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Altitude-Extended Solution Space Diagram for Air Traffic Controllers

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ALTITUDE-EXTENDED SOLUTION SPACE DIAGRAM FOR AIR TRAFFIC CONTROLLERS

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The solution space diagram was developed to assist air traff c controllers and pilots in dealing with traff c. Up until now, it has been used to solve conf icts in the horizontal plane. Especially in the context of Air Traff c Control, it is important to also include the vertical dimension. This paper describes an approach to incorporate this vertical dimension in a two dimensional display. The altitude extended solution space diagram will be calculated taking into account the Altitude Relevance Bands of all aircraft involved. In this way, the algorithm can discard conf ict zones that can never lead to a conf ict. Based on this algorithm, a display prototype has been developed that is able to show the effect of altitude changes to the controller. This display will be used to perform an evaluation experiment to assess the benef ts of including altitude information.

The solution space diagram (Figure 1) has been introduced to assist pilots and air traff c controllers (ATCos) to deal with handling traff c situations (Dam, Abeloos, Mulder, & Paassen, 2004; Velasco, Mulder, & van Paassen, 2009). The diagram presents a visualization of the heading and speed constraints imposed by traff c surrounding traff c. Such a constraint-based approach to interface design was inspired by the Ecological Interface Design (EID) framework (Vincente & Rasmussen, 1992). By showing the constraints, instead of showing a predef ned solution, an operator can see all the boundaries of his operational envelope. Based on this the operator can make an informed decision on how to handle a particular situation.

A key task in the Air Traff c Control (ATC) domain is merging a number of aircraft at a specif c waypoint (Hermes, Mulder, van Paassen, Boering, & Huisman, 2009). A number of aircraft enter an ATCos sector, and have to leave at a specif c waypoint without getting into conf ict with each other. In an ATC context, a conf ict is def ned as a situation that will lead to loss of separation. In other words, a conf ict occurs when an aircraft is on a trajectory that brings it within a specif ed minimum distance from an other aircraft. The distance requirement can be split into a horizontal and a vertical requirement. In the vertical plane, aircraft must be spaced by at least $1000\ ft$. In the horizontal plane the minimum distance is between 3 and $5\ Nm$. Both requirements can be combined to def ne the protected zone (PZ). The PZ is a volume of airspace surrounding an aircraft in the shape of a hockey puck with a radius of 3 to $5\ Nm$ and a thickness of $2000\ ft$.

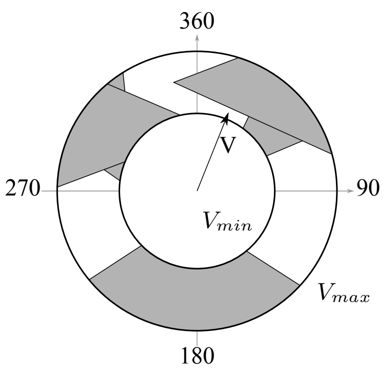


Figure 1: The Solution Space Diagram

The solution space presents the constraints imposed on an aircrafts velocity by the horizontal part of the conf ict zone in a velocity diagram as shown in Figure 1. It shows which combinations of speed and heading will eventually lead to a loss of separation. The diagram is constructed by f rst calculating the velocities that will lead to a conf ict with each surrounding aircraft, called the intruding aircraft. The calculated conf ict zones are then clipped by an annular section that has an internal radius equal to the minimum velocity, V_{min}, and an outer radius equal to the maximum velocity, V_{max}, of the controlled aircraft. The annular section represents the full performance envelope in the horizontal plane, the gray areas represent the subset of this envelope that leads to a conflict. In this way, an ATCo can see how how the traffic surrounding an aircraft under observation affect the instructions that can be given.

A drawback of the solution space is that it is only presenting conflicts in the horizontal plane. Flying, on the other hand, is a three dimensional activity. This vertical component becomes especially important in climb and descent maneuvers. When only aircraft on the same altitude are shown on the display, it cannot be used during climb and descent maneuvers. When all aircraft are shown, regardless of altitude, the display will provide false conflicts.

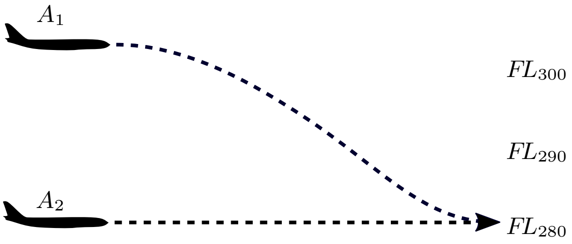


Figure 2: Two aircraft involved in a descent

Consider the situation in Figure 2. When an SSD would only be calculated taking into account traffic at the same altitude, A_1 would start a descent without knowing about A_2. If the speed of both A_1 and A_2 are approximately equal, A_1 would fly straight into the protected zone of A_2. This would only show up once A_1 has actually entered the protected zone.

Treating all aircraft as if they were on the same altitude would put A_2 in the SSD of A_1, but it would also indicate a conflict because both A_1 and A_2 are in the same horizontal position. Wether or not the situation remains a conflict depends on the velocities of A_1 and A_2. If the difference in velocity is large enough, A_1 would end up either in front or behind A_2 without loss of separation. To avoid this, the conflict zones will need to be calculated taking this into account. This procedure will be explained in the Estimated Overlap Section.

The goal of this research is to develop a display that incorporates information in the vertical plane on a solution space display in the context of ATC. This paper will first introduce the procedure to decide which surrounding aircraft are relevant during a vertical maneuver. Next, a technique to determine the time interval during which the conflict zone for a specific intruder is valid will be discussed. The final section describes the resulting display that will be used to evaluate the altitude extended SSD.

Altitude Based Filtering

In order to make sure an aircraft can be allowed to climb or descend, the ATCo has to verify that there will be no conflicting traffic interfering with the maneuver. The aircraft that could potentially interfere can be determined by a technique called Altitude Based Filtering.

The first step in altitude based filtering is to compute an Altitude Relevance Band (ARB). The ARB is the altitude interval in which an aircraft will move during a vertical maneuver as shown in Figure 3. One side of the interval will be determined by the current altitude of the aircraft, the other end of the interval is defined by the altitude the aircraft is climbing or descending to. When an aircraft is not performing a vertical maneuver, the ARB has no thickness and is equal to the current altitude.

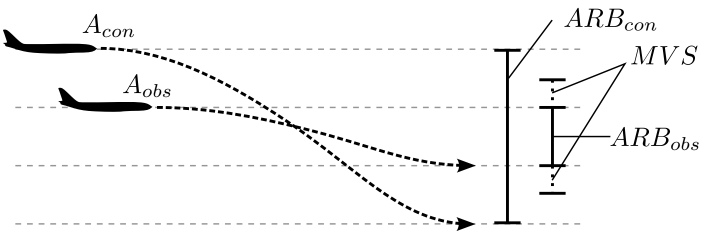
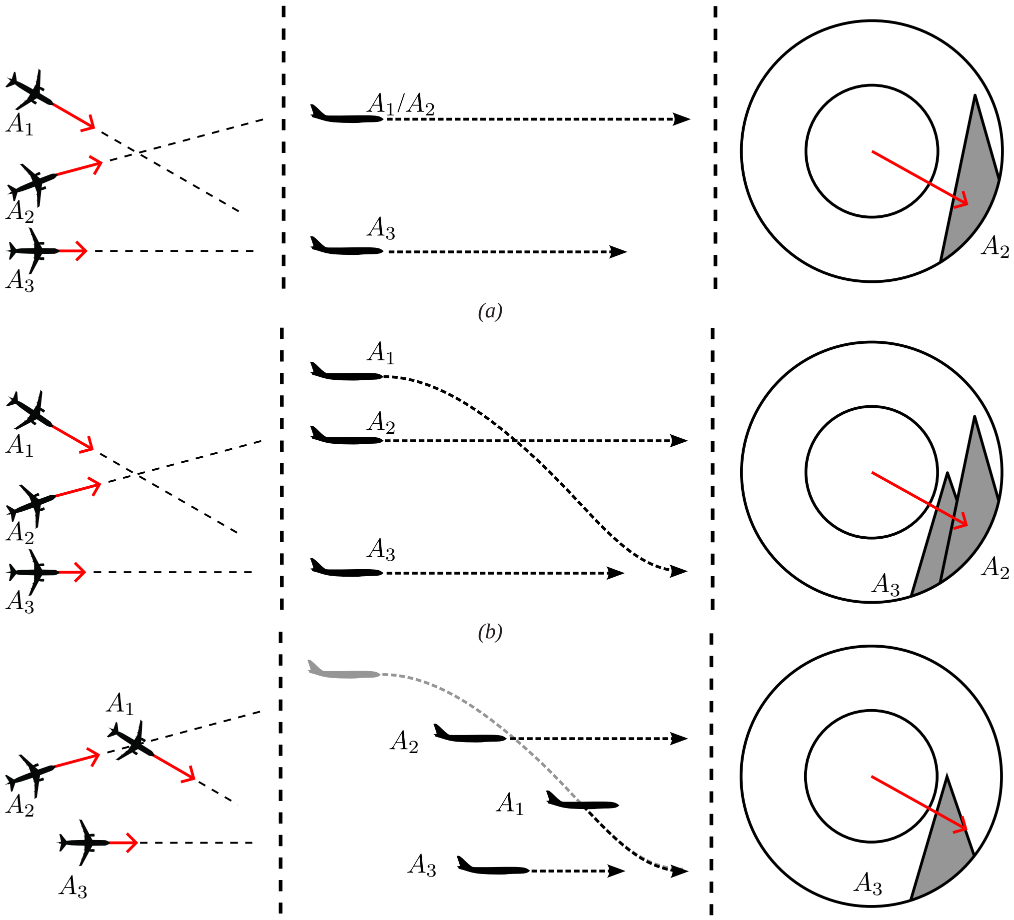


Figure 3: Definition of the Altitude Relevance Band

The second step is to add the minimum vertical separation to the ARBs of the observed aircraft. In the context of the solution space, the observed aircraft are the aircraft surrounding the aircraft for which the solution space is being calculated.

The f nal step is to determine which aircraft have overlapping ARBs. These will be the aircraft that could potentially get into a conf ict. Figure 4 shows an example of using altitude based f ltering to draw the solution space. Figure 4 (a) shows the horizontal and vertical situation of two aircraft on the same altitude and one on a different altitude. The right column shows the solution space calculated for aircraft A_1. Since no vertical maneuvers are performed, only A_1 and A_2 can be in conf ict. In the solution space diagram, only the conf ict zone of A_2 shows up.

Figure 4 (b) shows the situation when A_1 would start a descent. In this case, A_1 is crossing altitudes of A_2 and A_3. This results in both conf ict zones being drawn in the solution space diagram. When the situation progresses, A_1 will have descended below A_2. At this moment, A_1 will not be able to get into conf ict with A_2 anymore and only the conf ict zone of A_3 will be drawn on the solution space.



(c)

Figure 4: Altitude based f ltering example

Estimated Overlap Time

Altitude based f ltering only looks at the ARBs of aircraft to determine if there could be conf icts. This effectively gets rid of all aircraft which will never be on the same altitude and can never be in conf ict. After this procedure, there can still be aircraft left which will never get into a conf ict with the controlled aircraft. Consider a controlled aircraft at 30000 ft that needs to descend to 15000 ft. There could be an observed aircraft that will be at the exact same location in 60 s, but at 15000 ft. Since it is physically impossible for any commercial aircraft to descend 15000 ft in 60 s it will never be possible to get in conf ict even though the ARBs are overlapping.

When performing vertical maneuvers, an aircraft crosses all intermediary altitudes between its current altitude and its required altitude. The time at which an aircraft crosses a certain altitude depends on two main factors. The vertical speed and the time at which the aircraft will start its descent. This time is mainly driven by ATC. When the ATCo gives a command, the pilot will initiate his maneuver. There might be some delay between receiving a clearance and executing the maneuver. In the best case scenario, the delay can be close to zero, in the worst case, it might be in the order of a few minutes. Next to this unknown time delay, the actual rate of climb or descent is also unknown. As with the time delay, it should be possible to make assumptions about the fastest and slowest maneuvers for a specif c situation.

Based on these time delay and vertical speed intervals, a time versus altitude diagram can be plotted as shown in Figure 5. This diagram is created by computing the fastest and slowest descent. The diagram shows the evolution of altitude with time. At t_{0_f} a controller issues a command. The fastest descent, which has no time delay and maximum vertical speed, starts immediately and can be seen as the left line in the diagram. After the maximum delay, at t_{0_s}, the slowest maneuver with the lowest vertical velocity is initiated. This is represented by the right line.

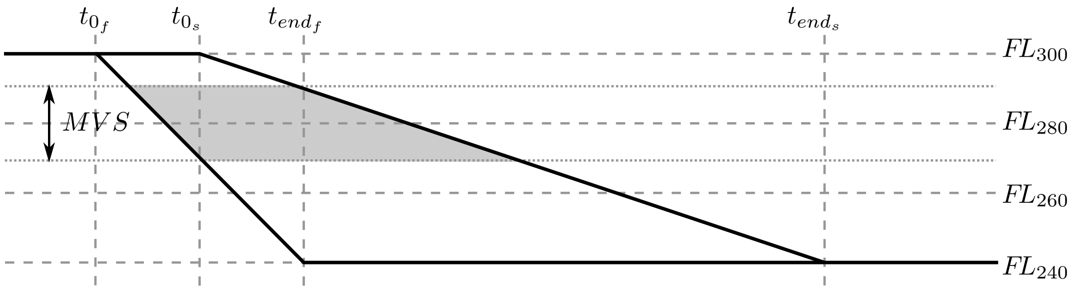


Figure 5: Time-altitude diagram for a single aircraft

The time-altitude diagram immediately shows the estimated time interval during which an aircraft will be on a given altitude. When taking into account the minimum vertical separation discussed before, a prediction of the time interval during which a conf ict can occur can be estimated. An example of this is shown in Figure 5 by the gray area. The gray area represents the relevant combination of time and altitude for an aircraft f ying at 28000 ft taking into account a minimum vertical separation of 1000 ft. The lowest and highest time value of the gray area determine the relevant interval when crossing an aircraft f ying at constant altitude.

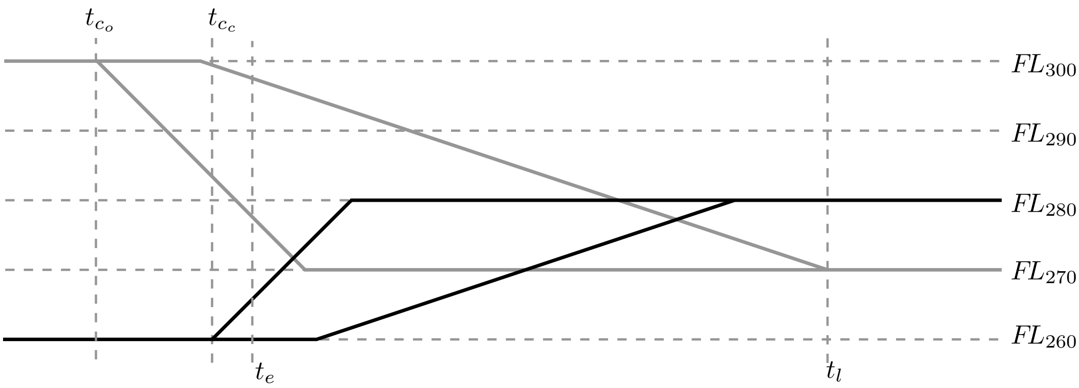
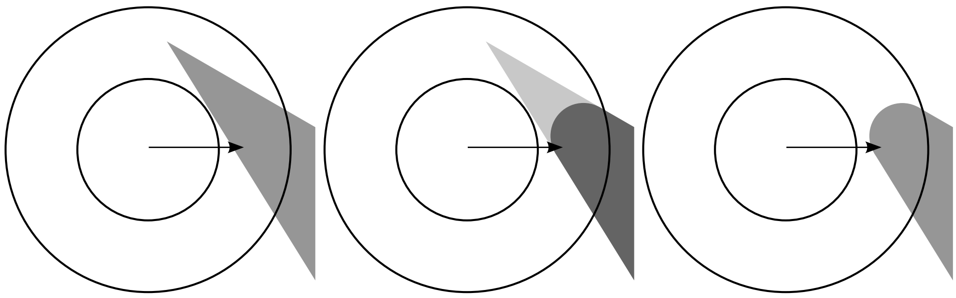


Figure 6: Time-altitude diagram for a climbing and descending aircraft

Figure 6 shows an example of a time altitude diagram for a situation where traff c is not maintaining altitude. While the higher observed aircraft is descending, the controlled aircraft is climbing. The earliest possible conf ict time, t_e, occurs when the distance between the fastest descent line and the fastest climb line become smaller than the minimum vertical separation. The latest possible conf ict time, t_l, is determined by the point at which the vertical distance of the slowest prof le becomes larger than the minimum vertical separation.

Based on the predicted conf ict time interval, the solution space can be truncated. In its most basic form, a conf ict zone shows all conf icts that can occur in a time interval from 0 s to ∞ s. The time it will take until loss of separation takes place depends on the position of the velocity vector within the conflict zone. The shorter the distance to the tip, the longer it will take. If, for example, the velocity of the controlled aircraft is exactly at the tip of the solution space, it will fly with exactly the same velocity as the observed aircraft. Therefore, both aircraft are flying in parallel and will never move closer. In other words, it will take an infinite time to get a loss of separation. Moving the velocity just a little into the conflict zone will result in a small relative velocity which will gradually bring the two aircraft closer. The further the velocity is moved into the conflict zone away from the tip, the higher the relative velocity becomes and the faster the aircraft will enter each others protected zone. Based on this principle, it is possible to truncate the conflict zone based on a time interval. In this way, only the relevant part of the conflict zone will show up in the solution space.

Figure 7 shows an example of the truncation process. Figure 7a shows the full conflict zone for a conflict ranging up to infinity. In this case, the conclict zone is a sharp triangle. As explained before, the tip of the triangle corresponds to the velocity of the observed aircraft and represents a conflict at infinity. Decreasing the range of the conflict time interval will result in a situation shown in Figure 7b. The original conflict zone is shown in light gray while the remaining part is shown in darker gray. Because of the circular nature of the protected zone, the endcap of the truncated conflict zone will also be circular. The end result of the truncation process is shown in Figure 7c.



(a) Complete Conflict Zone *(b)* Part to be truncated *(c)* Resulting truncated Conflict Zone

Figure 7: Truncation of the conflict zone

Interface prototype and proposed experimental evaluation

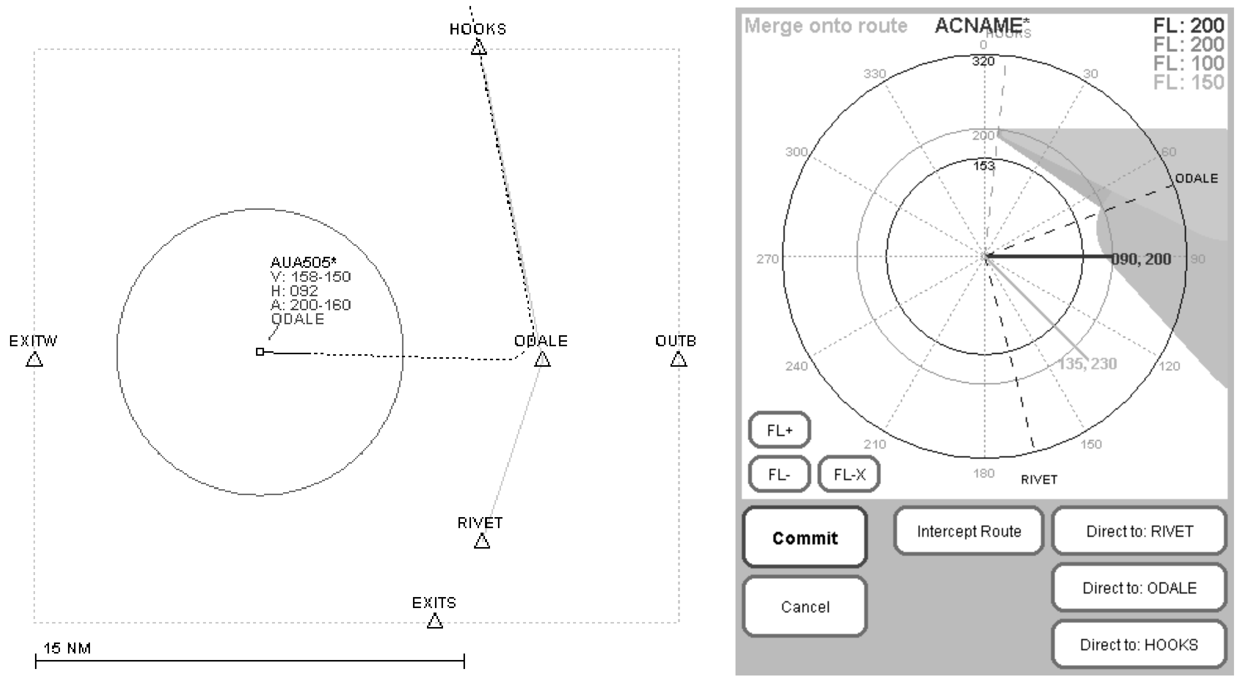
To evaluate the altitude based filtering method, an ATC simulation has been developed that incorporates the altitude extended solution space display. The simulation consists of a standard plan view display, Figure 8 (a) and a solution space diagram, Figure 8. The controller can select an aircraft in the plan view display and give the selected aircraft heading and speed commands in the solution space display like in previous experiments (?, ?). The controller can press the FL- and FL+ buttons to inspect the effect of issuing a vertical command. Once the controller is satisfied he can commit his commands and the aircraft will change its trajectory.

An evaluation experiment will be conducted to investigate the effect of including altitude information in the solution space diagram. Six subjects will take part in the experiment. They will control four different scenarios, two with a low traffic level, two with a high traffic level. The scenarios will be flown with the solution space visible or not visible. This will result in four combinations of high & low traffic and solution space on & off. At one minute intervals the test subjects will be prompted to rate their experience workload level on a scale of 1 to 5.

After each experiment condition the test subjects will be asked to fill in a questionnaire. This questionnaire aims to investigate what elements of the simulator aids in alleviating workload and generating a mental picture of the traffic situation.

Several performance metrics will be calculated from the gathered data. These metrics are for example number of separation losses during a run, number of aircraft delivered at their requested exit condition, distance of aircraft traveled through the sector versus optimal travel path and number of commands given during an experiment run.

The combination of the workload measurements, questionnaire results and performance metrics will be used to investigate the areas where the display can be improved.



(a) Plan View Display

(b) SSD Display

Figure 8: Experiment display

Conclusions

This paper presented a technique to improve the solution space diagram to assist Air Traff c Controllers in planning vertical maneuvers. Altitude based f ltering was used to determine which aircraft will never be able to get in conf ict with each other. By calculating an estimate of the earliest and latest time an aircraft can reach an altitude, the conf ict zones can be truncated to remove even more irrelevant information.

These techniques were used to develop a simulation which will be used to conduct an evaluation experiment. This experiment will use scenarios with varying complexity to assess the benef ts of an altitude extended solution space display.

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