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Development of a Time-Space Diagram to Assist ATC in Monitoring Continuous Descent Approaches

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1. Introduction

Continuous Descent Approaches (CDA) have shown to result in considerable reductions of aircraft noise during the approach phase of the flight (Erkelens, 2002). Due to uncertainties in aircraft behaviour, Air Traffic Control (ATC) tends to increase the minimum spacing interval in these approaches, leading to considerable reductions of runway capacity (Clarke, 2000). To enable the application of such procedures in higher traffic volumes, research has advanced in the creation of airborne tools and 4-dimensional prediction algorithms.

Little research has addressed the problem of sequencing and merging aircraft in such an approach, however. In this chapter we present the Time-Space Diagram (TSD) display that shows the aircraft along-track distance to the runway versus the time. On this display, the in-trail separation is presented as the horizontal distance between two predictions. It is hypothesised that this display will enable the air traffic controller to meter, sequence and merge aircraft flying a CDA at higher traffic volumes. In this chapter, the TSD will be introduced and the effects of various common separation techniques on the predictions of the display are discussed in detail. The display is currently being evaluated by actual air traffic controllers in a simulated traffic scenario to provide an initial validation of the design.

2. Problem statement

Aircraft noise is considered to be the most important cause of resistance to increases of flight operations and the expansions of airports (Dutch Ministry of Transport, Public works and Water Management, 2006; UK Dept. for Transport White Paper, 2003). CDA's such as the Three-Degree Decelerated Approach (TDDA) have shown to considerably reduce the aircraft noise footprint during approach (Clarke et al., 2004). In this particular procedure, aircraft descend along a continuous 3°glide slope at idle thrust (Clarke, 2000; De Prins et al., 2007).

The speed profiles of the descending and decelerating aircraft, however, are highly influenced by the aircraft types involved, the atmospheric conditions (wind in particular), and crew responses. The nature of the procedure, combined with the uncertainties in predicting the air-

craft trajectories, currently require air traffic controllers to increase initial spacing to assure separation throughout the approach (Clarke, 2000; Erkelens, 2002).
The 3°glide slope further requires the aircraft to fly a fixed lateral route from the top of descent (TOD). After this point, ATC can no longer give lateral instructions without compromising the TDDA. Once idle thrust is selected, the aircraft will not be able to change its speed profile without increasing thrust, or changing its configuration, and speed instructions from air traffic controllers are highly undesirable. In the example of a TDDA procedure starting from 7,000 ft (Clarke, 2000; De Gaay Fortman et al., 2007), this prevents ATC instructions from 22.1 nm to the threshold. Therefore, ATC has to space aircraft accurately beforehand, in such a way than the separation will not fall below the minimum required throughout the remainder of the approach. In order to do so accurately, controllers must be able to predict the future spacing over the remaining aircraft trajectory from the current aircraft position to the runway, and work on these predictions. Without some automated support, however, this is an impossible task.
The objective of this chapter is to discuss the potential benefits of a novel display for air traffic controllers. The Time-Space Diagram (TSD), as it is called, provides the aircraft 4-dimensional trajectory information to the controller. To this end, these predictions will be assumed available, and the means nor the accuracy of such predictions will be addressed within the scope of this work. It will be shown that when the aircraft trajectory predictions are available, the problem is reduced to one of obtaining a meaningful graphical representation.
The chapter is structured as follows. Section 3 will explain the task of ATC and the current availability and use of 4-dimensional trajectory information. Section 4 describes how, by reducing the 4-dimensional problem to a two dimensional one, the controller can be provided with the predicted separation on a two-dimensional display. The effect of instructions given by ATC to aircraft can now be translated to changes of the representation of the trajectory. The implementation of the display would require some adjustments to current procedures. As this display can only show trajectories to one runway, separation from other traffic needs to be ensured by other means.

3. ATC in CDA procedures

According to Annex 11 to the Convention on Civil Aviation (ICAO, 2003), the primary goal of ATC is to provide service for the purpose of safe, orderly and expeditious flow of traffic. In approach control, this task can be described as minimising delays while maintaining sufficient separation between the aircraft. During the TDDA, the in-trail distance between two approaching aircraft should therefore reach, but not go below, the minimal distance required. To achieve this, the primary tool common to all approach controllers is the two-dimensional Plan View Display (PVD). This screen shows the, mostly radar-derived, planar positions of the aircraft combined with numeric data on their velocity and altitude. Using this data, the Air Traffic Controller (ATCo) builds a mental model of the traffic scenario, commonly referred to as the "picture" (Nunes & Mogford, 2003). By mentally predicting the trajectories of the aircraft on the screen, the controllers can anticipate on the future spacing and select the appropriate actions to adjust spacing if necessary. The certainty of predicting the aircraft future positions depends on the skill of the controller, the behaviour of the aircraft involved and the length of the interval over which the prediction is made (Reynolds et al., 2005).

3.1 Controller prediction accuracy in TDDA

In a TDDA, aircraft will decelerate at different rates. Research with actual controllers has shown that humans perform rather poorly in estimating separation in such scenarios (Reynolds et al., 2005). Furthermore, it is likely that approach routes merge within a distance of 22nm from the runway threshold. Two aircraft that land in sequence might not need to be in trail at their TOD. The actual spacing may therefore not be observable from the conventional PVD.
Implementation of continuous descent procedures requires controllers to predict spacing over a longer horizon with a reduced certainty of aircraft behaviour. In implemented CDA procedures at Amsterdam Schiphol airport, ATC was required to increase the landing interval from 1.8 to 4 minutes (Erkelens, 2002). Currently, the resulting 50 percent reduction of capacity prevents the use of the procedure outside night hours, as the required daytime capacity can not be met (Hullah, 2005).

3.2 4D Navigation technologies

Developments in aircraft Flight Management Systems, communications and prediction algorithms enable new procedures which are based on four-dimensional trajectory predictions. In flight trials at Amsterdam (Wat et al., 2006) and San Francisco (Coppenbarger et al., 2007), long term predictions have shown to achieve accuracies in the order of seconds when predicted at cruise level. In those trials, ATC provided CDA-clearances based on those predictions. The availability of 4D trajectory predictions and the ways to communicate them, have proven to be technologically feasible.
Research at Delft University of Technology has shown promising results in maintaining separation during CDA procedures using airborne trajectory prediction. In these trials, pilots were provided with the predicted spacing with the aircraft in front of them (In 't Veld et al., 2009). Using this information, the pilots could adjust their speed profile to achieve but not go below minimal separation.
However, research has also shown that such procedures will only achieve optimal spacing when the initial spacing is already close to that optimum (De Leege et al., 2009). Furthermore, these scenarios have assumed all aircraft on a single approach path, not requiring merging of different streams. If ATC is to assist such procedures, it will have to establish this optimum spacing by metering and merging all aircraft from all routes.

3.3 4D Information available to ATC

The current approach control systems use – ground-based – 4D predictions. These predictions mostly provide controllers with Estimated Time of Arrival (ETA) at the runway threshold. Using the prediction at the threshold, the controller can then establish the required spacing.
Spacing using these tools implicitly requires that minimal separation is achieved at the threshold. Analysis of different aircraft in TDDA scenarios has shown that minimal separation might occur at an earlier point in the approach (De Leege et al., 2009). When the tools indicate a predicted separation violation, the controller is not aware of the moment at which this violation occurs for the first time. Therefore, controllers can not apply an appropriate technique to adjust spacing as one has no indication of the available time and distance.

4. Providing predicted spacing information to ATC

The current ATC system relies on flexible routing of aircraft in the final stages of the approach. In this segment, ATC uses procedures which are often only defined the local ATC manuals.

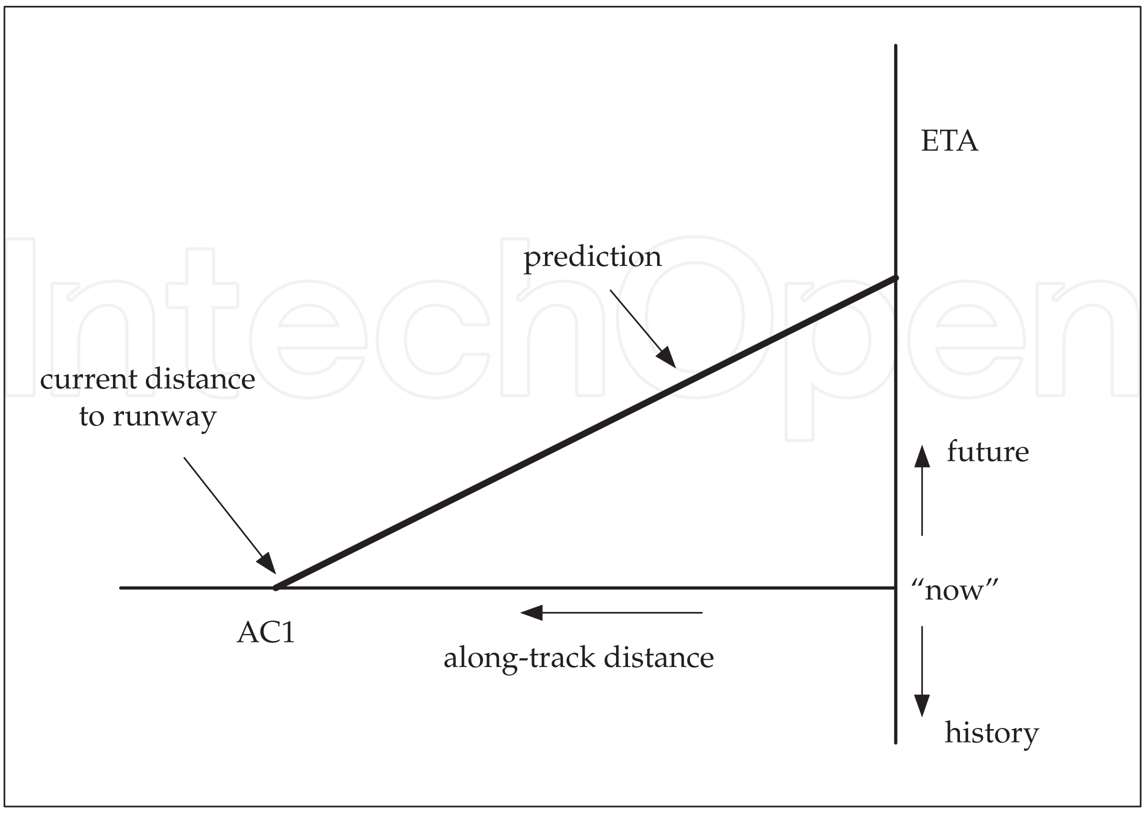


Fig. 1. The basic elements of the Time-Space Diagram (TSD).

Using these procedures, the approach controller is capable of metering, sequencing and merging the inbound flows of aircraft while maintaining separation.

The need for more consistent routing has prompted a move toward more rigid trajectories (EUROCONTROL, 1999). By 2006, over 1,500 aircraft in the European airspace were compliant to this navigation standard, which included 95% of the flights at airports like Amsterdam Schiphol and London Heathrow (Roelandt, 2006). With the advent and progressive implementation of Precision-Area Navigation (P-RNAV), and hence predictable and feasible lateral trajectories, more complex procedures like the TDDA may be realised (Erkelens, 2002).

4.1 Time-Distance Diagram

As the TDDA has a known lateral and vertical trajectory, the position of the aircraft can be defined by its distance to the runway. For all aircraft, the TSD (De Jong, 2006) plots the aircraft's distance to the runway versus the expected time at that distance, see (Figure 1). The figure shows a situation where an aircraft flies at constant ground speed to the runway. Typically, aircraft decelerate during the approach which would mean that the trajectory prediction in time/space is not a straight line but curved. Flying faster means that the line becomes less steep, as more ground is covered in less time. Flying slower means that the curve becomes more steep, as here less ground is covered per unit of time. Note that although only straight lines are shown in the following figures, to illustrate the basic concepts, generally the time/space trajectories of decelerating aircraft will be curved more steeply when closer to the runway threshold.

When the time/space trajectory can be shown for one aircraft, based on the trajectory predictions, the same can be done for the other aircraft. Consequently, the required in-trail separation distance can be represented as an *area* between a particular aircraft pair. Figure 2(a) shows this area, created by offsetting the leading aircraft's prediction with the distance required between the two aircraft. The goal of the controller will now be to avoid any trajectory to fall within such a separation area of another trajectory.
When a prediction falls within the separation area, a separation violation occurs. However, this does assume that both aircraft are on the same trajectory. When two aircraft are on different, but merging, routes this assumption is not valid. The conflict occurs when both aircraft have joined the common remainder of their approach. To indicate this point, the different tracks are represented below the graph, see Figure 2(b), with an indication of the aircraft on the horizontal line representing its route. For a conflict that starts when two aircraft merge, the location of that merging point indicates the remaining time and distance to resolve a predicted conflict. Using this information, the controller can select an appropriate technique to adjust spacing.
The required in-trail separation between the approaching aircraft is mainly dependent on the aircraft wake turbulence categories. The size of this separation area depends on the types of aircraft involved. To enable an early assessment of changing the aircraft arrival sequence, all possible separation minima behind the aircraft are indicated. The target separation distance, based on the *current* sequence at the threshold, is indicated by a fill area (Figure 3).

5. ATC options on the TSD

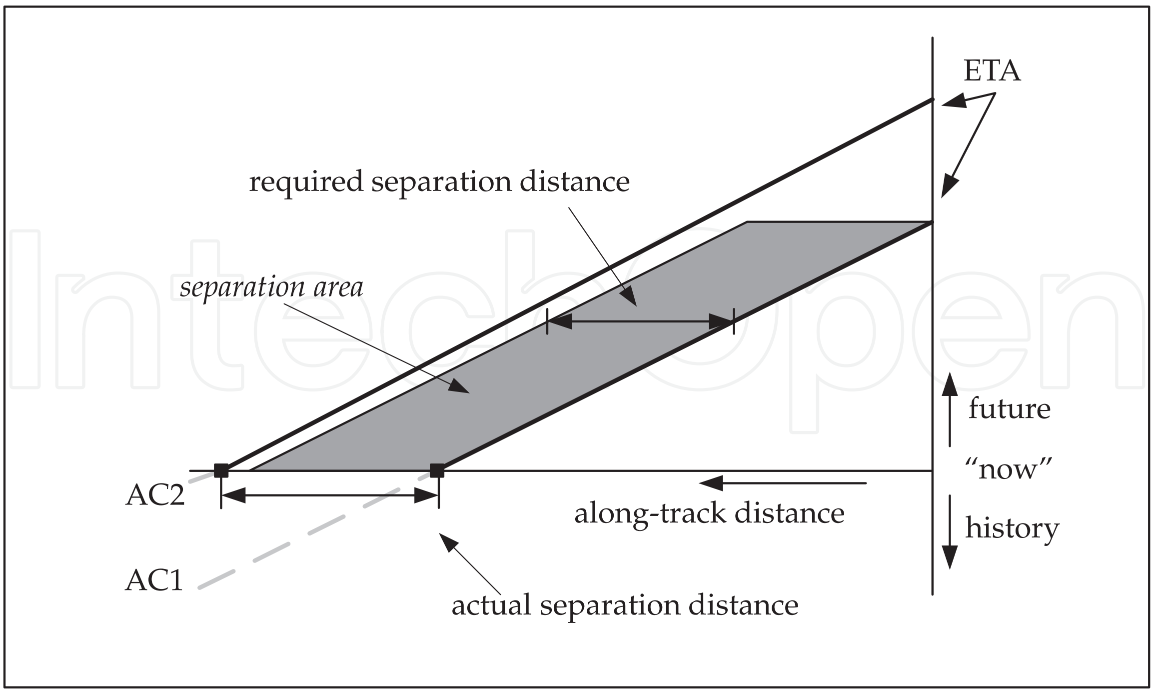
When instructions from the ATCo are executed, the predictions change according to the new state of the aircraft. This state includes the aircraft positions and velocities, as well as the changed speed profile and lateral trajectory. The instructions can now be divided into three categories based on their effect on the 4-dimensional trajectory.

5.1 Speed instructions

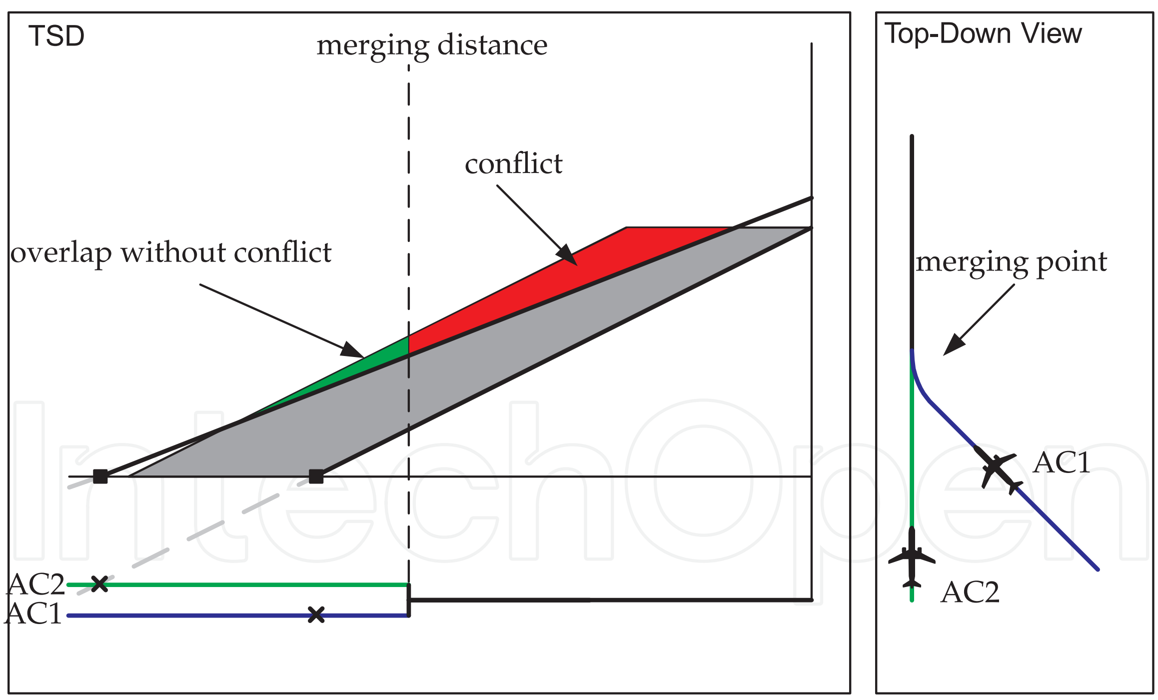
An *increase* of speed is unlikely during the approach phase of the flight. A speed instruction during approach will therefore imply the reduction of the constant speed before the deceleration phase of the TDDA. The reduction of speed translates to the increase of the slope of a prediction. Figure 4 shows two possible scenarios in which merging traffic is predicted to conflict. A similar application of speed reduction in both situations only resolves the conflict in one of the two scenarios. The figure also demonstrates the advantage over an indication of the arrival time only. Both situations are resolved and identical at the threshold, but Figure 4(d) shows that a conflict is still predicted at the merging point. In this figure, note that in all cases the effect of the speed instruction was identical in arrival times and resolved the conflict at the runway threshold. An indication of the separation at only the runway threshold would not have indicated the existence of the last conflict.

5.2 Changes to the planned route

The use of P-RNAV trajectories does not prevent the use of lateral instructions. As long as those instructions are given before the TOD of the TDDA, they can be used for spacing purposes. Crucial in this technique is the direct inclusion of the new routing in the prediction.
The second set of conflict possibilities includes 'directs to' waypoints further down the route, effectively providing shortcuts, see Figures 5(a) and 5(b). This set also includes holding patterns that consist of a known lateral trajectory. In the first case, the predictions will instantly



(a) The basic Time-Distance representation. Note that all predictions are drawn as straight lines for the sake of clarity.



(b) Overlapping predictions that indicate a conflict once both aircraft have merged on the common remainder of the approach. The positions of the aircraft are indicated on the 'now'-axis as well as on the line representing their routes.

Fig. 2. The Time-Space Diagram concept, including separation minima. Note that here and in the following figures, the 'top-down' views are included for the sake of explanation, they are not included in the TSD.

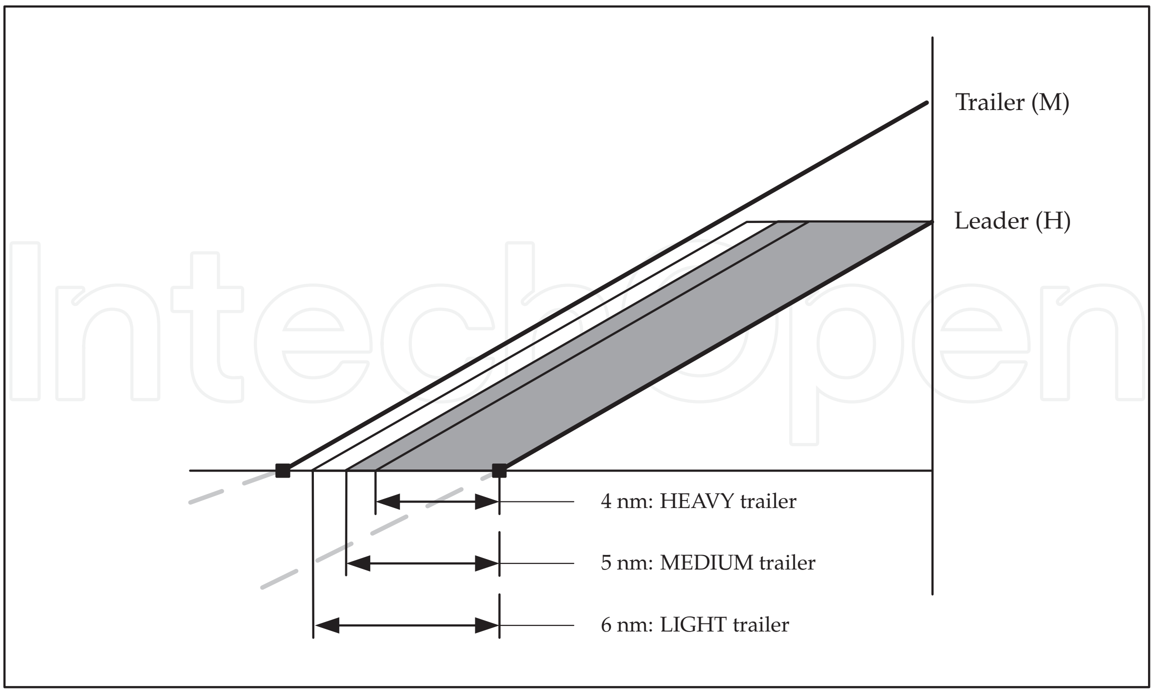


Fig. 3. The indication of separation minima based on wake turbulence categories. The current pair of aircraft (HEAVY (H) leader, MEDIUM (M) trailer) requires an in-trail separation of 5 nm according to ICAO Doc 4444 - PANS-ATM Section 8.7.4.

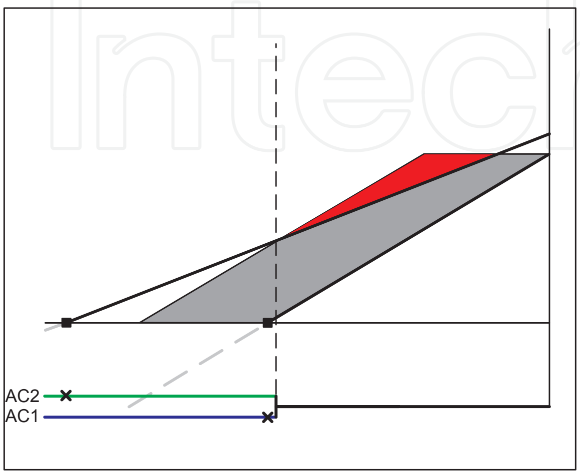
shift to the left on the TSD. In the latter, the prediction will instantly shift to the right, see Figures 5(c) and 5(d).

5.3 Temporarily abandoning the planned route

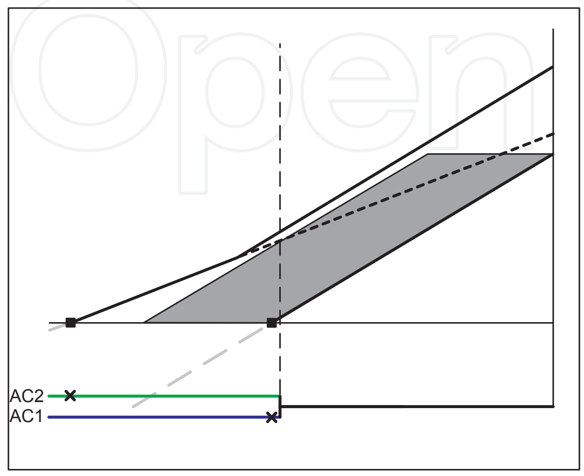
In current approach operations, many separation adjustments are done using vectors. The aircraft are issued a heading and will be returned to the planned route when the required spacing is attained. Although such heading instructions reduce the correlation between the distance to the runway and the location of the aircraft, they can be used in combination with the display. These instructions require the aircraft to predict the lateral trajectory starting at their present position and heading. The initial segment of the trajectory then includes a return to the route and the continuation of the route at that point, see (Figure 6). The advantage of this technique is that the separation is adjusted smoothly and the controller does not need to estimate the size of the shifts made in the speed and routing instructions.

6. Safety issues

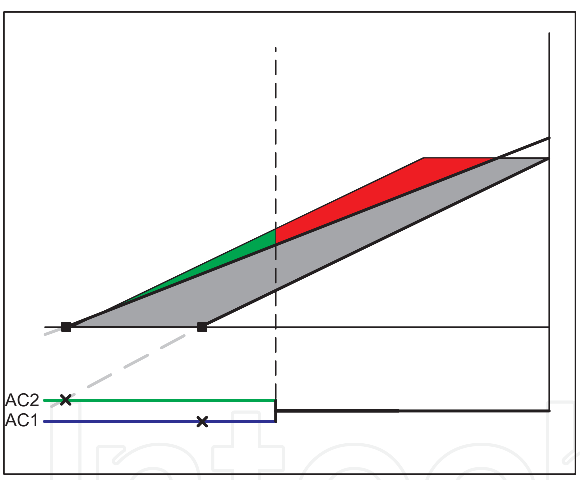
The TSD only shows the in-trail spacing between aircraft that fly toward the same runway. It is not possible to provide a meaningful representation of other aircraft on the display. Furthermore, sufficient in-trail separation does not imply that the aircraft are actually separated. The latter can be demonstrated by two examples. Figure 7 shows a geometry that might provide sufficient along-track separation while the aircraft are actually flying head-on. A second problem occurs when the ground track intersects itself. This might be needed in confined airspace such as when in the vicinity of mountainous terrain. In such procedures, vertical separation is



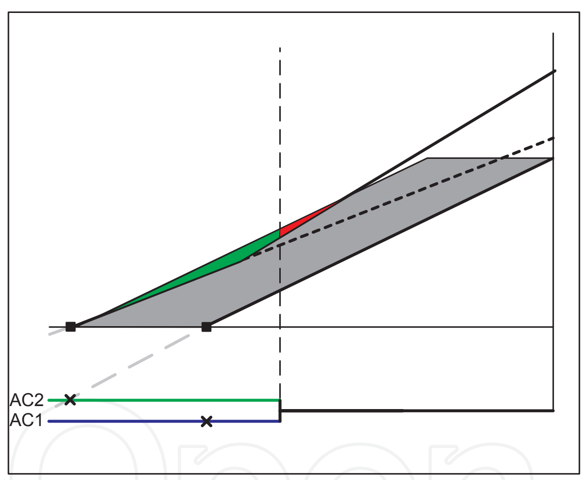
(a) Conflict 1: Aircraft 2 flies faster than aircraft 1.



(b) Resolution 1: By reducing the speed of aircraft 2, the conflict is resolved.

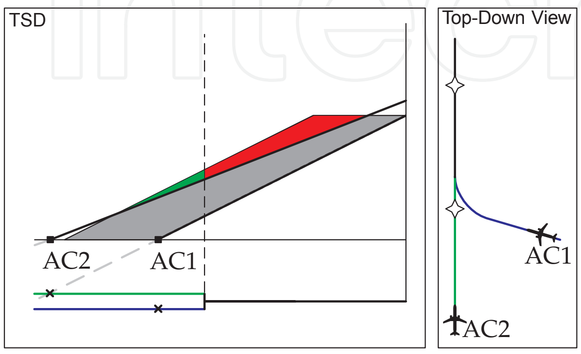


(c) Conflict 2: Similar to conflict 1, but now aircraft 1 is flying a little faster and the initial separation is smaller. A conflict occurs when both aircraft merge on the remaining track.

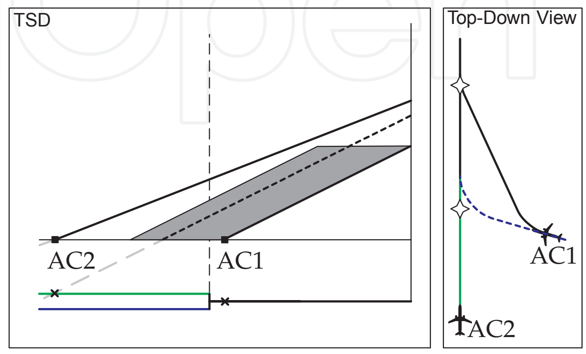


(d) Resolution 2: A separation violation still occurs after the aircraft have merged.

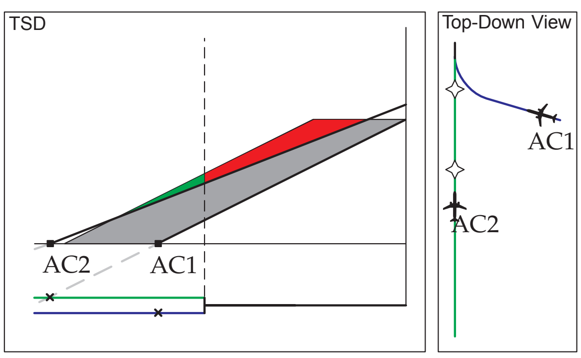
Fig. 4. Conflicts' resolution through a speed reduction. The slanted dashed lines in the right hand figures represent the original aircraft trajectories.



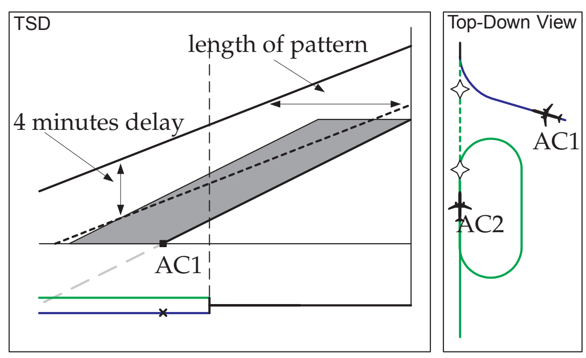
(a) Conflict 3: aircraft 2 flies faster than aircraft 1, and a conflict occurs when both aircraft merge on the remaining track.



(b) Resolution 3: aircraft 1 is directed to the next waypoint and shortens its route to the runway.

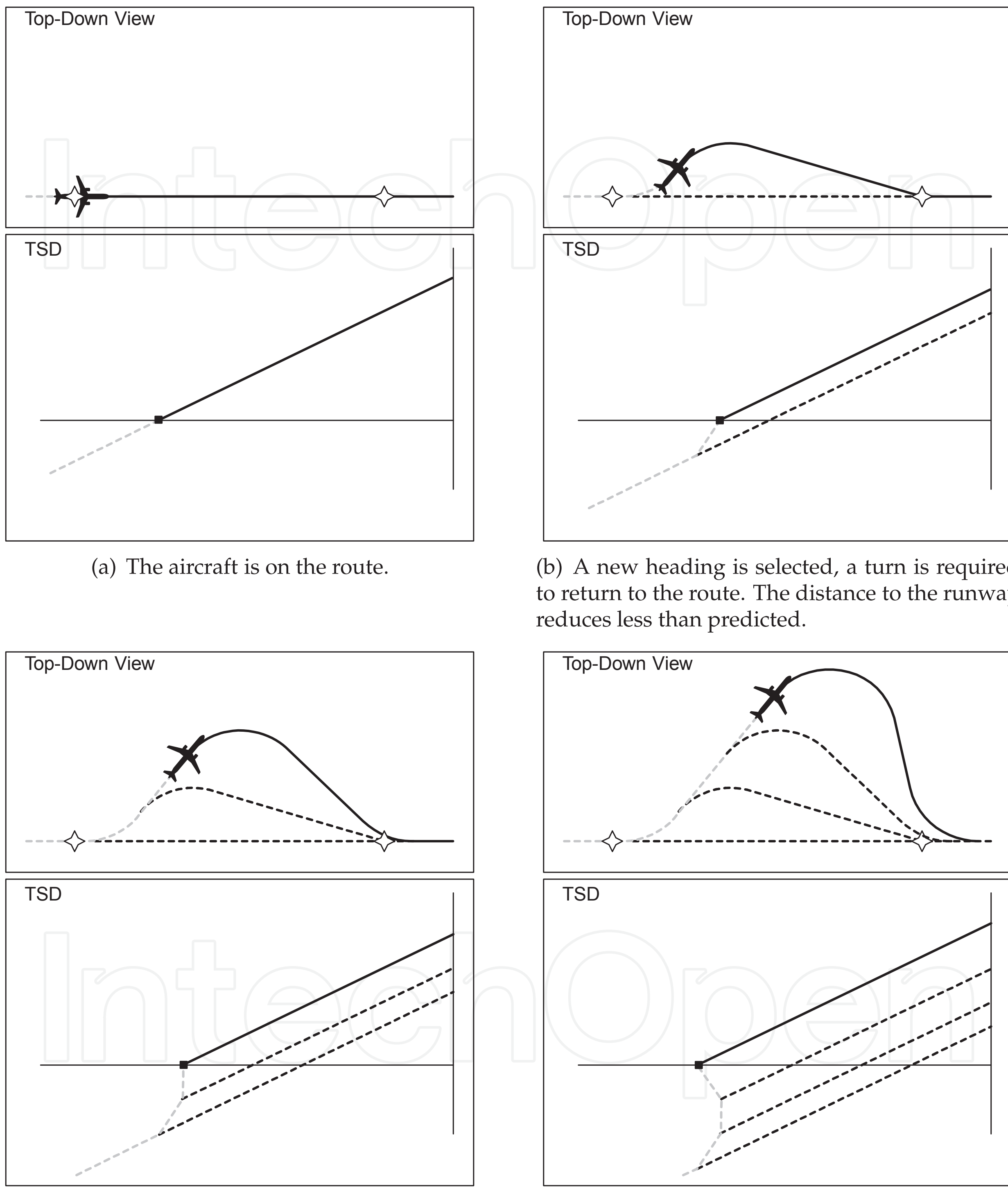


(c) Conflict 4: a situation identical to conflict 3.



(d) Resolution 4: aircraft 2 is instructed to enter the holding pattern, delaying it by 4 minutes. The delay is indicated by a shift upward of 4 minutes (or, equivalently, a shift to the left by the path length of the holding pattern).

Fig. 5. Conflicts' resolution through lateral instructions. The first resolution provides a solution without causing a delay and would be preferred. The slanted dashed lines on the resolutions indicate the original trajectories of both aircraft.



(a) The aircraft is on the route.

(b) A new heading is selected, a turn is required to return to the route. The distance to the runway reduces less than predicted.

(c) The distance to the runway no longer changes.

(d) The distance to the runway starts increasing.

Fig. 6. The effects of a heading instruction and the timing of the return to the planned route. The older predictions have been indicated by dotted lines to illustrate the motion of the predictions on the screen.

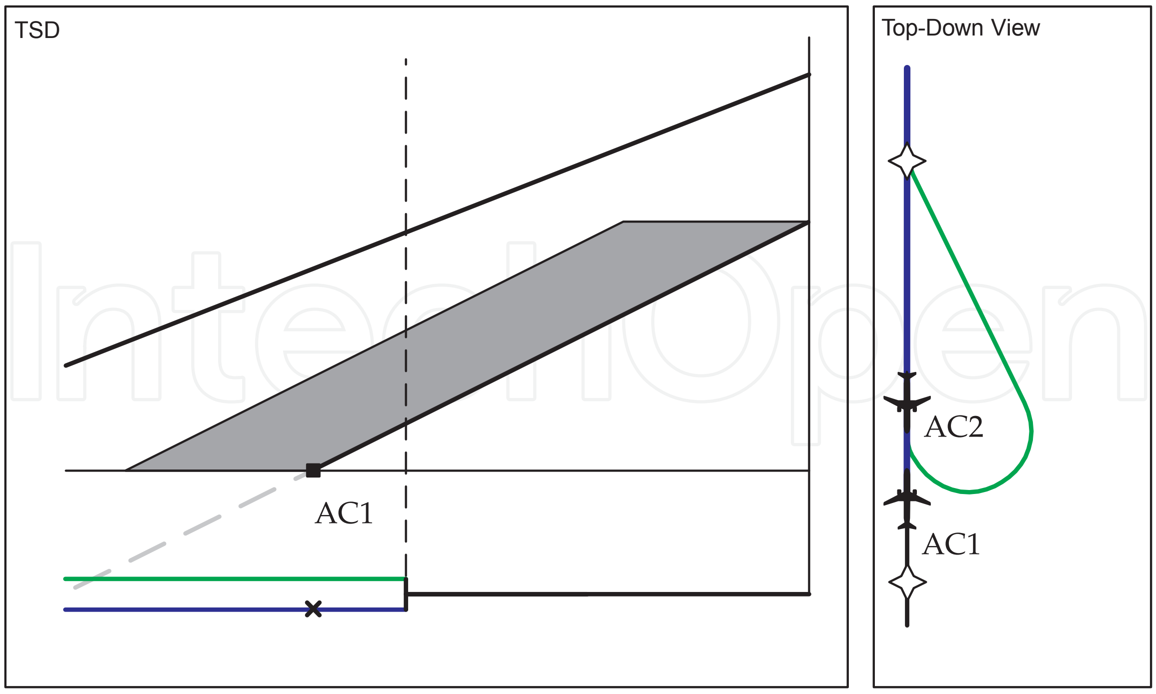


Fig. 7. A conflict geometry in which aircraft fly head-on while having sufficient along-track separation.

applied between the intersecting segments. However, the TSD can not show violation of the vertical trajectory.

Both the risks of undetected conflicts within the participating traffic as well as conflicts with other traffic, imply that the TSD should not be used without the PVD as currently used by ATC. Even more so, the PVD should be used as the first tool to assure separation, whereas the TSD should be used to adjust spacing such that the use of the runway can be maximised while still executing TDDA.

7. Procedural consequences of the TSD

In current P-RNAV operations, the radius of the turns is not defined. This radius nowadays depends on the actual airspeed and ground speed, altitude and company policy. The TSD relies on the comparability of the along-track distance. The ground track should therefore be identical for all aircraft at the same point on the route. Therefore, the turn radius should be specified in the approach procedure.

The use of vectors to adjust spacing must allow aircraft to leave the known trajectory. To allow this, while still providing a useful prediction, the trajectory algorithm should assume that the aircraft will return to the next waypoint on the route.

The requirement that all trajectories must have the same endpoint implies that the display can only be used for a single runway. For airports with multiple runways, the approach controller should be either assigned to one runway or needs more than one TSD. Currently, a version of the TSD is being developed that supports the use of more than one runway.

As this procedure is based on the exact following of paths, the airspace that is needed for the approaching aircraft can be accurately defined. The safety and procedural consequences of

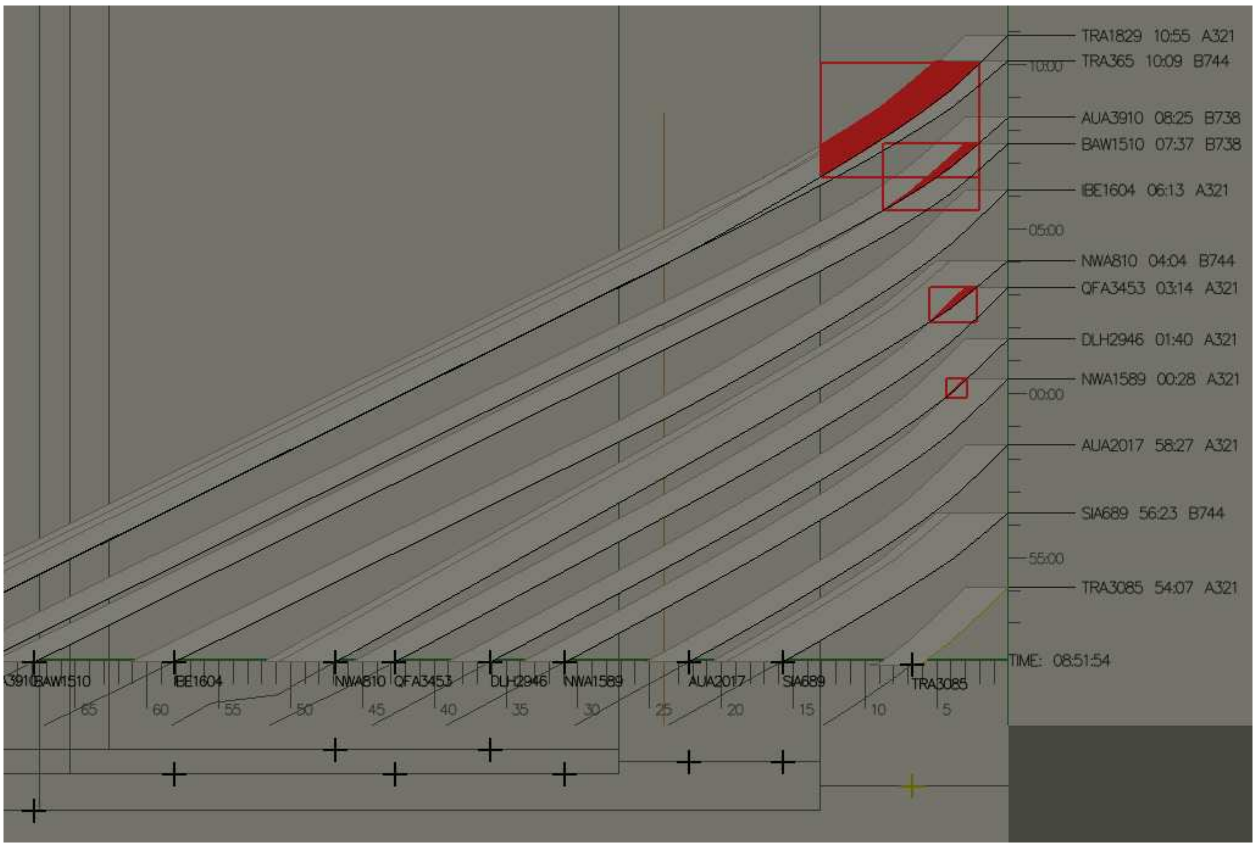


Fig. 8. The time space diagram displays as implemented in the simulator.

the display might be addressed through a restructuring of the airspace. Separation from other traffic could then be assured using airspace violation detection.

8. Future work

This chapter has presented the initial design of the Time-Space Diagram (TSD) display. It is hypothesized that the TSD, through the visual presentation of the 4D trajectory predictions of aircraft conducting a continuous descent approach, supports air traffic controllers in their task of safeguarding sufficient separation, while optimizing runway throughput.

The TSD has been implemented in DUT's real-time air traffic management simulator, and is currently being evaluated with experienced air traffic controllers. Figure 8 shows the Time-Space Diagram display as used in the evaluation.

The main questions that we hope to answer with the experimental evaluation are whether the work of the air traffic controller *changes* when operating with an additional display, and the user acceptance. It can be expected that, since the TSD provides information on the display that is currently not available with conventional plan view interfaces, the air traffic controllers will need to learn how to use the information correctly. Hence, different strategies may emerge from using the TSD. Second, it is important to investigate whether air traffic controllers will accept the introduction of a new interface in their workspace, and whether they will indeed appreciate and use the additional information that is provided.

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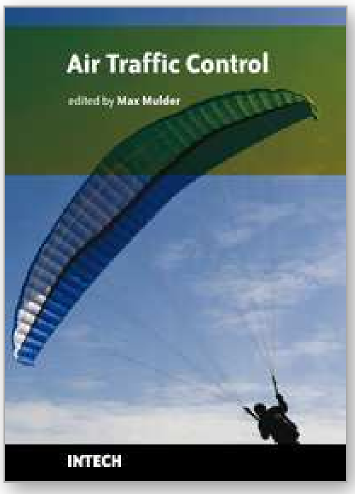

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Improving air traffic control and air traffic management is currently one of the top priorities of the global research and development agenda. Massive, multi-billion euro programs like SESAR (Single European Sky ATM Research) in Europe and NextGen (Next Generation Air Transportation System) in the United States are on their way to create an air transportation system that meets the demands of the future. Air traffic control is a multi-disciplinary field that attracts the attention of many researchers, ranging from pure mathematicians to human factors specialists, and even in the legal and financial domains the optimization and control of air transport is extensively studied. This book, by no means intended to be a basic, formal introduction to the field, for which other textbooks are available, includes nine chapters that demonstrate the multi-disciplinary character of the air traffic control domain.