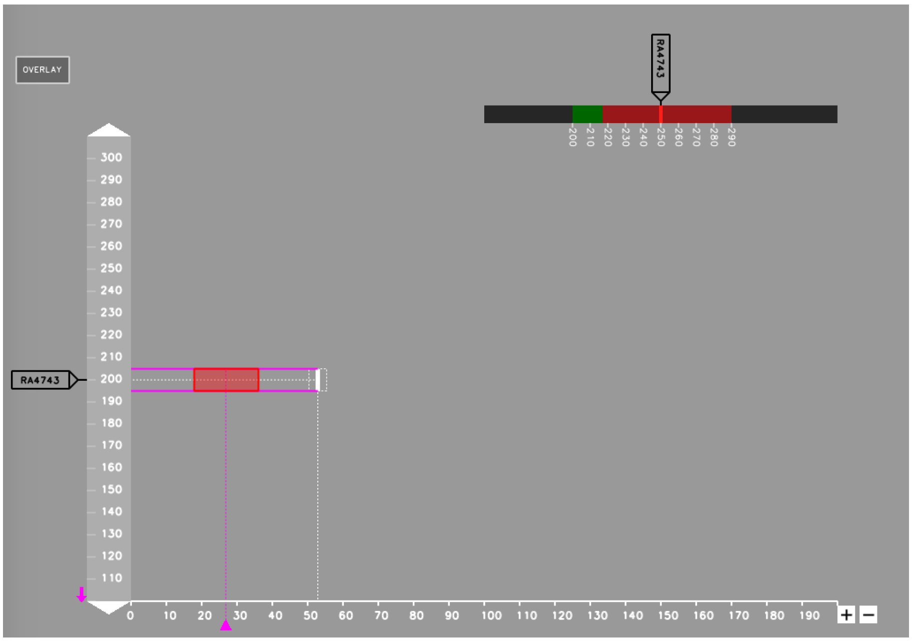


Figure A-8: altitude display when aircraft selected

rather than time in this display. This interval, where the conflict will take place is show by a red box. This red box corresponds to the earlier discussed red segment on the PVD.

On the y-axis, an arrow pointing down can be found, this indicates that there is an altitude constraint on the waypoint the aircraft is flying towards, but that the view should be lowered in order toe see this altitude constraint. The purple triangle, accompanied by the purple line, show the distance to the sector border, at which the aircraft should start it's descend at latest in order to meet the altitude constraint.

There are a couple of ways to solve a conflict. First of all, on the altitude display, an altitude change command can be given simply by dragging the aircraft label (the black arrow with the aircraft ID in it) at the flight level axis up or down. Committing this change can be done by pressing the ENTER key on the keyboard. Before committing an altitude change command, one can thus look for the best solution for the problem. An example of the display, when dragging the aircraft label down can be seen in Figure A-9.

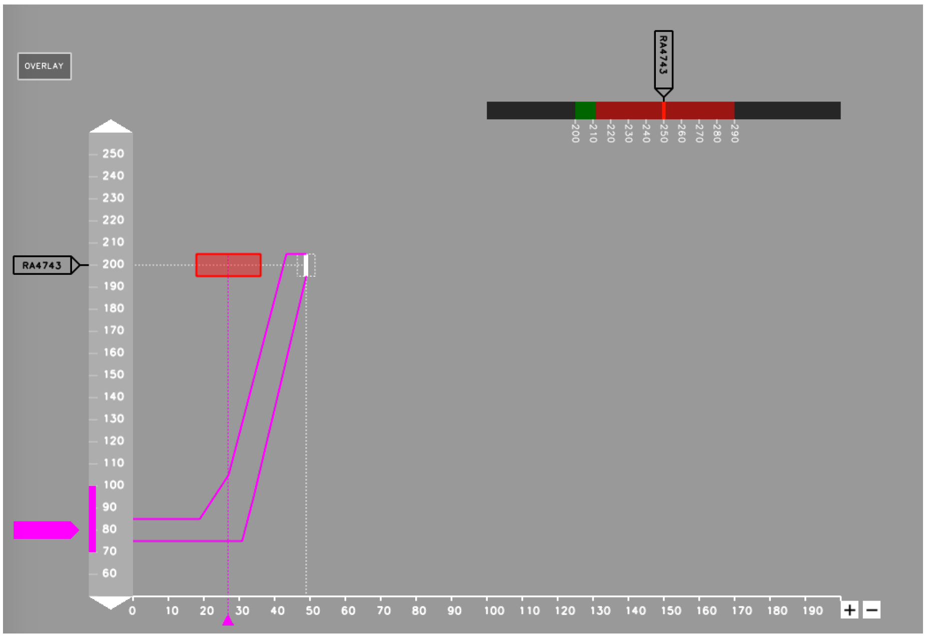


Figure A-9: altitude display with dragged altitude label

The second variable to manipulate directly on the altitude display, is the velocity. The velocity bar can be found in the most right-up corner of the screen. In order to avoid a conflict, using a speed change, drag the velocity label into the green area and confirm the speed change by pressing the ENTER key on the keyboard. The Information shown on the velocity strip on the altitude display corresponds to the blocked areas on the PVD.

When a speed change is given, while an altitude change command has already been issued, the altitude command will stop, by guiding the aircraft to the closest 10th flight level (i.e FL 290 if the aircraft is at FL 294, and FL 300 if the aircraft is at FL 296).

Another way to solve a conflict is by making use of speed and heading changes on the PVD. When an aircraft is selected, a speed change can be done by scrolling the mouse wheel and confirming the change by pressing the ENTER key. A heading change can be done by clicking anywhere on the solution space diagram around the aircraft and confirming the change by pressing the ENTER key.

Now let's look at some extra features. Current air traffic regulations specify that certain flight levels should not be used depending on the direction in which the aircraft is flying. Since all aircraft will be flying below FL 410, the following rules apply: magnetic heading 0 to 179 should be cleared on odd flight levels with intervals of 2000 ft, magnetic heading 180 to 379 should be cleared on even flight levels with an interval of 2000 ft. In the left-top corner, a button called overlay can be found. When this button is activated, an overlay will show up indicating the blocked flight levels in red, as seen in Figure A-10.

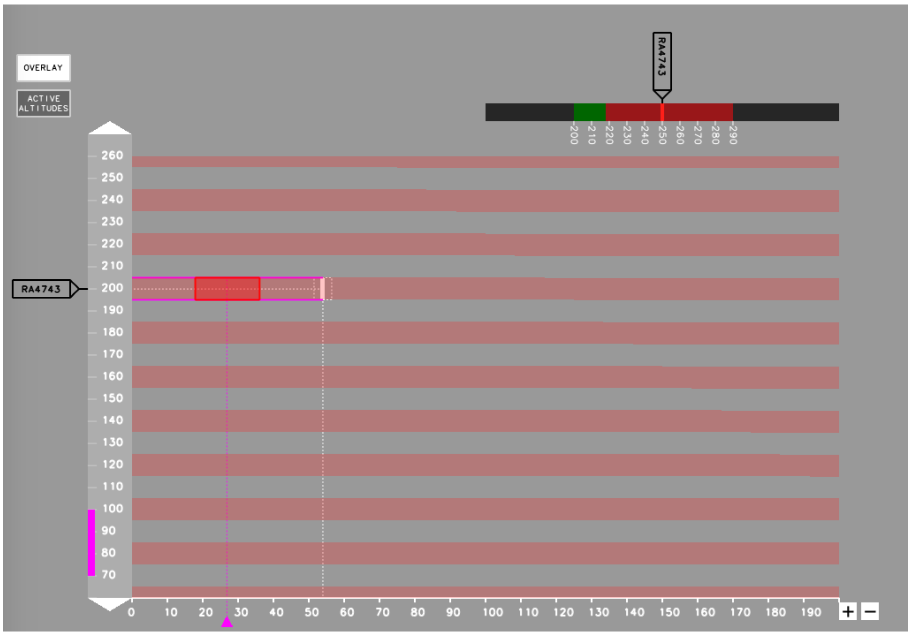


Figure A-10: altitude display with dragged altitude label

As can be seen in Figure A-10, a new button pops up when the overlay is activated. When this button (active altitudes) is selected, only the flight levels which are not blocked can be selected with the altitude label, thus preventing the controller to put aircraft on blocked altitudes.

A-5 Training Scenarios

What follows is a brief description of what the goal is of the different training scenarios.

Training Scenario 1

In training scenario 1 the air traffic controller has to guide a single aircraft towards it's end point. In doing this, the air traffic controller has to make sure that the rules of the sector are respected.

Training Scenario 2

In training scenario 2, the air traffic controller will have to guide 2 aircraft to different waypoints, the aircraft will be crossing. The rules of the airspace have to be followed.

Training Scenario 3

In training scenario 3, the merge of 2 streams going to the same waypoint will be practised.

Training Scenario 4

Training scenario 4 deals with different streams going to different waypoints.

Training Scenario 5

Training scenario 5 adds more aircraft to the streams.

Training Scenario 6-9

A few real scenarios in order to prepare for the test.

Appendix B

Questionnaire

Subject ID:

Date:

I feel that I ...

- ☐ totally do not understand the altitude display
- ☐ understand some aspects of the altitude display, but not all
- ☐ understand most aspects of the altitude display
- ☐ fully understand the altitude display

Remarks?

I feel the representation used on the altitude display is ...

- ☐ confusing
- ☐ not so intuitive
- ☐ mostly intuitive
- ☐ intuitive

Remarks?

I feel the coupling between the PVD and altitude display is...

☐ not present

☐ not sufficiently present

☐ sufficiently present

☐ clearly present

Remarks?

I feel that the altitude display ...

☐ totally reduces my understanding of the airspace

☐ moderately reduces my understanding of the airspace

☐ slightly reduces my understanding of the airspace

☐ neither reduces nor improves my understanding of the airspace

☐ slightly improves my understanding of the airspace

☐ moderately improves my understanding of the airspace

☐ totally improves my understanding of the airspace

Remarks?

I feel that my attention ...

☐ totally goes to the altitude display

☐ most of the time goes to the altitude display

☐ is equally focussed on the altitude display and the PVD

☐ most of the time goes to the PVD

☐ totally goes to the PVD

Remarks?

I feel the altitude display ...

☐ distracts me all the time

☐ distracts me most of the time

☐ distracts me sometimes

☐ does not distract me

Remarks?

I mainly used the altitude display to ...

☐ proactively search and solve conflicts

☐ mostly proactively search and solve conflicts

☐ equally proactively and reactively search for conflicts

☐ mostly reactively solve conflicts

☐ reactively solve conflicts

Remarks?

I feel the altitude display did ...

☐ not at all help me in conflict resolution

☐ help a bit in conflict resolution

☐ help a lot in conflict resolution

Remarks?

I feel the altitude display latest climb/descend (magenta triangle on x-axis) did ...

☐ not help at all to meet the waypoint's altitude constraints

☐ sometimes help to meet the waypoint's altitude constraints

☐ often help to meet the waypoint's altitude constraints

☐ always help to meet the waypoint's altitude constraints

Remarks?

I feel the latest climb/descend (magenta diamond on the PVD) did...

☐ not help at all to meet the waypoint's altitude constraints

☐ sometimes help to meet the waypoint's altitude constraints

☐ often help to meet the waypoint's altitude constraints

☐ always help to meet the waypoint's altitude constraints

Remarks?

I ...

☐ completely distrust the information that the altitude display provides

☐ moderately distrust the information that the altitude display provides

☐ slightly distrust the information that the altitude display provides

☐ neither distrust or trust the information the altitude display provides

☐ slightly trust the information that the altitude display provides

☐ moderately trust the information that the altitude display provides

☐ completely trust the information that the altitude display provides

Remarks?

I feel the altitude display would

☐ be good as a stand alone screen without the PVD

☐ be almost good as a stand alone screen without the PVD

☐ be reasonable as a stand alone screen without the PVD

☐ be bad as a stand alone screen without the PVD

Remarks?

What was your strategy for controlling the traffic?

Any suggestions for improvements to the display?

Any Other remarks?

Appendix C

Velocity Strip Calculations

In the display not only the solution space for the the altitude domain will be represented, also the solution space in the velocity domain will be shown with a velocity strip. The blocked velocities will be calculated and indicated with red in the velocity strip, while velocities that do not result in any conflict will be shown in green.

In order to find the blocked velocities the minimum and maximum velocity that does result in a conflict for the controlled aircraft with a certain aircraft has to be calculated. Doing this for all aircraft in the sector will result in the total solution space for the velocity domain.

An aircraft is in conflict with another aircraft if and only if the resultant velocity of the two aircraft is within the cone shown in Figure C-1. The only variables that influence the relative velocity are the observed aircraft's velocity (V_{OBS}) and the controller aircraft's velocity (V_{CON}) as well as both aircraft their headings. In this display it has been chosen to only make the velocity and the altitude the controlled variables. The heading can be controller on the main SSD display. Thus when an aircraft has been selected only the controlled aircraft's speed will influence the relative velocity, since at this moment the observed aircraft's speed is a constant.

In order to see if the resultant velocity will be inside the forbidden beam zone, the heading of the resultant velocity has to be compared at to the angles of the forbidden beam zones. If the heading of the resultant velocity is inside the boundaries of the forbidden beam zone, the aircraft will be in a conflict.

The heading of the relative velocity (ψ_{REL}) can be expressed in terms of the velocity of the controlled and observed aircraft as following:

$$tan(\psi_{REL}) = \frac{V_{CON} \cdot \cos(\psi_{CON}) + V_{OBS} \cdot \cos(\psi_{OBS})}{V_{CON} \cdot \sin(\psi_{CON}) + V_{OBS} \cdot \sin(\psi_{OBS})} \tag{C-1}$$

The angles and velocities that are given in the formula can be seen in Figure C-3. In order to find the minimum and maximum speed for the controlled aircraft that will result in a conflict,

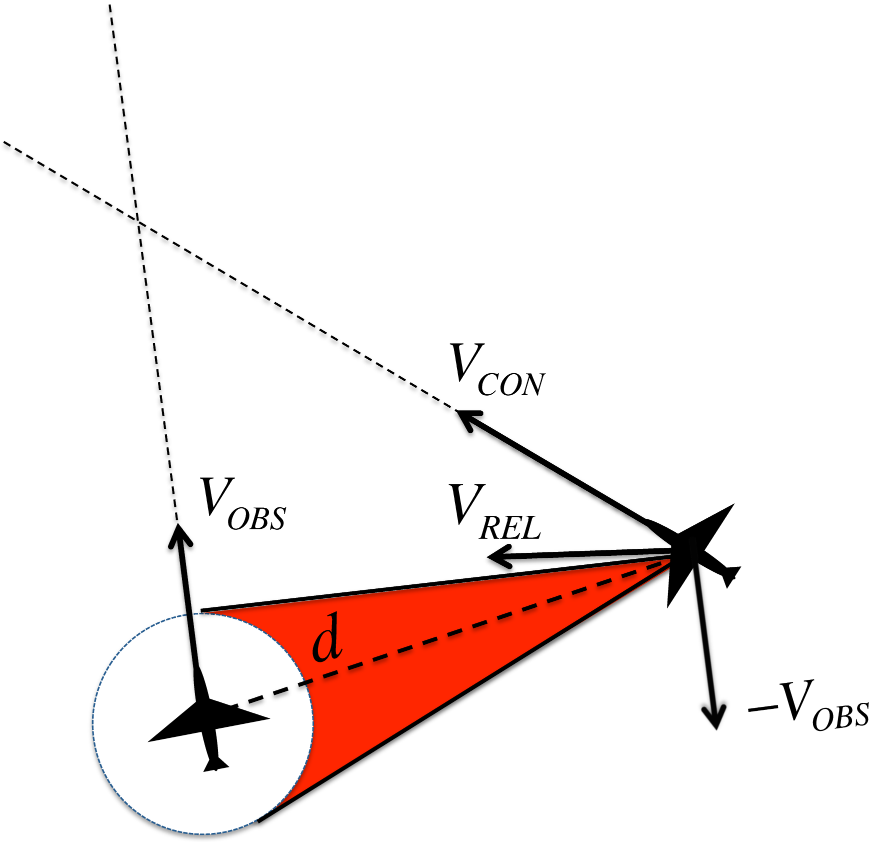


Figure C-1: Forbidden beam zone for resultant speed

the resultant velocity's angle has to be equal to the minimum and maximum angle that result in a conflict.

The maximum and minimum angles that result in a conflict are given by Equation C-2 and C-3 respectively.

$$\alpha_{LOS_{max}} = \alpha_d + \alpha_{FBD} \tag{C-2}$$
$$\alpha_{LOS_{min}} = \alpha_d - \alpha_{FBD} \tag{C-3}$$

The angle of the distance between the two aircraft (α_d) and the angle of the forbidden beam zone (α_{FBD}) can be found by means of Equation C-4 and C-5.

$$\alpha_d = \tan^{-1}\left(\frac{\Delta x}{\Delta y}\right) = \tan^{-1}\left(\frac{x_{obs} - x_{con}}{y_{obs} - y_{con}}\right) \tag{C-4}$$
$$\alpha_{FBD} = \sin^{-1}\left(\frac{5NM}{d}\right) \tag{C-5}$$

In Equation C-1 the only variable that is controlled is V_{CON}. Equations C-6 and C-7 show the maximum and minimum speed for V_{CON} that will result in a conflict.

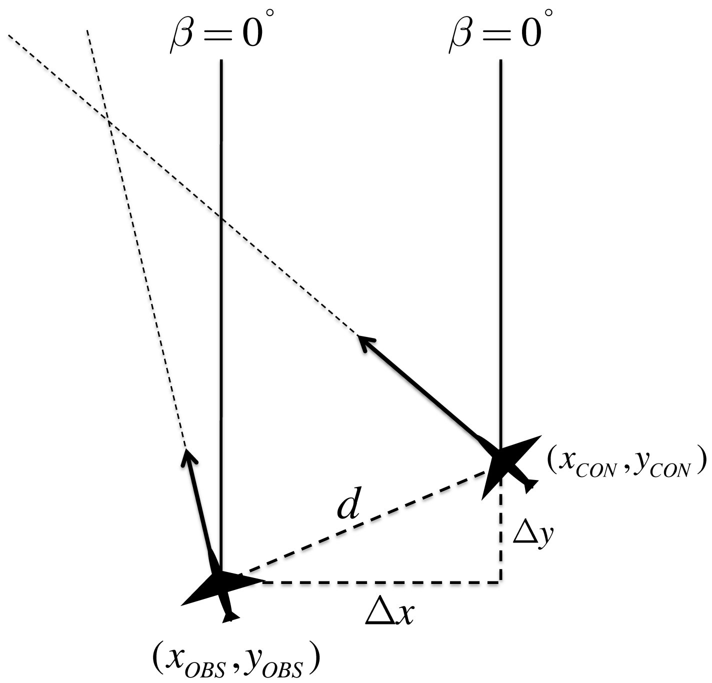


Figure C-2: Calculation of α_d

$$V_{max_{conf}} = \frac{V_{OBS} \cdot \cos(\psi_{OBS}) - V_{OBS} \cdot \sin(\psi_{OBS}) \cdot \tan(\alpha_d + \alpha_{FBD})}{\tan(\alpha_d + \alpha_{FBD}) \cdot \sin(\psi_{CON}) - \cos(\psi_{CON})} \tag{C-6}$$

$$V_{min_{conf}} = \frac{V_{OBS} \cdot \cos(\psi_{OBS}) - V_{OBS} \cdot \sin(\psi_{OBS}) \cdot \tan(\alpha_d - \alpha_{FBD})}{\tan(\alpha_d - \alpha_{FBD}) \cdot \sin(\psi_{CON}) - \cos(\psi_{CON})} \tag{C-7}$$

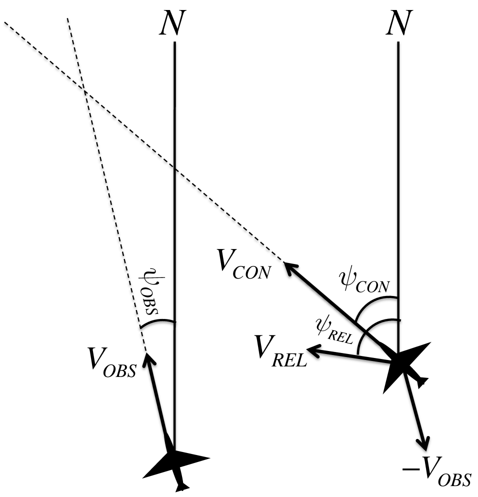


Figure C-3: Forbidden beam zone for resultant speed

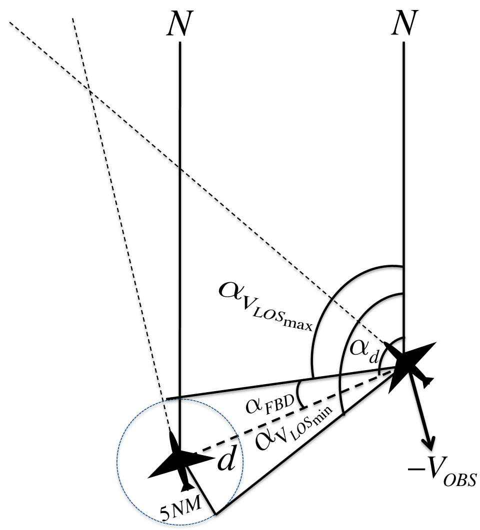


Figure C-4: Forbidden beam zone for resultant speed

When doing this for all the aircraft in the sector and taking into account the velocities which fall in the range from the minimum to the maximum velocity, the blocked velocities can be calculated. These can then be represented in a velocity strip

Appendix D

Flow Diagram

In this section a work flow diagram of the program is presented. It gives an overview of the data that is shown on the altitude display.

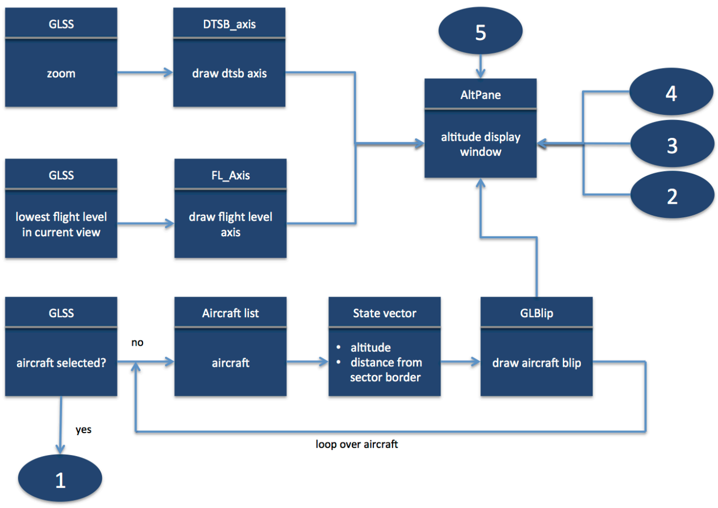


Figure D-1: Work flow diagram display

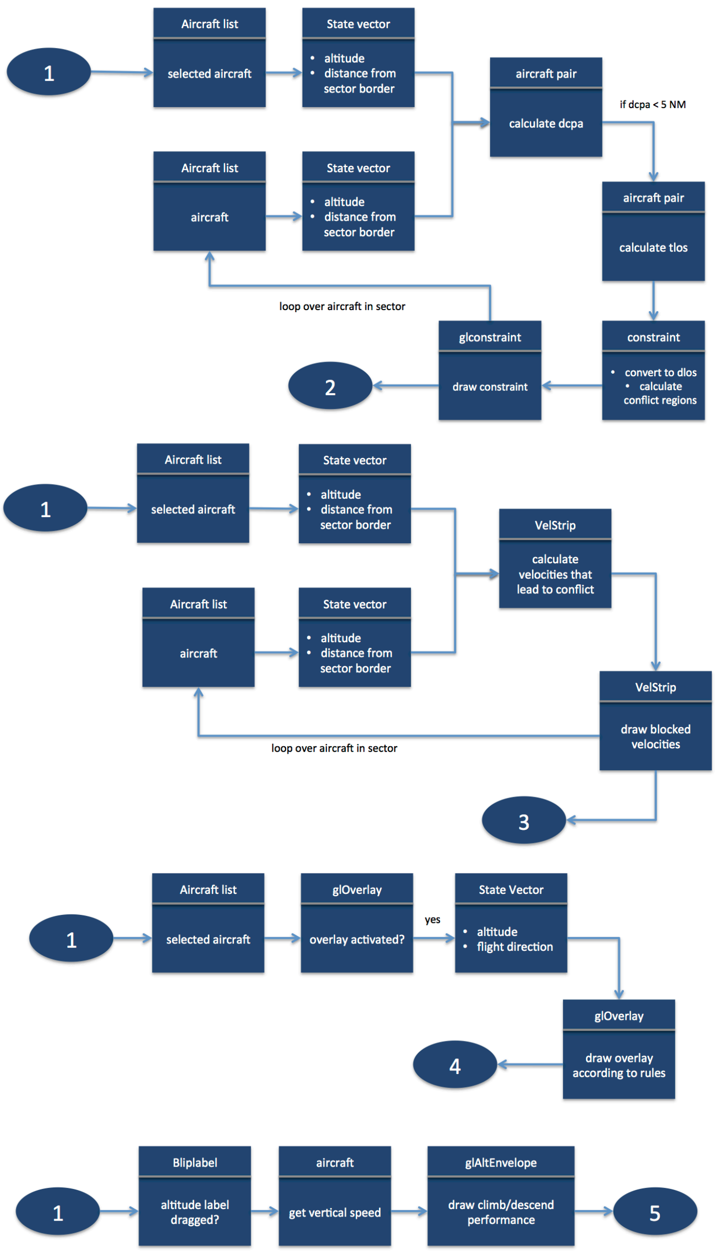


Figure D-2: Work flow diagram display

Appendix E

Complexity Results

In this appendix all results from the complexity analysis will be represented.

E-1 Scenario one

The results for the complexity of scenario one can be found below in Figure E-1 and E-2. The first figure shows the results for the experiment where the altitude display is availabel to the user, while Figure E-2 shows the results for the experiment with the state-of-the-art tools.

E-2 Scenario two

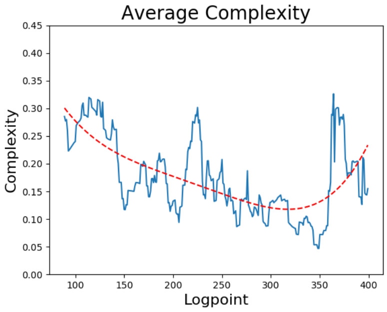
Figure E-3 shows the complexity results for the experiment with the altitude display available, while Figure E-4 shows the complexity during the experiment with the state-of-the-art tools available.

E-3 Scenario three

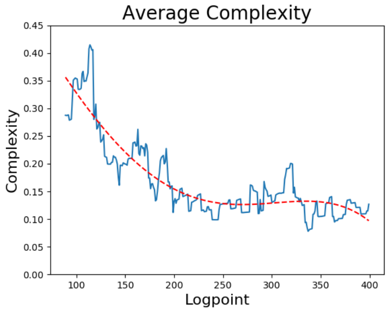
Figure E-5 and E-6 show the complexity results for the experiment with the altitude available and the state-of-the-art tools respectively.

E-4 Scenario four

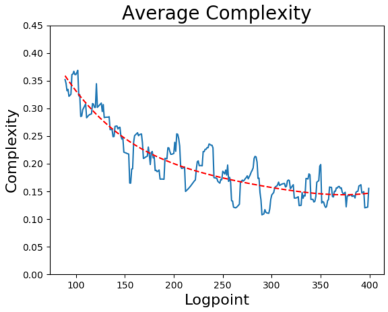
Figures E-7 and E-8 show the complexity of scenario four during the experiment with the altitude display available and the state-of-the-art tools respectively.



(a) P1

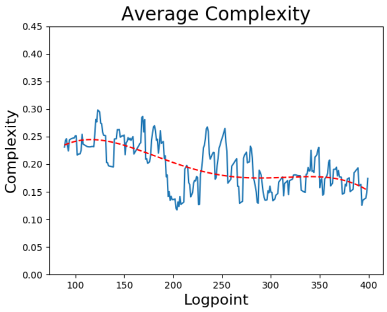


(b) P2

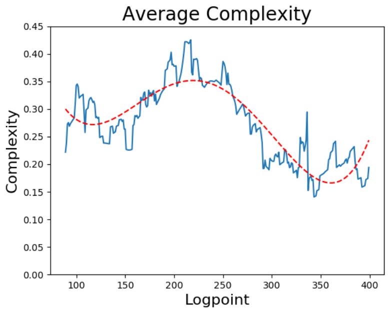


(c) P3

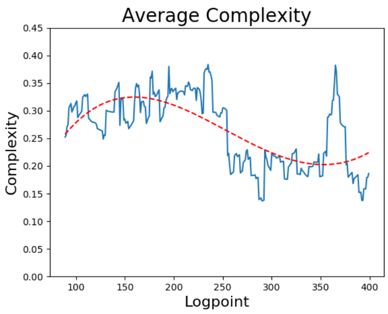
Figure E-1: Experiment with altitude display



(a) P1

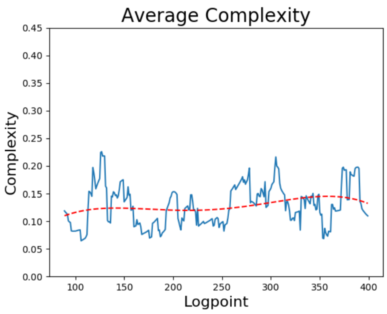


(b) P2

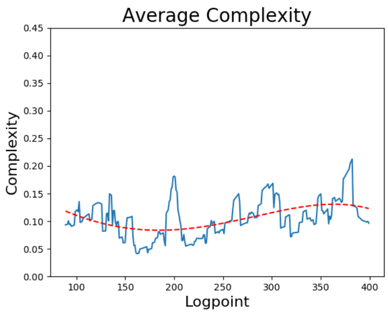


(c) P3

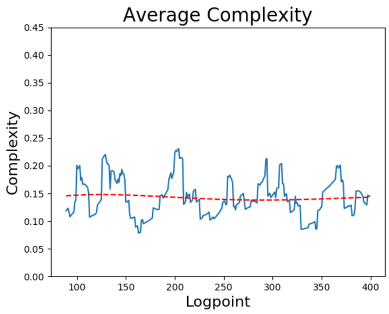
Figure E-2: Experiment with state-of-the-art tools



(a) P1

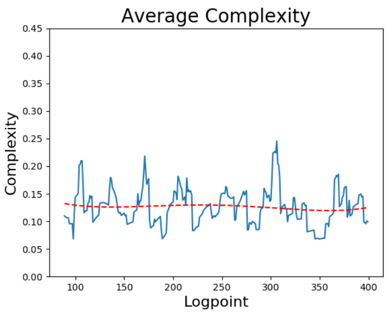


(b) P2

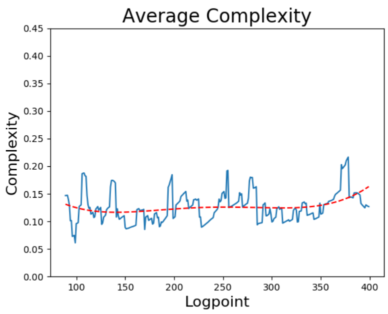


(c) P3

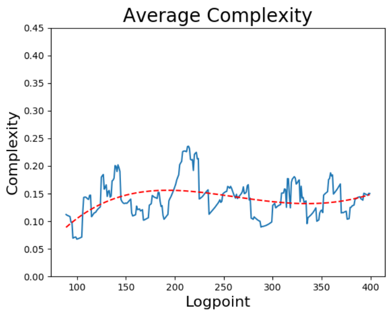
Figure E-3: Experiment with altitude display



(a) P1

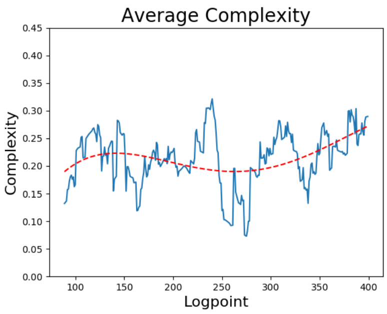


(b) P2

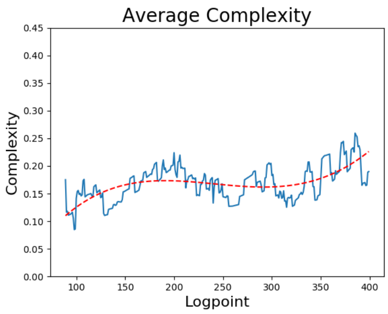


(c) P3

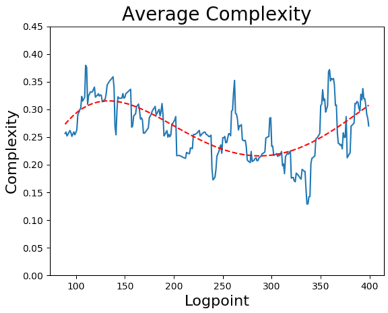
Figure E-4: Experiment with state-of-the-art tools



(a) P1

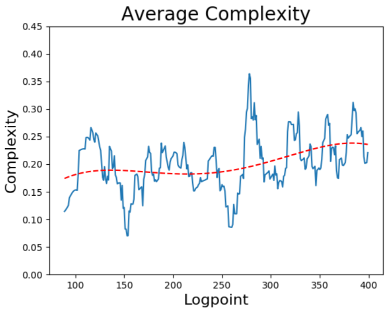


(b) P2

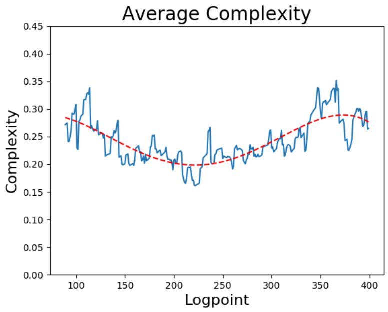


(c) P3

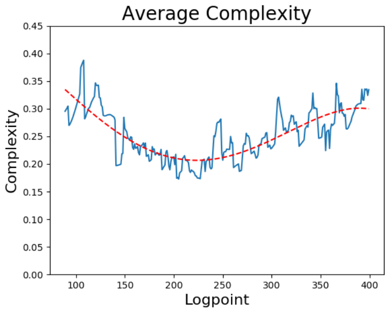
Figure E-5: Experiment with altitude display



(a) P1

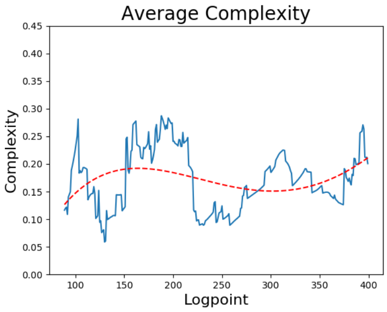


(b) P2

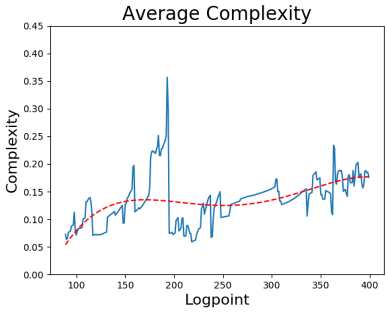


(c) P3

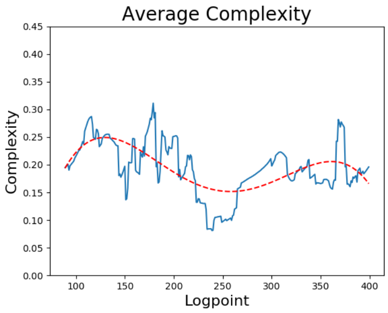
Figure E-6: Experiment with state-of-the-art tools



(a) P1

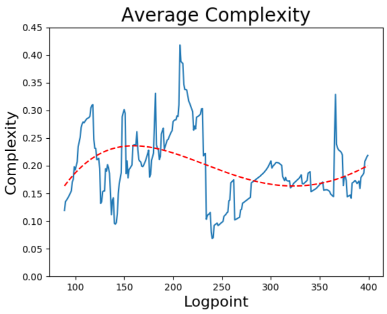


(b) P2

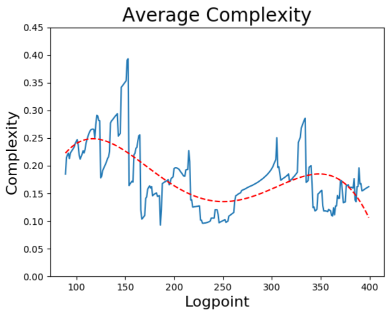


(c) P3

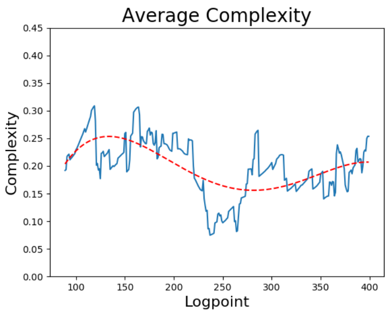
Figure E-7: Experiment with altitude display



(a) P1



(b) P2



(c) P3

Figure E-8: Experiment with state-of-the-art tools