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# Designing future advanced controller displays

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## Summary

This paper describes the design of an advanced human-machine interface for well-trained, professional users, i.e. air traffic controllers. The safety implications of their tasks, combined with the short reaction time available to the user, result in high demands on the interface between the human and the supporting information system. The increasing demand for air traffic capacity (which can not be accommodated by just deploying more personnel as the additional co-ordination offsets the workload reduction) necessitates the introduction of innovative support tools to prevent human overload. Experience with the introduction of such tools stresses the need to design their user interface using a “human-centred approach”, contrasting with the traditional “technology-centred approach”.

# Contents



(22 pages in total)

# 1 Introduction

During peak hours at a major airport there is an almost continuous stream of arriving and departing aircraft. Watching all movements at and around the airport (out of interest or because your flight has been delayed) you may wonder about its organisation. How are all these aircraft kept at a safe distance from each other? How are aircraft coming from different directions merged into one stream for each runway? Why has your flight been delayed?

To answer such questions one has to step into the world of Air Traffic Control (ATC). Invisible to the general public, air traffic controllers (further referred to as *controllers*) watch all aircraft in a designated part of the air and direct the pilots on the most safe and efficient route to their destination. Essential to perform this work are radar, display systems and Radio/Telephony (R/T). Radar (derived from *ra*dio *d*etecting *a*nd *r*anging) detects, locates and identifies aircraft. These observations are combined with additional information and presented to the controllers on radar displays: large computer screens (typically 50x50 cm, 2048x2048 pixels) that show aircraft as little symbols on top of a map of the area. R/T allows a controller to communicate with the pilots of the aircraft in his airspace.

With the help of these tools, controllers maintain a mental picture of the situation in their airspace. Currently, a pilot flying through this airspace has only a limited awareness of the situation around the aircraft, since the full radar picture is not available in the cockpit. For a safe and expeditious flight the pilot therefore depends on the controller's overview of the whole airspace.

The pilot controls the aircraft and navigates from departure to destination airfield. Of course he would like to follow the shortest possible route. Many restrictions interfere with this wish. Parts of the airspace are in use for military operations, or closed to air traffic because they are situated above special objects, like nuclear power plants. Around airports the use of airspace has to be strictly arranged to allow aircraft to descend and take off while taking environmental concerns (like noise and risk) into account. And finally, before the introduction of modern navigation systems, keeping an aircraft flying on track was a difficult problem. Traditionally, pilots navigate using beacons that transmit radio signals. Equipment in the aircraft uses these signals to detect deviations from the required course and to measure the distance to the beacon.

As a consequence, almost all aircraft fly along predetermined routes, which act as highways in the sky. To maintain safety, aircraft must keep a minimum distance (*separation*) from each other, both horizontally and vertically. Maintaining safety by ensuring separation and allowing pilots to fly the most efficient route are the most important tasks of a controller.

Over the last decades ATC and the encompassing field of Air Traffic Management (ATM) have evolved into a set of finely tuned interactions between controllers, procedures and systems. The resulting controller display is defined based on extensive experience with displaying a relatively limited set of available radar and flight plan information. Saturation of the air transport system, combined with limited opportunities to increase the capacity based on current practice, provide the economic incentive to innovate ATM. This can only be done by deploying advanced support tools complemented by innovative displays.

In a “human-centred” ATM paradigm, the displays that convey traffic information to a controller form an essential component of the total system. With the advent of various advanced ATM tools, the controller can be provided with a lot of new and potentially useful information. Every tool developer is acutely aware of the fact that a tool's success critically depends on its interaction with the controller and its integration with the ATM concept. As in any safety conscious industry, there is a tendency to rely on proven technology above promising, but unproven, new concepts and solutions.

ATM tool developers traditionally do not base their human-machine interface (HMI) on an underlying theory for the total controller task. HMI designs tend to focus on subtasks instead and are often based on what can be done practically and efficiently, using the HMI of the existing target system as a constraint. This approach is known as the “technology-push” or “technology-centred” approach. The alternative to the technology-centred approach is the human-centred approach to system design, which starts by defining the characteristics of the underlying concept. Based on the characteristics, an integrated view of the user’s task is developed, including his interactions with the supporting tools.

The next chapter contains a cursory overview of an operational ATM concept plus a short description of its implementation and the conducted experiment. The main chapter, entitled *Description of advanced display design* contains a detailed discussion of all components of the HMI design. Subsequently, the *Case analysis* chapter provides the analysis from a technical perspective, while the last chapter summarises the conclusions.

# 2 Air transport context description

## 2.1 Operational ATM concept

ATM research centres of the UK, France, Germany and the Netherlands, plus EUROCONTROL Experimental Centre, combined in the PHARE consortium, initiated a real-time simulation of a future ATM concept supported by a number of innovative tools. The main concept enhancements relevant to this paper were:

- integration of the air and ground systems;
- support of pilot and controller with automated tools while retaining the human in-the-loop paradigm;
- *4D-trajectory negotiation* and planning in a multi-sector environment.

The concept of a 4D-trajectory is new and contrasts with the traditional way of navigating described in the introduction. Instead of being restricted to existing beacons and airways, new equipment (like satellite navigation systems) allows position determination all over the globe with a high degree of accuracy. The degree of accuracy provided is sufficient for aircraft navigation, except for the landing phase, where additional equipment is required. As a consequence the most efficient route can be used for every individual aircraft. Starting with a straight line from departure to destination airport, the controller adds the minimum number of deviations required to avoid closed airspace and bad weather and to maintain the required distance between all aircraft.

For turning points along the resulting route, the controller can establish a time at which the aircraft will have to pass such points. The combination of three-dimensional route and time constraints is called a *4D-trajectory*. The 4D-trajectory will be a treated as a contract between controller and pilot. Using computers and digital communication they can exchange several trajectories until both parties are satisfied. This process is called trajectory negotiation. Once the negotiation is completed, the pilot is responsible to comply with the 4D-trajectory.

To share aircraft information with the ground system, a digital communication channel (data link) is used instead of currently used voice communication. With the same high quality information becoming available to both the pilot and the controller, automated tools can be utilised to reduce workload and enhance situational awareness. One example is a flight path monitor, which verifies whether actual position updates from the radar comply with the agreed 4D-trajectory. Other examples are long-term conflict detection and resolution tools (e.g. with a look-ahead time of 5 to 20 minutes) and arrival/departure schedulers.

To ensure that all these elements which gather, communicate and process information can work together and can be visualised to pilot and controller in a consistent and intuitive way, a coherent, human-centred ATM concept has been established. Automated tools provide pilot and controller with a visualisation of an aircraft's 4D-trajectory and allow these users to obtain more information of and make modifications to the 4D-trajectory. Using the data link, trajectories are automatically communicated and negotiated between the ground systems and the aircraft involved. All advanced tools work on the basis of these 4D-trajectories.

The same integrated, human-centred approach is also used for the design of the controller HMI. As a result, information is combined and shown as much as possible in the familiar radar display. When information is shown in more than one window, this is done in a consistent way. Selecting one instance of the representation will also highlight all other instances in all windows (Jackson, Pichancourt, et. al. August 1997). As a result, the controller HMI becomes more intuitive which reduces learning time. Inconsistencies between different representations of the same information are avoided. More information on the operational concept can be obtained from (NLR/EEC/CENA, 1997a; 1997b; Wilson, 1998) and the website of Eurocontrol (http://www.eurocontrol.be/projects/~eatmp/phare).

An implementation of all these enhancements, called the PHARE Demonstrator 3 (PD/3), has lead to a prototype of an ATM environment capable of dealing with predicted 2005-2015 traffic levels (NLR/EEC/CENA, 1997a). This represents a 150% increase over 1995 levels (Post, 2000).

### 2.2 Experiment description

Due to the inherent complexity and safety implications of ATM systems, a new ATM concept needs to be verified before it can be deployed in the real world. The large amount of detail needed for a realistic assessment requires large real-time simulations to arrive at a judgement on the proposed concept (Kjaer-Hansen, 1998), while (Post, 2000) even states that a full understanding of the operational concept only comes when a real-time simulation is available. The findings discussed in the following two sections would not have been obtained in a less realistic environment, confirming the need for such costly exercises.

To indicate the effort of executing a major real-time simulation, 25 controllers from 8 countries evaluated the tool-cluster at NLR during the experiment, which consisted of 3 measured sectors complemented by 8 feeder sectors. (A *sector* is a part of airspace under control by one controller.) 15 “pseudo” pilots controlled up to a total of 300 aircraft complemented by real pilots flying a research aircraft.

From an operational perspective the experiment required the integration of a number of tools, like a trajectory predictor (that calculates 4D-trajectories using aircraft data) and the mentioned flight path monitoring and conflict prediction tools, and the controller’s HMI.

Most of these tools, with the exception of the HMI, were developed in different European research centres using the technology-centred approach. They were subsequently integrated into a tool-federation on NLR's ATC Research Simulator (NARSIM). NARSIM's client/server based architecture (called GEAR), has been designed to facilitate the integration of various components, even when supplied by different organisations. The experiment contained 29 different server types, with up to 15 concurrent incarnations of a single server type. The HMI integrates all system communication with the controller, that is, for the user it is the glue of the system.

From an ATM point of view the experiment was successful. During the evaluations, controllers mentioned feeling confident about handling the expected air traffic volumes for the period 2005-2015. A more elaborate description of the ATM aspects is provided in (Kesseler and Knapen, 2000).

# 3 Description of advanced display design

## 3.1 Design guidelines

In order to appreciate the functions and complexity of the HMI, its design will be described in more detail. For some design features the design rationale and the evaluation will be provided. Overall, the design is based on the premise that the controller is highly skilled, well trained, and depends on the HMI for his safety provision task. These aspects will not be elaborated further.

The following design guidelines were developed in (Karat, Campbell, Fiegel, 1992). to ensure usability:

- use a simple and natural dialogue
- provide an intuitive visual layout
- speak the user's language
- be consistent
- provide feedback
- provide shortcuts
- allow user customisation
- minimise mode effects
- support input device continuity.

### 3.2 General display design features

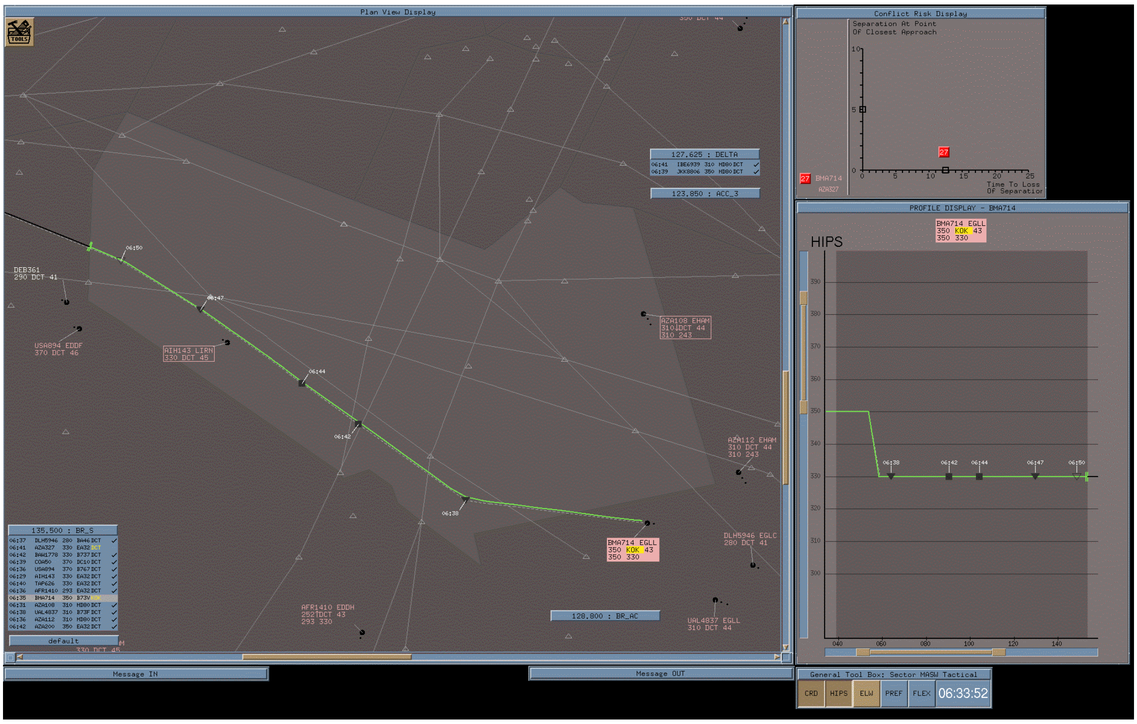


*Figure 1 Overview of the advanced air traffic controller's HMI*

Figure 1 shows an advanced radar display in use by a controller in charge of the (upper) airspace above the entire country of Belgium, which is one of the busiest in Europe. The largest window shows the airspace (depicted in a lighter shade of the background colour) as if it where viewed from above. The black dots represent aircraft, the smaller dots trailing behind them show previous positions and allow the controller to estimate speed and direction of movement. Every aircraft is shown with a small block of information, including a flight identification, altitude and speed. The grey lines represent airways, which lead from beacon (indicated by a small triangle) to beacon.

The second largest window shows a vertical view ("profile") of the 4D-trajectory of a selected aircraft. This and other windows are discussed in the following sections.

The following general features apply to all windows visible in Figure 1:

- the basic design principle is, that for non ATM-specific characteristics, the behaviour should be similar to PC-based window systems. In cases where this would result in a deviation from existing ATM systems, compatibility with such systems prevailed. In this way the controller's expectations can be met and the learning effort reduced in accordance with the first three design guidelines. This choice is fine for an experiment. In an operational system the conversion training may be less of a problem, and the fast evolution of commercial window systems may result in a need to regularly update the available HMI to the new features of such systems;

- the standard use of the window decorations:
  - each window is labelled with an identification inside the upper window border;
  - each window can be resized using the familiar dragging of the border. In regular applications changing a window's size sometimes results in a different scale of the contents and sometimes does not. This behaviour is incompatible with the controller's task. To avoid such inconsistencies, the actual radar display has two extra controls, which allow window resizing with constant scale and constant area respectively.
- scrollbars to select the displayed area for those windows which display an area ("PLAN VIEW DISPLAY" and "PROFILE DISPLAY BMA714"). The size of the scrollbar indicates the relative size of the displayed area with respect to the total area available;
- the colours, font size, and default availability, size and position of each window can be saved. Up to ten preferred configurations can be stored in accordance with the customisation guideline. Example usage includes different configurations for different sectors;
- a window may contain sub-windows. The sub-windows can be repositioned inside the corresponding window to avoid clutter of information.

### 3.3 Plan View Display design

The main window is called the Plan View Display (PVD). This window provides all information, which is available in traditional ATM systems. The major features are:

- the controller's airspace is depicted in a lighter shade of the background colour;
- to be intuitive, the window mimics a conventional radar display for all standard features;
- only aircraft which satisfy *filtering* rules are displayed to avoid clutter. Note that these rules are context specific; when a 4D-trajectory is edited using the problem solver tool, all unrelated aircraft are automatically made invisible;
- labels with minimal information (identification, destination, altitude, heading and speed) are provided to avoid clutter and information overload (Figure 1a). On request, extended labels


*Figure 1a Minimal label (Detail of Figure 1)*


*Figure 1b Full label (Detail of Figure 1)*

can be provided (Figure 1b). Label colours are used consistently to provide status information on the flight while labels of aircraft in need of a controller action are boxed;

- a 4D-trajectory is shown in green. The corresponding label will be highlighted and expanded into a full label. Only one 4D-trajectory can be edited at a time, by “picking” any point on the trajectory and “dragging” it to the desired position;
- the “DELTA”, “ACC-3” and similar sub-windows (Figure 1c) list all aircraft which will enter the controller’s sector from the adjacent sector with the corresponding name. (The “DEFAULT” sub-window collects all remaining aircraft.) The border above these sub-windows also provides the radio frequency of the corresponding sector’s controller voice channel;

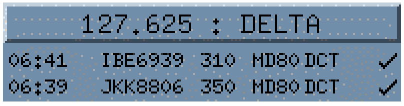

*Figure 1c Sector Inbound List (Detail of Figure 1)*

- the “Message IN” sub-window (Figure 1d) lists the status of the incoming digital messages for the controller. For consistency a single window is used for computer system messages, messages from adjacent ATM centres and messages from aircraft;

*Figure 1d Message IN sub-window (Detail of Figure 1)*

- the “Message OUT” sub-window lists the status of all outgoing messages sent by the controller. (Both message lists are empty in Figure 1);

### 3.4 Plan View Display usage

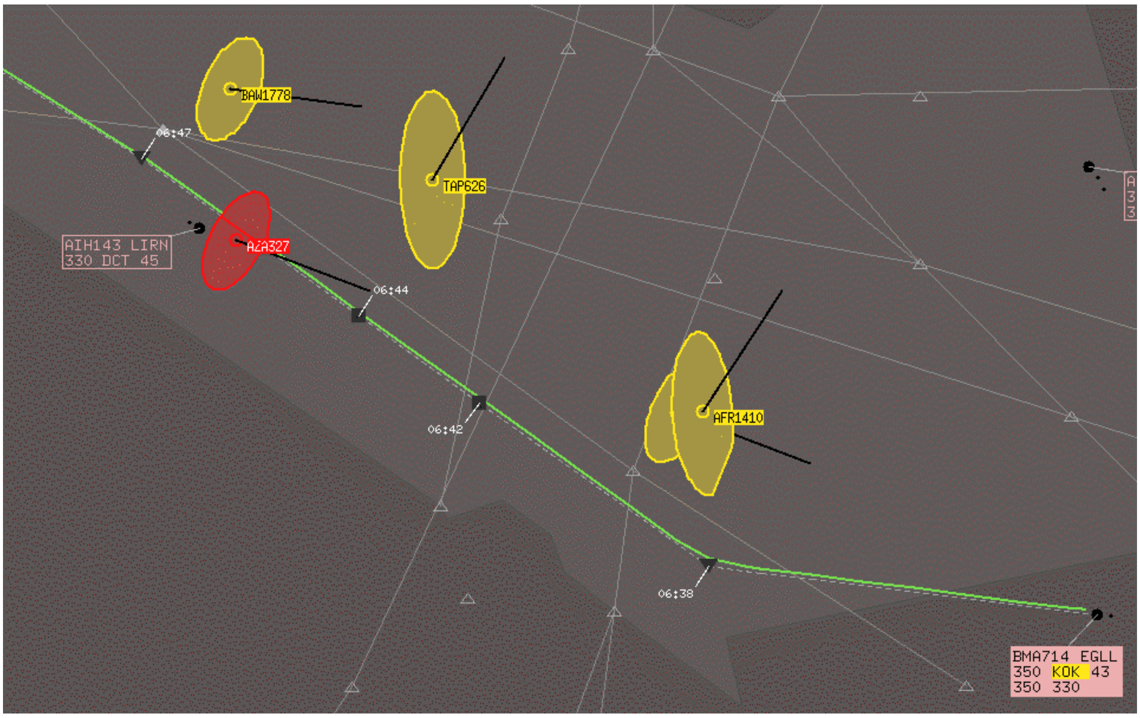


*Figure 2 Interactive ATM tool detects a possible conflict*

Figure 2 shows that the conflict probe tool has detected a potential conflict, based on information from the full accuracy trajectory prediction tool. After selecting the aircraft concerned, the display shows the predicted positions of aircraft that will come into close proximity. These aircraft are shown with a red or a yellow zone and a speed vector. A yellow zone depicts a warning (another aircraft is close but will not infringe the separation criteria); a red zone depicts a conflict (another aircraft is predicted to infringe the separation criteria). The speed vectors show the direction and speed of the aircraft.

The controller investigates a solution to this conflict using the intuitive interface of the problem solver tool to “pick” a point of the 4D-trajectory and “drag” it outside infringement area (see Figure 3). The real-time response of the tool is an essential feature for this problem solving activity, because every modification of the 4D-trajectory changes the possible conflicts.

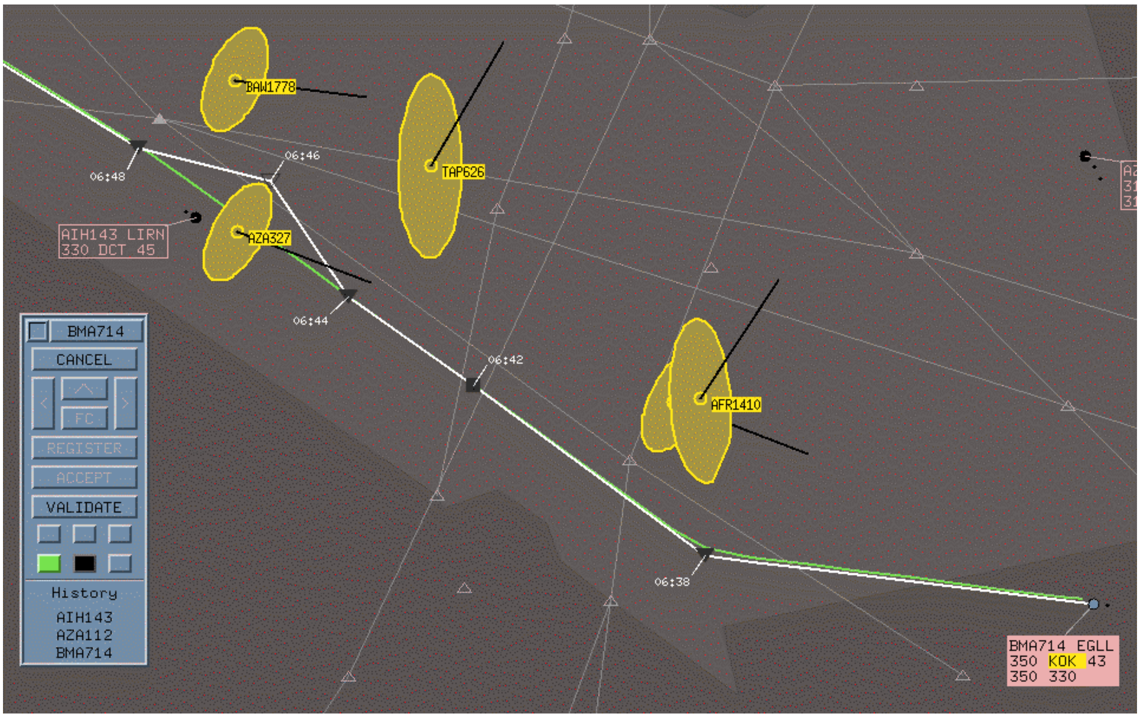


*Figure 3  Controller solves conflict with tool, minimising trajectory interference*

In order to minimise disturbance of the aircraft's preferred 4D-trajectory, the solution only just avoids the warning area of the infringing aircraft. To inform the controller, the red zones on the PVD and the vertical view display have disappeared, however the conflict remains in the “conflict and risk display” (explained in below its own section) as at this moment the modified trajectory has not yet been accepted. After the controller is satisfied with the solution, it needs to be validated using the full accuracy trajectory predictor. This is accomplished by clicking on the validate button of the “trajectory support tool” sub-window (described in below its own section). This window appears automatically when a trajectory has been modified.

As shown in Figure 4, the result of the trajectory predictor tool's more accurate modelling of the aircraft's turn behaviour is that the conflict remains, although the risk of infringement is significantly reduced. From a safety perspective the solution of course remains unacceptable and, even when such behaviour is quite rare, it means the system will have to be modified.

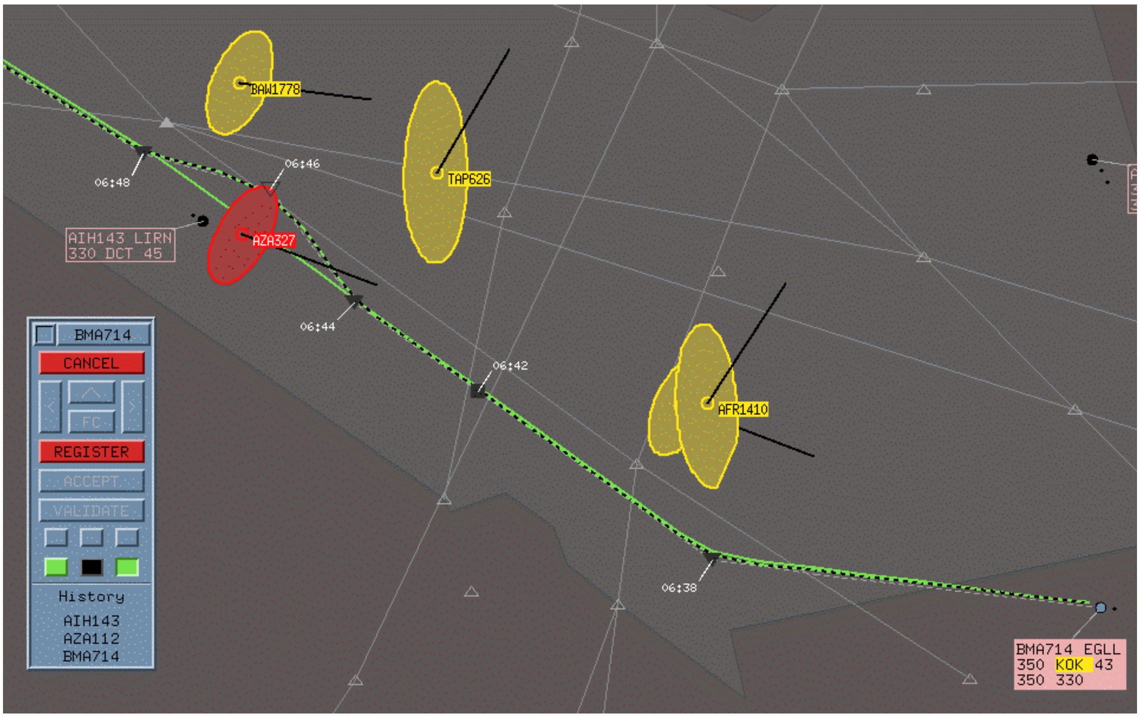


*Figure 4 Slower, full accuracy tool rejects solution*

Consequently the controller has to pay attention to this conflict again, by proposing a second solution (see Figures 5 and 6). Due to the time delay involved, this second problem solving action disturbs the scheduling of the controller's mental tasks. As such this is not a minor technical inconvenience, but a major interference with the controller's routine distribution of effort over his normal tasks of monitoring, controlling, checking, diagnosing and problem solving (Kjaer-Hansen, 1998). Of the HMI design guidelines listed the "be consistent" and "minimise the use of modes" have been violated.

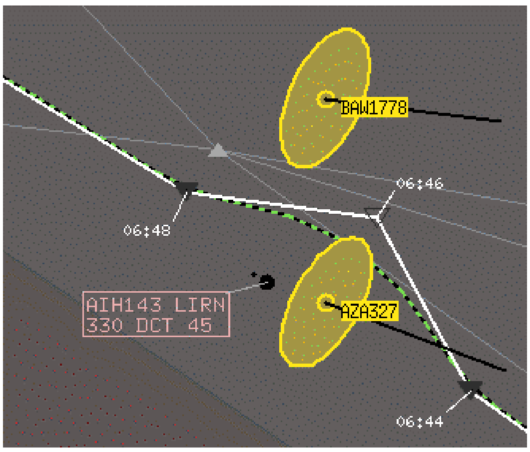


*Figure 5 Controller solves conflict again*

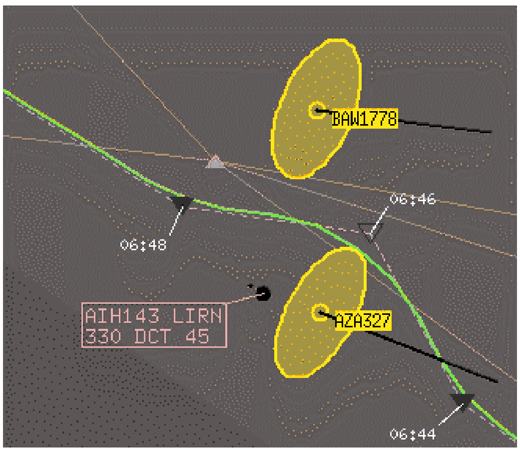


*Figure 6 Second solution confirmed*

### 3.5 Profile display design

The Profile display window (see Figure 7) provides a vertical view of a selected flight. The major features are:

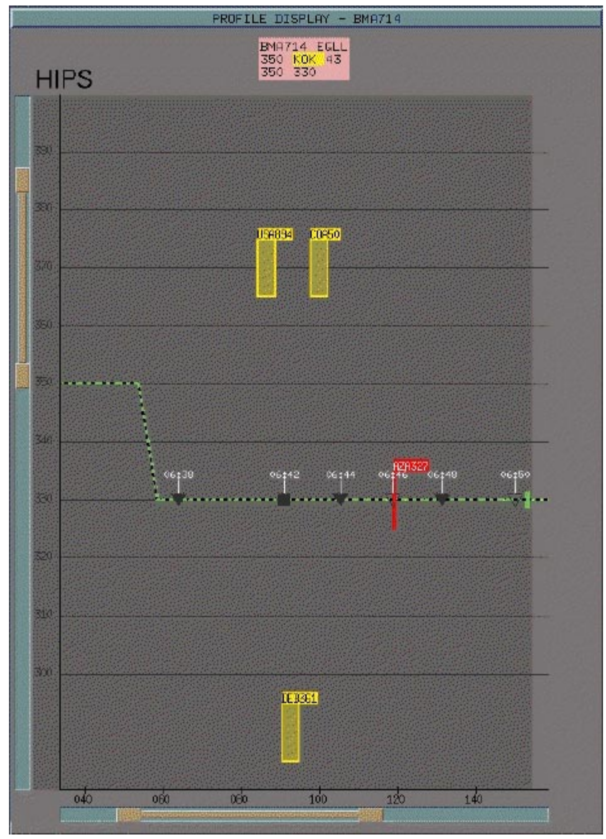

*Figure 7 Profile display*

- the vertical scale with flight level information (a flight level corresponds with 100 feet);
- the horizontal scale with distance information (in nautical miles);
- the same colours as used in the PVD;
- different filtering rules applied to the zones in the horizontal and vertical views;
- the (highlighted) full label of the selected aircraft displayed at the top of the display;
- a red zone to indicate a conflict. Note that this conflict is the same as the one shown in the Plan View Display (see Figure 2). A conflict only exists when both the horizontal and vertical separation criteria are predicted to be infringed;
- a yellow zone to indicate a warning;
- the selected 4D-trajectory shown as a green line. The 4D-trajectory can be modified interactively by picking any point on the trajectory and dragging it to the desired position. The same real-time tools are used as in the Plan View Display.

### 3.6 Conflict and risk display design

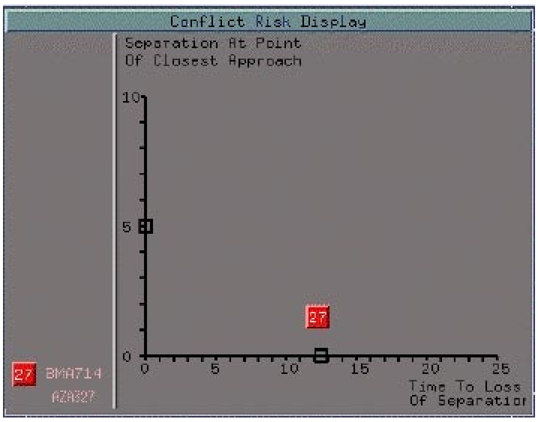

*Figure 8 Conflict and risk display*

To provide the controller with an intuitive way to assess the severity of potential conflicts the "conflict and risk display" (Figure 8) has been developed. This provides a severity indication for all conflicts. The vertical axis provides the distance between two aircraft at the point of their closest approach (in nautical miles), the horizontal axis provides the "time to loss of separation" (in minutes). The squares on the horizontal and vertical axis are used to scale the corresponding axis. On the left the identification ("BMA714" and "AZA327") of each conflicting aircraft pair is provided. For an operational display the annotation at the axis would be omitted to improve picture clarity.

The controllers appreciated the simple and intuitive graphical design, but also noted that the link with the relevant aircraft in the main display was not intuitive and hence the design needs to be improved.

### 3.7 TST sub-window design

While modifying a 4D-trajectory, the HMI will provide feedback in real-time. In order to minimise clutter, the special Trajectory Support Tool (TST) sub-window (Figure 9) only appears when a 4D-trajectory is manipulated. The sub-window is labelled with the flight's identification (i.e. "BMA714"). Given the highly trained controllers, all relevant functions and their feedback are combined in this single sub-window. The function of the buttons is (describing the buttons from the top downwards):

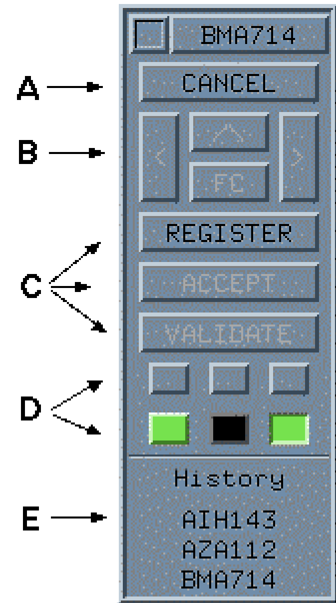


*Figure 9 Trajectory Support Tool*

- (A) “cancel” will remove any modification;
- (B) the three buttons labelled with a left, upward and right pointing arrow are used to start negotiations with the upstream sector, aircraft and downstream sector respectively. The button labelled “FC” denotes a “Formalised Clearance” (explained in Jackson, Pichancourt, et. al. August 1997);
- (C) “register” will set the modified and validated trajectory to the active 4D-trajectory;
- (C) “accept” will accept a proposal from either an adjacent centre or the aircraft. Note that a proposed 4D-trajectory can only be rejected by submitting a counter proposal;
- (C) “validate” will validate the 4D-trajectory by using the full precision trajectory prediction tool. Due to its higher accuracy the trajectory predictor can not calculate 4D-trajectories fast enough for interactive use;
- (D) the top row of these six buttons displays the status of an incoming trajectory from an adjacent sector, from a pilot and an outgoing trajectory to an adjacent sector respectively (not in use here);
- (D) the bottom three buttons are used to recall the current, the original and the working trajectory. To ensure consistency the same colour coding is used as for the 4D-trajectory on the PVD and the profile display;
- (E) the “history” section shows the last few flights of which the 4D-trajectories were modified.

The controllers appreciated the design of this concentrated information display.

# 4 Case analysis

## 4.1 Human-centred approach

In the example provided, effort has been made to implement a human-centred solution. Both the ATM concept and the HMI design complied with this approach and were appreciated by the controllers. The resulting intermittent failure in the implementation (discussed in section *Plan view display usage*) was caused by two independently developed tools which were not *integrated* but merely *harmonised*. Consequently in special circumstances they behaved inconsistently. This kind of problem can be solved by extending the human-centred approach to the integration of separate tools into tool-clusters or tool-federations. Such integration comprises:

- using consistent input data. Partly, this can be accomplished by splitting a tool into separate modules and using software specifications like Application Programming Interfaces (APIs) to unambiguously define the interfaces. The input processing should then be a separate module apart from the actual algorithm. A similar argument holds for splitting output processing in separate modules;
- analysing the sensitivity of the integrated tool-cluster for inaccuracies in the input data provided;
- redesigning the computationally efficient (trajectory prediction) tool based on a conservative approximation of the results of the full accuracy tool.

In the operational evaluation the controllers agreed that the discussed inconsistencies between tools caused confusion (Post, 2000). This result confirms that such issues should be dealt with prior to embarking on costly full-scale experiments.

### 4.2 Display design

To avoid inconsistencies in the controller HMI, the APIs of all components should be agreed upon as early as possible. These APIs can be used to test interactions between tools for inconsistencies and deadlocks. This approach can be extended to assess the response time of tool-clusters. Using appropriate methods, this can be done before the tools themselves are implemented. These checks reduce the number of defects that show up later in the development process, at which time resolving them is more expensive (Boehm, 1981).

The “conflict and risk display” (discussed in its own section above) received mixed reviews, indicating that more design work needs to be done on this display. Possibly this is the result of this window being technology-centred (it was easy to provide) instead of human-centred (based on what the controller needs to know for his task). This conclusion is supported by the development of the Activity Predictor Display within PHARE (Jackson, Pichancourt, et. al. August 1997) as a replacement of the conflict and risk display.

The “message in/out” sub-windows (discussed in its own section above) were not deemed relevant by the controllers. This illustrates Karat's (Karat, Campbell, Fiegel, 1992) guideline that the HMI has to be consistent, which in this case means providing information in the controller's preferred graphical format instead of the tabular format used. The same holds for the “Sector Inbound Lists”.

The large relative size of the software implementing the HMI, even compared to the entire simulation software, implies that a design based on generic modules reduces both time-to-market and costs. NLR's subsequent controller display redesign project (called wARP) implements this (Knapen, 1999). The many changes during the realisation of the HMI suggest a spiral development model (Boehm, 1988) might be more appropriate then the waterfall model used. For other safety critical applications the same conclusion is reached (Kesseler, 1999).

## 5 Conclusions

Saturation of the air transport system, combined with limited opportunities to increase the capacity based on current practice, provide the economic incentive to improve Air Traffic Management (ATM). This can only be done by deploying advanced support tools complemented by innovative displays. Due to the size, complexity and history of the ATM system, advanced tools are usually conceived, designed, developed and evaluated independently, including a dedicated locally optimised human-machine Interface (HMI). The most promising tools are subsequently integrated into existing ATM environments. During this process the tool's HMI is integrated with the existing ATM system's HMI. This traditional technology-centred approach can yield unexpected inconsistencies, which may reduce any potential capacity gains. It may even lead to unjustified repudiation of the tools being evaluated.

Based on the experience described, a better way to proceed is the human-centred approach. Starting from a clear ATM concept to guide the design decisions to be made, human factors considerations should be taken into account from the start of the development process. Items to take into account during this human-centred system development process are:

- design an HMI based on the information needs of the user instead of what is available and check the users' reaction during actual usage;
- take HMI guidelines seriously, especially with respect to consistency and intuitive use;
- use generic modules and tools to construct complex HMIs, as the design will inevitably evolve;
- use software specifications early in the system development process to check consistency and timing requirements within tool-clusters;
- use consistent or at least harmonised tools (i.e. fast response type tools that produce conservative estimates of the results of the full-precision tools within the same tool-cluster);
- analyse the data accuracy required by various tools within the tool-cluster;
- use consistent data sets between tools.

Integration tests of tool-clusters are a necessary step between research and an industrial product. These tests are expensive and time consuming. What appear to be minor inconveniences from a technical point of view can severely disturb the controller's workflow. The resulting additional workload can even invalidate an entire experiment. This implies the need for a "first-time-right" approach. A human-centred approach is essential to obtain this objective.

## Acronyms and abbreviations

| | |
|---|---|
| API | Application Programming Interface |
| ATC | Air Traffic Control |
| ATM | Air Traffic Management |
| EUROCONTROL | European Organisation for the Safety of Air Navigation |
| HMI | Human-Machine Interface |
| NARSIM | NLR ATC Research Simulator |
| NLR | National Aerospace Laboratory |
| PD/3 | PHARE Demonstrator 3 |
| PHARE | Programme for Harmonised ATM Research in EUROCONTROL |
| PVD | Plan View Display |
| R/T | Radio/Telephony |
| TST | Trajectory Support Tool |
| wARP | ATC display Redesign Project |

## References

Boehm, B. (1981). *Software Engineering Economics*, p.40, Englewood Cliffs: Prentice-Hall.

Boehm, B. (1988). *A spiral model for software development and enhancement*, IEEE Computer, 21 (5), pp. 61-72.

Jackson, A., Pichancourt, I., et al. (1997). *PD/3 Ground Human Machine Interface Specification*, version 2.1, Brussels: EUROCONTROL.

Karat, C.M., Campbell, R., Fiegel, T. (1992). 'Comparison of empirical testing and walkthrough methods in user interface evaluation', *CHI92 Conference proceedings*, (pp. 397-404) Association for Computing Machinery (ACM), New York.

Kesseler, E. (1999). “Quality first, measuring a safety-critical embedded software development process”, (NLR-TP-99272) *International Conference on Product Focused Software Process Improvement Profes'99*, VTT, Finland.

Kesseler E., Knapen, E.G. Interactions (2000). Advanced controller displays, an ATM essential*, 3rd FAA / EUROCONTROL ATM R&D seminar* EUROCONTROL, FAA (also as NLR-TP-2000-399 Amsterdam: NLR).

Kjaer-Hansen, J. (1998). *Human factors in the development of air traffic management systems*, HUM.ET1, ST13.4000-REP-01, EATCHIP, Brussels: EUROCONTROL.

Knapen, E.G. (1999). *ATCoDis Redesign Project, User and Software Requirements document*, NLR-TR-99417 (private publication).

NLR/EEC/CENA, (1997a). *PD/3 Operational Scenarios Document Volume 1*, DOC97-70-04. Amsterdam: NLR

NLR/EEC/CENA, (1997b). *PD/3 Operational Scenarios Document Volume 2*, DOC97-70-08, Amsterdam: NLR

Post, W. (2000). *NLR PHARE demonstration 3 Final Report*, DOC 99-70-01, Brussels: EUROCONTROL.

Wilson, I.A.B. (1998). *Trajectory Negotiation in a Multi-sector Environment*, DOC 97-70-14.