EUROPEAN ORGANISATION
FOR THE SAFETY OF AIR NAVIGATION

EUROCONTROL EXPERIMENTAL CENTRE

RADICAL REVISION OF
EN-ROUTE
AIR TRAFFIC CONTROL

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### RADICAL REVISION OF EN-ROUTE AIR TRAFFIC CONTROL

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**Abstract:**

A study of the En-route Air Traffic Controllers’ Interface with the ATC system led to wider consideration of the display and handling of ATC information for en-route air traffic.

Initial consideration of the surface ergonomics led to an in-depth consideration of the proper allocation of tasks between the controller and the system, and of the optimal distribution of information flow, employing currently available technology. A simple demonstrator is provided on the attached disk.

This leads to a proposal for a radical revision of En-route Air Traffic Control, the consequences of which are briefly considered.
Radical Revision of En-route Air Traffic Control

by

H. DAVID

SUMMARY

A study of the En-route Air Traffic controller's interface with the ATC system led to wider consideration of the display and handling of ATC information for en-route air traffic.

Initial consideration of the 'surface ergonomics' leads to an in-depth consideration of the proper allocation of tasks between the controller and the system, and of the optimal distribution of information flow, employing currently available technology.

This leads to a proposal for a radical revision of the En-route Air Traffic Control process, the consequences of which are briefly considered.
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<td>Airborne Collision Avoidance System</td>
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<td>ATC</td>
<td>Air Traffic Control</td>
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<td>CAA</td>
<td>Civil Aviation Authority (UK)</td>
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<td>CRD</td>
<td>Conflict Risk Display</td>
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<td>CARD</td>
<td>Conflict And Risk Display</td>
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<td>CENA</td>
<td>Centre d'Etudes de la Navigation Aerienne (France)</td>
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<td>DRA</td>
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<td>EATCHIP</td>
<td>European ATC Harmonisation and Improvement Program</td>
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<td>EC</td>
<td>Executive controller</td>
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<td>EEC</td>
<td>EUROCONTROL Experimental Centre, Bretigny, France</td>
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<td>EGA</td>
<td>Extended Graphics Adaptor</td>
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<td>The European Organisation for the Safety of Air Navigation</td>
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<td>FAA</td>
<td>Federal Aviation Authority (USA)</td>
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<td>FPL</td>
<td>Flight Plan</td>
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<td>Flight Level</td>
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<td>HIPS</td>
<td>Highly Interactive Problem Solver</td>
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<td>ICAO</td>
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<td>Operational Displays and Input Devices</td>
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<td>PC</td>
<td>Procedural Controller /Planning Controller</td>
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<td>Program for Harmonised ATC Research in Europe</td>
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<td>PPI</td>
<td>Plan Position Indicator</td>
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<td>RAE</td>
<td>Royal Aeronautical Establishment UK - now DRA Farnborough</td>
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<td>System Data Display</td>
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<td>SID</td>
<td>Standard Instrument Departure</td>
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<td>STAR</td>
<td>Standard Terminal Arrival Route</td>
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<td>Short-Term Conflict Alert</td>
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<td>SSR</td>
<td>Secondary Surveillance Radar</td>
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<td>Upper Airspace Control Centre</td>
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WIMP  Windows, Interface, Mouse, Pointer (System)
1. INTRODUCTION

1.1 Warning

This report discusses a proposal which is strictly outside the orderly routine development of Air Traffic Control (ATC) as planned in the current formalised programs of Eurocontrol, the European Union and other ATC organisations. In this context, the formal disclaimer normally appearing on the title page of all EEC reports is amplified and repeated here in bold type for emphasis.

This report represents ONLY the opinions of the author. It does not IN ANY WAY represent the official policy of the Agency.

Although the author has benefited from discussions with Air Traffic controllers, ergonomists, researchers in Cognitive studies and experimental psychology over the past twenty-five years, he is not, was not and could never be an air traffic controller. The ideas presented here are entirely personal, and he is regretfully aware that they will not be welcomed by many practising Air Traffic Controllers.

1.2 Organisation of this report

This report begins with this Introduction.

Chapter 2 gives a brief summary of the origins and development of ATC.

Chapter 3 is a generic description of contemporary ATC practice.

Chapter 4 is a discussion of the principles underlying ATC.

Chapter 5 is a systematic task allocation to controller or computer system on basic ergonomic (human factors) principles.

Chapter 6 is a re-design of the controllers' system interface on ergonomic and cognitive engineering principles, with a working demonstration.

Chapter 7 discusses the use of data-links implied by this system, and considers some additional consequences.

Chapter 8 estimates the capacity of the revised system display. It suggests that increased individual capacity can greatly reduce the number of control units required.

Chapter 9 discusses some basic aspects of the implementation of such a system.

Chapter 10 summarises the conclusions of this report.
2. BACKGROUND

2.1 Origins

Air Traffic control has a long and honourable history. Proposals for collision avoidance rules, and customs controls were made as long ago as 1914 (Grahame-White and Harper 1914). The air traffic control system developed steadily between the wars, with the availability of radio communications supplementing the flag and pyrotechnic signals originally applied. The United States generally took the lead in this period, providing designated air routes based on visual signals. The German Lorenz company developed radio-based blind-landing systems in the 1930s. After the Second World War, military radars were converted to civil use.

2.2 International Standardisation

ICAO, founded in 1947, began the process of international standardisation necessary to cope with the increasing quantity and variety of civil international traffic. English was established as the generally preferred language for air traffic control, (although other languages were adopted for some regions and local languages are often used between controllers and pilots of the same nationality.) A standard vocabulary was also established (ICAO Document 44.44), which provided for all routine ATC operations. A standard form of Flight Plan (FPL) was developed. This provided all the necessary information about the intentions of the flight, from the type of aircraft, including the route that the flight was to follow, expressed in terms of airways, which themselves were defined by beacons. (When this system was initiated, aircraft navigated by tuning a radio receiver to the successive beacons and determining their distance and direction.) It also contains much routine information needed only rarely - such as whether life-belts are provided for passengers.

2.3 Strip

From this was developed the 'strip'. At first this was hand-written, later printed by an assistant, currently printed by computer-based systems deriving the necessary information from computer-stored flight plans. Most of these, representing regular scheduled flights, are provided well in advance on computer-compatible media by airlines.

2.4 Planners and Executive Controllers

The contemporary ATC system consists (in Europe and most developed regions) of a system which collates and presents flight plan information - usually presenting this to the controllers in the form of 'strips' supplemented, and, at least at Maastricht UAC, replaced by Electronic Data Displays. This information is used mainly by Planners, or Organic controllers, who compare flights in terms of their times of passing over entry and exit beacons, and their planned heights, and plan interventions (mostly, in Europe, changes of flight level or changes in the time of planned flight level changes) Traditionally, the Planner marked these changes on the strip, which was passed to the Executive controller before the aircraft physically entered the airspace. The Executive's main tool is the Radar. The earliest civil radar systems were essentially PPI (Plan Position Indicator) displays, showing a rotating radar sweep.
2.5 Secondary Surveillance Radar

The first major innovation on the classic radar system was the introduction of SSR (Secondary Surveillance Radar). This system was added to the original (Primary) radar, and interrogated a responder in the aircraft. Initially this provided an indication, taken from the aircraft's altimeter of the height of the aircraft. (The determination of height by primary radar systems was never particularly satisfactory. Military systems, which cannot rely on the cooperation of their targets, employ special equipment for this purpose.) The aircraft height was normally specified to the nearest 100 feet, and displayed as a three-digit height code. SSR also provided an identification code, set by the pilot, which can be used, in modern systems, to link the flight plan to the aircraft position. This allows the system to show the aircraft's call-sign - usually in Europe a company identification and a flight number - at the location of the aircraft on the screen.

2.6 Radar Labels

This 'flight label' is usually linked to the position symbol by a leader line. As computer technology has advanced, such labels have become steadily more elaborate. In addition to the call-sign, a second line may provide the current Flight Level, a symbol indicating if the flight is climbing or descending, and a symbol indicating the level to which it is climbing or descending. Aircraft normally cruise only at levels designated in thousands of feet (100 feet is one Flight Level), and cruising levels below 27000 feet (FL270) are allocated so that alternate levels are employed by eastbound and westbound traffic. This reduces the number of potential conflicts, at the price of giving some aircraft a less-than-optimal cruising flight level. Above FL270 the levels are allocated at 2000 feet intervals, because, at the time the system was established, height could only be estimated by barometric pressure altimeters, which were less reliable at higher levels. A flight may cruise at FL330 or FL350, but never at FL340.

2.7 System Data Displays

As computer technology has become more powerful, and cheaper, the original radar system has been replaced by systems which combine the signals received by several radars to provide a continuous indication of the aircraft's position. The original analog radar tube, with its rotating sweep has been replaced by a System Data Display (SDD). This is a TV-type raster-scan display, showing a computer generated image. The traditional 'trail' provided by a slowly-decaying phosphor on the radar tube, is replaced by a synthetic trail, or by a 'speed vector' showing the direction and speed of the aircraft's flight, derived by computer analysis of the combined radar plots. The position of the aircraft may be marked by a symbol which itself conveys information (such as what sector is currently controlling the aircraft, or the type of data on which it is based, or the weight category of the aircraft.) The actual flight level may be supplemented by the cruising flight level assigned by the controller and by the level requested by the aircraft. When these levels are identical they may be combined to form a simple two-line label, becoming larger as there is more work to be done. Because the computer system maintains continuous records of the aircraft's movements, and collates these with its flight plan, it can provide additional items which may be called up by the controller if required. These may include the company name (Speedbird for British Airways, shown as BAW in the callsign), origin or destination airports (by their four-letter ICAO code, rates of climb or descent estimated from the combined radar track, and other potentially relevant items.)
In ‘traditional’ systems these may appear as an additional line in the label for all aircraft on the screen. In ‘study’ simulations, such as ODID III or PHARE, a basic label may be replaced by an enlarged label containing virtually the entire ‘strip’ at the click of a mouse, or by passing the mouse over the basic label.

2.8 Short-Term Conflict Alert

Some advanced ATC systems now employ a Short Term Conflict Alert (STCA) system, which compares aircraft in terms of their position velocity and height, providing an alerting signal, usually via the aircraft labels, if the aircraft will come into conflict within a few minutes. This function is not often activated, but its presence reduces the controllers’ background fear of having missed a potential conflict. Most STCAs take no account of future planned alterations of track, and are therefore limited in range.

2.9 Automated Transfer of Control

The routine transfer of control from one sector to another is now, in some systems, carried out through the computer system. This can eliminate a significant amount of routine communication.

2.10 Additional Displays

In recent ‘study’ simulations, the process of departure from the traditional display system has been accelerated. In ODID III for example, additional displays were provided to give the controller alternative views of the airspace. The exit point display showed a height by time display of the traffic over the exit point, showing which levels were free and at what time. Additional lists were provided of the traffic approaching each entry point, and a plan view of relevant traffic around the entry point was also provided. The most interesting innovation was the Conflict Risk Display. This display based originally on an idea by Falzon (1982), showed potential conflicts and near-conflicts. These were indicated as horizontal lines on a time-to-go (horizontal) by distance (vertical) display. The height of the line represented the minimum distance, and the length of the line the time for which minimum separation was infringed. A symbol was placed at the time of closest approach. Each conflict was numbered, and a table showed the callsigns of the aircraft in each conflict. This display was greatly appreciated by the controllers, since it relieved them of the constant worry that they might have missed a potential conflict.

2.11 Highly Interactive Problem Solver

The development of alternative displays continues. The HIPS (Highly Interactive Problem Solver) is an example of a contemporary development based on extremely sophisticated mathematical analysis, developed at EEC Bretigny. This tool shows ‘no-go areas’ for an aircraft, such that if the aircraft's trajectory passes through these areas it will enter into a conflict.
2.12 Three Dimensional Displays

Several attempts have been made to develop three-dimensional ATC displays, on the principle that airspace is a three dimensional structure, so that it should be easier to control if the display corresponds to reality. These have not so far shown significant advantages over conventional displays. Some reasons for this may be suggested. Most such displays have been used to display existing airspace structures, which are essentially designed to suit the existing control systems. Experienced en-route controllers seem to think of airspace as a series of layers, like the floors of a house, rather than as a three-dimensional structure. (Lafon-Millon 1981.)

2.13 Data-Link Systems

At the same time, Data-link systems are being developed to provide better information on aircraft position to the ground based system, and provide more reliable transmission of ATC instructions to aircraft. Modern civil airliners are very expensive vehicles, and operators are willing to go to considerable trouble to make efficient use of them. Satellite-based aircraft navigation systems are now replacing systems relying on ground beacons and inertial navigation equipment. A modern airliner usually knows its position more precisely that it can be located by the ground based radar system. If this information can be transferred to the ground ATC system, and made adequate use of, considerable savings and increased safety may be obtained.

2.14 Airborne Collision Avoidance Systems

Airborne Collision Avoidance Systems (ACAS) are being generally installed in civil aircraft, providing, in principle, last-ditch emergency warning of potential collisions. Naturally, the question is being asked if the ACAS system could provide a self-contained airborne Air Traffic Control system. The prospect is particularly attractive where ground control is not available.

2.15 Evolutionary Development

ATC development has been, and continues to be, largely piecemeal and 'evolutionary'. In view of the enormous efforts being devoted to EATCHIP, PHARE, and many other projects, I hesitate to describe it as unplanned, but contemporary effort is essentially directed at introducing improvements to the existing system, under the basic assumption that the controllers will continue to do much what they have done for the last fifty years.

I believe that this process cannot provide the ATC system that will be needed within the next ten to fifteen years. Although some problems may be soluble by flinging money at them, ATC is not, or is no longer, one of them. Evolution is efficient only in the long term, and at the cost of selection. The implicit analogy to natural selection is simply not acceptable in this context. There is neither the time nor the money to continue developing piecemeal improvements, nor is there much to gain by minor improvements to a highly efficient system. The process of 'survival of the best adapted' implies the non-survival of the less-well adapted. We cannot afford to build, implement and scrap competing ATC systems.

New systems are so tightly integrated that real-time simulations need as much planning, programming effort and, above all, time as was spent on real systems twenty years ago. We must produce better systems, and get them right without wasting money, time, equipment and, potentially, lives.

2.16 Revolution Not Evolution
A radical re-design of the Air Traffic Control System is needed, identifying the weak links in the current system, and applying generally accepted principles to produce a system that combines the reliability of computer-based systems with the flexibility of human control. Much is now known about human capabilities and limitations, and, within the last ten years, an considerable body of theory and practical experience has been accumulated that can be applied to this domain.

This report carries out such a re-design for en-route air traffic control. It originated as a study of the controller-system display interface, but has developed into a review of the complete system, involving revision of the entire airspace structure as well as the communication methods. This report includes a description of a revised interface, adapted to the revised ATC methodology, and a simple demonstrator program is provided which shows how the capacity can be increased, by transferring most routine work to computer systems and using data-link systems for communications.
3. CONTEMPORARY SYSTEM

3.1 General

This is a generic description of the contemporary ATC system. It is not a catalog of all possible or even all existing systems. It does not claim to be complete, but serves to set the scene for further discussion. Even within the current Eurocontrol area there are regions having additional facilities, and others lacking some of the features described here.

3.2 Flow Management

The first element in the development and operation of a flight in which Air Traffic Control is concerned is Flow Management (originally called 'Flow Control' - a name felt to have negative implications cf. Birth Control, Pest Control). It is not possible for the existing system to handle all the flights that wish to fly through the most densely occupied European regions. This problem was initially tackled by imposing limits to the number of aircraft that would be accepted on various routes, or from adjacent centres or sectors, on an ad-hoc basis. These individual, uncoordinated limits resulted in accumulating restrictions, and a consequent waste of capacity. A centralised European Flow Management System is now in place, which allocates 'slots' to flights - specifying the time at which they may take off. This has produced a significant reduction to the delays experienced by passengers, particularly during the peak (holiday) seasons.

3.3 Flight Planning

The ICAO flight plan remains the cornerstone of day-to-day Air Traffic Control. Most standard commercial flights operate in accordance with repetitive flight plans agreed long in advance between the companies and the ATC authorities. Some flights are based on traditional flight plans filed a few hours before the aircraft departs. The ICAO flight plan includes routes, specified as a series of beacons, and preferred flight levels. (The preferred flight level is in general the level most suited to the airline's economic priorities. ATC tries to provide that level, but may have to allocate another to avoid conflict with other aircraft.) Transatlantic flights are specified slightly differently, to take advantage of day-to-day shifts in the jet stream and other air movements.

Once a flight plan has been agreed, ATC knows almost all it needs about the flight, except that the actual time the aircraft leaves the ground is never really known in advance, even where Flow Management has allocated a slot.

Depending on the system, strips may be prepared beforehand on the basis of the assigned take-off time, generated electronically at the actual time of departure, or for more remote parts of the journey, produced at a defined time before sector entry (but after the aircraft is in the air).

3.4 Departure

The activities of the aircraft before it leaves the ground are not strictly the concern of ATC, (although Eurocontrol has carried out studies to analyze the degree to which aircraft keep to their assigned 'slots' and to attempt predictions of actual take-off time based on earlier events.) The actual time of take-off is, however, often the first definite indication that the flight will take place, and is the first reliable indication of the actual time of the flight.

After departure the flight usually follows a Standard Instrument Departure (SID), which defines the route the aircraft will take from the runway until it leaves the Terminal Manoeuvring Area (TMA). This route is pre-defined, including restrictions on height, to reduce perceived noise at
ground level, to avoid conflicts with arriving aircraft at other levels or to avoid rising ground or obstacles. The flight will arrive at the edge of the TMA at a predetermined height and position. (In practice it may be climbing, so that the uncertainty of its actual height may be considerable)

3.5 En-route

After leaving the TMA, the flight will pass through a succession of en-route sectors. A sector is usually defined as a volume of airspace defined by lines on a map and upper and lower flight levels, although airspace may be reserved within this volume, for military purposes or for TMAs. In each sector a Planning Controller (PC) will have considered the planned flight profile, verifying that there are no conflicts with other aircraft, usually in terms of separation time and cruising flight level at selected beacons on the route. If there are conflicts between two or more aircraft he will try to find a solution by changing the assigned flight level of one or more aircraft. This may involve co-ordination with the planning controller of the next sector, or a notification, by voice, code mark or electronic tag to the Executive Controller (EC), that the EC will have to change the flight level(s) assigned. In some cases, the PC will not be able to find a conflict-free trajectory and will leave conflict resolution to the EC.

In principle, the PC should not need to intervene in a flight after it has entered the sector, although he must retain information on it to compare with other aircraft. In general the PC compares future heights and times over fixed points. The PC acts by changing plans for the future, and communicates these planned changes to the EC and to neighbouring PCs.

The EC acquires control of the aircraft at or before it enters the relevant volume of airspace. He is usually contacted by the aircraft on RTF at this time, and usually then verifies the actual position of the aircraft on his radar or SDD. He usually carries out a check for potential conflicts or for deviations from track. He may give changes of level required by the flight plan or for conflict avoidance at this time or later. The EC maintains a watch on the flights in his area, and may order changes of direction to avoid conflicts. (He may request speed changes, either directly as a number of knots or a mach number, or as a time over an exit point.) He may also instruct a flight to proceed direct to a later point, cutting off a corner, or to return to its flight planned track. Eventually, at or before the flight leaves his airspace, he instructs it to change to the frequency of the next sector and hands it over to the next EC. It is good practice, although not always possible, to hand it over at the correct flight level and on track.

The EC works in and around the present time. He acts by communicating with the aircraft, giving instructions that are (usually)
for immediate action. ICAO standards lay down that the pilot should repeat back every instruction, and that the EC should listen to the repeat and acknowledge that it is correct. This is inconsistent with what we know about human cognitive mechanisms. It is psychologically impossible for human beings to maintain sustained attention to purely routine activities.

3.6 Arrival

When approaching the destination airport the flight will normally enter a TMA and employ a Standard Arrival Route (STAR). In what are now less frequent instances, it will be directed into a 'stack' where it will fly a 'race-track' oval pattern while waiting for previous aircraft to land (and, if only one runway is in use, depart) until it is directed to land. TMAs can be extremely complex structures, involving interleaved SIDs and STARS to several airports, stacks and other features, such as intruding terrain which may limit freedom to manoeuvre. Many of the aircraft in the TMA are climbing or descending. In some large TMAs, corridors for light aircraft further complicate the problems. This report does not cover the problems of the TMA, which differ considerably from those of en-route sectors.

3.7 Comment

In practice, life is rarely as clear-cut as is implied above. EC and PC work as a team, sharing tasks and checking each others' work. Where traffic is light, for example in parts of Canada, EC and PC may be the same person. Eye-movement studies have shown that PCs may spend up to 40% of their time looking at the radar. The EC may discuss height allocations with the PC. Much non-verbal communication goes on between the EC and PC. These deviations from the schema are typical of real systems, and exemplify the adaptability of the human operator, who will find a way of making even the most clumsy system work. (In fact, "working to rule" will usually cripple any major co-operative system.)

The current system has 'evolved'. As tools became available, they were brought in and added to the existing system. At no time did anyone stop and think about the system as a whole. The various improvements have steadily increased capacity, but at the same time, it has been necessary to reduce sector sizes, and multiply coordination and supervision processes, and to place more and more pressure on the controllers. Eventually (sooner rather than later) a limit will be reached. This will probably take the form of increased delays at airports, increased sickness among controllers, and increased incidence of electronic system failures rather than an increased incidence of accidents.
4. ABSTRACT PROBLEM TASK DEFINITION

4.1 Introduction

This document originates from a self-imposed mental exercise, an attempt to design an Air Traffic Control System from first principles. (The initial aim was confined to the Air Traffic Controller's Human-computer interface, but it quickly became clear that this was not sufficient.)

4.2 Aims

Any Air Traffic Controller, if asked about the overall aims of ATC will quote:

'The safe, orderly and expeditious treatment of air traffic'

These three conditions are the equivalent of the Ten Commandments of Judaeo-Christian tradition, and have much in common with them. They are admirable, generally respected, partly obsolete, widely misunderstood and more honoured in the breach than the observance. However they do merit some discussion.

4.2.1 Safety

Safety is the primary justification for Air Traffic Control. The ground-based controller is continuously aware of all the air traffic in his sector, while pilots are aware only of their immediate surroundings. The controller is therefore better able to see what must be done to remedy dangerous situations. Any method which does not employ a single decision maker must involve rules for deciding which aircraft should manoeuvre to avoid conflict. Since the information available to each aircraft is necessarily not identical, there is always a finite probability that spontaneous actions undertaken by several aircraft may lead to a worse situation than the original. This is the 'Radar Induced Collision' that troubled the marine navigation world thirty to forty years ago (Oudet 1960), and which led to the introduction of traffic control in the more congested sea lanes. The ground-based controller can make decisions based on his experience (taking into account, for example, aircraft that have not yet entered the sector) and considering an overall strategy for safe traffic, rather than solving each problem on a short-term ad-hoc basis. This reasoning, while convincing in principle, is being eroded in practice by the failure of the ground system to match the sophistication of the navigation and control systems available aboard the aircraft.

4.2.2 Order

Order, or orderliness, appears in the traditional definition, rather as the second commandment. In the original context, it was a practical necessity. There was an intuitive feeling that a sky full of aircraft 'doing their own thing' would be a more dangerous place than one where aircraft followed predefined routes at predetermined levels. If the system relies entirely on human perceptual abilities this is a valid point since the human operator is far better at spotting a deviation in an orderly array than at finding one in an collection of random items. Modern computer-based systems are not subject to the same constraints. Although the beacons and airways of the traditional system were established because the early post-war navigation systems needed them, their current purpose is to allow Procedural controllers to make comparisons. As an anonymous
observer has remarked "We are now making aircraft fly closer together in order to keep them apart."

4.2.3 Expedition

The expeditious element in the defined aims of Air Traffic Control is the second potential justification from the airlines' point of view. If aircraft arrive at their destinations without delay then a minimum of fuel, crew time and passenger annoyance can be obtained. Ideally, each flight would like to take off as soon as it reaches the runway threshold, turn towards the destination as soon as airborne, climb to optimal cruising height and maintain that height at optimal speed until the descent towards the destination airport, at which it would turn into the approach path and land without delay. Unfortunately, other aircraft have the same ideal, and some compromise is therefore necessary. At present the airlines accept that they may have to wait before they can take-off, and that they may have to accept a non-optimal flight level or a slightly extended flight path to avoid conflicts. They accept the necessity for approach control, since runway capacity is necessarily limited, although 'stacking' is an obvious waste of fuel, time etc. The airlines accept the contemporary beacon/route structure because it appears to be necessary for safety, although they would prefer to use direct routings. These are often available where traffic loads are light, but the current system makes them least available when they are most needed.

4.3 Revised System

The Air Traffic Control System exists for the benefit of Air Traffic. Although ultimately it concerns the passengers and freight operators of Europe and the world, it is in practice the airlines who are our clients. We should try to provide them with the 'best' possible service. This is not necessarily the service they ask for. Airlines are under constant pressure to cut costs, either to increase profits or for simple survival. For the most part they resist temptation to cut corners by neglecting safety considerations, but they should be provided with the most economic service compatible with safety. In practice this means, within European airspace, a close approximation to Great Circle routes from airport to airport. For en-route control, this should mean from the end of the departure takeoff process to the start of the landing approach. This implies that optimal routes are not necessarily fixed in space, since these points will depend on the runways in use. Since runway changes are relatively infrequent, they should not greatly complicate planning.
5. TASK ALLOCATION

5.1 Introduction

It is a truth universally acknowledged, at least by ergonomists, that a satisfactory interface cannot be designed unless the designer knows what the user will be using it for. There are some tasks for which human operators are well adapted and some which they enjoy. Conversely, there are some at which they are particularly poor and some which they do not enjoy. (The two pairs are not identities). The early studies by Bisseret and others at INRIA (e.g. Lafon-Milon 1981), summarised in Bisseret (1995) and the contemporary work of Leroux and Gaillard (1995) on ERATO (En-route Air Traffic Organiser) are particularly relevant.

Since we are here attempting an ab-initio re-design, we will enumerate current tasks, then examine which should be human responsibilities and which should be eliminated. (The following design and analysis are based on Dee(1995) which is necessarily simplified.)

5.2 Tasks

Controllers: -

1) 'learn' sectors,
2) manipulate and mark strips,
3) plan future streams of aircraft entering their sectors,
4) check that they will not conflict with each other within the sector,
5) determine how to resolve conflicts,
6) match radar images to strips,
7) acknowledge aircraft coming on to the frequency when they enter,
8) intervene to resolve conflicts,
9) co-ordinate their actions with the next sector,
10) monitor aircraft behaviour for deviations from track,
11) hand aircraft over to the next sector,
12) attempt to comply with any special requests, for example for direct routings or changed routings,
13) handle unexpected emergencies.

5.3 Allocation Criteria

The major weaknesses of human beings as operators in complex systems are their low reliability, poor recall memory, and tendency to boredom. Their strengths are their capacity to recognise patterns, self-awareness and ability to adapt.

In principle, tasks should be designed to suit the human operator, and the computer should do the rest. In addition, the computer should provide an automatic 'fall-back' if the operator becomes overloaded. This 'fall-back' should concentrate on safety, and should provide a lower level of efficiency than the man-in-the-loop' system.
5.4 Allocation

5.4.1 'Learn' sectors

Controllers spend a great deal of time and effort 'learning' sectors as the current system is organised. Their 'learned' ability is fugitive, so that a controller who does not practice for a month requires several days to regain the necessary skill even on a sector with which he is familiar. This phenomenon is generally accepted in Air Traffic Control, but, from an ergonomic point of view, suggests that the controller is being required to carry out a task for which humans are not adapted. It is significant that in most instances, working controllers choose to suppress beacon names and airway names, preferring to rely on memory. Exactly what it is that controllers learn (and forget so easily) has never been investigated scientifically, largely because the methodology does not exist and resources have never been available.

In principle, if route and beacon structures are suppressed, and a more 'natural' interface provided, this task should disappear.

5.4.2 Manipulate and mark strips

In traditional systems, planning controllers spend most of their time handling, matching and marking strips. It is often considered that this activity helps to fix information in the controllers' memory, (Hopkin 1990), although there is some evidence from simulation studies (Manning 1995) to suggest that this is not the case. It has been suggested that one reason for the relative lack of success of 'electronic strip' systems has been the loss of this physical reinforcement factor. Strip marking, theoretically, also serves in some circumstances as legal evidence. In practice heavily loaded controllers simply cease to mark strips. Some sectors at Maastricht UAC do not use strips, relying on electronic tabular displays.

This task should disappear in future systems.

5.4.3 Plan future streams of aircraft entering their sectors

In conversation, experienced controllers emphasise that good controllers exercise a strategic sense, organising the traffic, with which they are familiar, into streams so that potential conflicts do not arise. This appears to be a cognitive task almost invisible to the outside observer. It serves to reduce the amount of routine intervention, reducing communication workload, possibly at the expense of internal strain. Failure to maintain the 'mental organisation' is often associated with 'losing the picture'.

This task will not be necessary and may not possible in free-route systems, but may well re-appear as controllers become experienced in the new system.
5.4.4 Check that they will not conflict with each other within the sector

The procedural controller currently carries out this task by comparing strips, and by referring to his memory. This is an extremely demanding task, and generates considerable strain, since the controller can never be sure that he has not missed a conflict. The CARD (Conflict and Risk Display) introduced in ODID III (Prosser et al 1991) and ODID IV (Graham et al 1994) is particularly valuable because it provides such an assurance. The STCA (see 2.5 above) performs a similar function for Executive Controllers. In the absence of strips, or more precisely, in the absence of an airways structure, this task becomes virtually impossible. In the presence of precise data and efficient computer software, it becomes a trivial task for the system. Aircraft movements, however speedy in comparison with other means of transport, are far slower than electronic systems.

This task will be carried out by the computer system.

5.4.5 Determine how to resolve conflicts

Having assimilated the traffic, the (procedural) controller decides what actions will be needed to resolve the conflicts. It is important to note that, contrary to most logical top-down models of the system, he does not detect a conflict and solve it, then repeat the process for the next conflict. He operates on groups of flights, determining what combinations of actions will be necessary to solve the complete problem. It is proverbial that the more experienced the controller the less he intervenes. Attempts have been made to 'automate' conflict resolution, but these have generally failed for two good reasons. The (human) controller has an enormous reserve of information and experience that is practically impossible to codify. (One rule-based system uses about two thousand rules to cover about 70% of the conflict resolutions in a specific region.) Secondly, this task is the most humanly rewarding. Controllers refuse to be reduced to mere button-pushers. This agrees with the ergonomic observation that if the human is kept in the loop, then it must be as a useful part of the system. Operators rapidly see through 'make-work' tasks.

This task will be carried out by the controller.

5.4.6 Match radar images to strips

At present, the radar controller has to match the aircraft he sees on his radar display to the information he receives on strips. Since the radar, or SDD now shows the aircraft callsign, it is, generally easier than it used to be, but it is still a time-consuming task. The controller must memorise (or more often recognise) the flight plan so that he can maintain a mental picture of what is going on. This is a very demanding task. Since it involves non-verbal perceptual skills, it is particularly difficult to describe, and its importance is often neglected. It originates in the separation of the aircraft-by-aircraft along-track data on the strip from the 'current time' relative position data on the SDD. This separation should not occur in a well designed system.

This task should not be present in a future system.

5.4.7 Acknowledge aircraft coming on to the frequency when they enter

The Executive (radar) controller communicates by voice with the aircraft. In the present system, each aircraft coming under the control of a particular sector announces its arrival by a message to the radar controller. This message serves several purposes in the current system.
- It reminds the radar controller that the aircraft is now under his control. (There are technical and legal problems in the actual transfer of control, which may be defined by the passage of a boundary, so that the controller may be responsible for aircraft which he has transferred to another sector, or be in communication with aircraft he has, officially, no right to manoeuvre.) It usually triggers a check that the aircraft is where he expects it to be. (Controllers are cynical about the navigational ability of aircrew, considering that a report that an aircraft is 'over' a beacon means it is somewhere in the vicinity.)

- It checks that the aircrew have in fact changed to the correct frequency. Even with relatively modern voice radio telephony systems, 'finger trouble' can leave an aircraft on a wrong frequency, leading to confusion and possible tragedy (Cushing 1996)

- It 'helps the controller to remember what traffic he has'. This justification arises from the strain imposed on controllers' memories by the current system.

This task should not be present in a future system.

5.4.8 Intervene to resolve conflicts

The Executive controller acts to solve conflicts by instructing aircraft under his control to make manoeuvres, monitoring the performance of these manoeuvres, and instructing the aircraft when and how to return to their planned track.

The choice of action to resolve conflict may come from the Procedural Controller, either directly as a verbal suggestion, or as an annotation on a strip. In this case, it is usually a change of cruising flight level. Conflicts that the Procedural Controller has not solved are usually dealt with by changes of heading, or changes in cruising speed. (The latter take longer to take effect, so need relatively large sectors.)

However the action is decided upon, it must be communicated to the pilot, who should acknowledge it, and whose acknowledgement should be checked by the controller. In practice, clearances are rarely checked, often not read back, and sometimes not acknowledged. In principle, the controller then monitors the aircraft to ensure that it actually does what has been requested.

The Executive controller must also return the aircraft to track when the problem has been resolved, preferably without significantly altering its trajectory in later sectors. The need to remember this is a major problem, and considerable effort is devoted to memory aids (Stein and Bailey 1994).

In modern systems, the controller must also indicate to the system that he has instructed the aircraft to deviate from its original planned trajectory. This, in current systems requires him to enter the instructions that he has given to the aircraft into the computer system. This is an additional workload, which (Prosser and David, 1988) may be neglected in heavy workload conditions, leading to false deviation warnings. In addition, the need to supply the same information by different modalities at the same time is a fertile source of potential errors, since the controller may forget to perform one or the other, or may make speech or keyboard slips while doing so.

While the controller must communicate his decisions, the manner in which he does so will be radically different in future systems. This task will continue to be performed by the controller, but in a simplified form.
5.4.9 Co-ordinate their actions with the next sector

At present, coordination between sectors may be the responsibility of the executive or planning controller depending on the state of the flight. Pcs usually communicate by voice links, while ECs may have a computer-based protocol. Future systems usually envisage some form of computer mediated communication system. The ODID IV system, for example, provides a communication window, using control inputs to propose and acknowledge actions.

The necessity for this type of coordination should be considerably reduced in future systems, although it must always be available. As a routine operation, it will be carried out by the computer, with controller intervention in exceptional cases.

5.4.10 Monitor aircraft behaviour for deviations from track

At present the Executive controller is expected to monitor all traffic in his sector for unplanned deviations from track. He is not equipped to detect any but the most extreme changes in aircraft speed, but he is expected to detect deviations from track and departures from planned flight levels. He must also verify, as mentioned above, that planned deviations take place according to plan. He has practically no aids for these tasks. If, however, the computer-based system has the necessary information, it is particularly suited to this form of monitoring, and can be designed to draw the controller's attention to unauthorised deviations.

This task will be carried out by the computer system.

5.4.11 Hand aircraft over to the next sector

At present aircraft are formally instructed to contact their next centre, and instructed what frequency they must use.

This task should not be required in future systems, but, if it is, it should be carried out by the computer system.

5.4.12 Attempt to comply with any special requests

Direct routings will be provided automatically by the revised system. It is always possible that aircraft may decide 'en-route' to change their routing, for some reason. The ATC system as a whole must allow for this, and must be able to use the flexibility of the human operator to provide such facilities.

This task will be carried out by the controller.

5.4.13 Handle unexpected emergencies

This task is particularly suited to human intervention. Indeed, almost by definition, it can only be handled by a controller.

5.5 Summary

In the future ATC system communications should be managed by the automated system, as should conflict monitoring and routine compliance monitoring. Conflict resolution, track changes
and the handling of emergencies should remain human activities. (As should 'system tweaking', which had better be left unexplained.)
6. INTERFACE DESIGN

6.1 Introduction

The design of human-machine interfaces has been a major preoccupation of ergonomists and human factors engineers for as long as the field has existed. Fitts and Jones (1947, reprinted in Siniako (ed) 1961) investigated pilot errors in the US Air Force during WW II, starting a process that has continued to the present day 'glass cockpits'.

The over-riding principle is that the display-control system should be compatible with human psychology and physiology. Early systems were limited by the problems of instrument design and manufacture.

This situation is no longer true. In modern computer-based systems, the display and control facilities should be designed to suit the user, in our case the Air Traffic Controller, since there are practically no engineering limitations on what can be shown to the controller.

6.2 Computerisation

The extraordinary flexibility of computer systems has led to their use in many control-display systems, and to a convergence in the appearance of control rooms, as they are designed to suit human parameters rather than machines. It is no longer necessary for the air traffic controller to sit in a darkened room peering at a flickering radar trace, for the railway signalman to heave on metre-high levers, the telephonist to face a spider's web of plugs and sockets, the directory enquiry operator to sit surrounded by rows of directories, or the power plant operator to patrol walls of charts, switches and indicators, while alarms blare out at irregular intervals. All may sit in comfortable seats, in clean, well-lighted rooms. In principle, control rooms and offices are becoming indistinguishable. Recent EEC study simulations (e.g. ODID IV - Graham et al 1994 ) used office furniture throughout. Only the large 50 cm square displays required any special treatment.

6.3 ATC Displays

Although conventional R/T systems were simulated in ODID simulations, telecommunications were controlled through the single large screen. In fact, apart from radio controls, the controller used only a two-button mouse to control the entire system. A keyboard was not needed. From an ergonomic point of view, this is a particularly desirable feature, since controllers, not being touch-typists, look at the keyboard, and are therefore not looking at their displays. They may therefore fail to notice changes that occur while they are looking away.

The (completed) ODID simulations and the (projected) PHARE simulations use what is now the conventional WIMP (Windows, Mouse, Pointer) architecture, although the windows structure is more complex than that used by most conventional office software. The traditional 'labels' of existing radar displays are replaced by small windows that can be opened to provide full 'flight strip' data, containing responsive elements, so that the bearing, speed or cruise level of the aircraft can be changed by calling up a menu and clicking on the required value. (The controller must still inform the aircraft by voice link of the action required, and monitor its correct performance.) These 'extended labels' are essentially tabular, resembling mini-strips. In particular, height is represented by three digits, as is direction and speed. The three digits 270 may mean 27,000 feet high, heading 270 degrees or a speed of 270 knots.
Great care has been taken to optimise the design of these screens. The UK CAA having gone so far as to consult the Royal College of Art on how colours should be employed (Reynolds and Metcalfe 1992). The most advanced contemporary thinking is embodied in EEC Report No. 292 (Jackson and Pichancourt 1995). This report is a work of art in itself, and contains much material for thought on present and future displays.

It is, however, essentially a transitional system. The information displayed is displayed because it has always been displayed, and, as far as possible, in the form that has always been used. For the most part, it is an electronic realisation of a system designed for paper, pencil, memory and mental effort. Although it foreshadows data-link based systems, and discusses briefly their implications, it assumes that the existing centre/sector/route/beacon structure and the Planner/Executive division of labour will continue.

6.4 Display Design Principles

Displays are subject to the general principles of good design for function.

- The display should show what the controller needs to know,
- The display should not show what he does not need to know,
- The display should show it in a 'natural' form,
- The display-control system should operate 'naturally',
- The display-control system should minimise the chance of making errors,
- The display-control system should minimise the need for the controller to memorise information.

It is also an observation from experience that the best way to design an interface is to make it. Designing by specification is like watching paint dry, designing by specification through a committee is like watching grass grow, and designing by ATC simulation of systems specified by committee is like watching artificial grass grow. Accordingly, the design exercise that is the core of this proposal was carried out by programming (in QuickBASIC), using an Extended Graphics Adaptor (EGA) colour (640x350 pixels, eight colours) screen and an 80386 processor. Since, as I have been reminded, trying to understand a dynamic interface on paper is like trying to appreciate a painting from a written description, the accompanying 3.5 inch disc contains a demonstration version of the revised interface in QuickBasic 4.5 source and compiled object code on 3.5 inch discs for PC compatibles with an EGA or better colour display. The disc also contains program documentation in Wordperfect 6.0 and ASCII form and various other possibly useful items.

(to see the demonstration:

From the DOS prompt Type A: (enter)

at A: type DEMON(enter)

continue typing (enter) or follow screen instructions.)

6.5 The 'Situation'

Although it is possible to investigate interfaces by making static models, it is much more useful to model the interface and the system on which it works. The difference is between choosing a car by sitting in the driving seat looking at the controls, and test-driving it on the road.
Unfortunately, this means that we must build, not only the car, but the road. This could be a gigantic task, but it can be made manageable by discarding as much irrelevant material as possible.

In this instance, the fundamental situation consists of the passage of aircraft from place to place at certain times. This is a four-dimensional problem. The average human being finds it hard to operate mentally in three dimensions, let alone four, and the available display provides only two in any case. Fortunately, there are physical constraints on the system. At the most basic, aircraft are continuous functions - they do not 'jump' from place to place, but proceed in essentially straight lines, usually at fixed levels, so that a flight path can be regarded, for planning purposes, as a series of straight line segments, which change instantaneously at points. (This analysis neglects the effects of curves followed at turns, different rates of climb at different levels, meteorological effects and many other real-world phenomena. These are vital in real systems, but form irrelevant complications in the early stages of design.)

We can therefore represent the traffic as a series of straight-line sections, including climbs, descents, changes of heading and changes of speed. The controller is concerned primarily with the future, and is concerned that, when the future becomes reality, no aircraft will infringe separation standards, and that all aircraft will reach their destinations with the least departure from their optimal path. We can maintain a continuous measure of whether aircraft will be in conflict by mathematical analysis of the collection of sections. This record changes when new aircraft enter the system, or when the controller requests a change in the flight path. The entry of a new aircraft means it must be compared with all the existing aircraft, but does not require re-analysis of conflicts in which it is not involved. If the controller requests a change in the flight of an aircraft, its current record of conflicts must be replaced by one calculated for the revised flight. (An advantage of hands-on design is that it showed that it is a relatively simple task to store the existing situation, and replace it if the changed plan is unsatisfactory. This can provide a 'try-out facility', before the order is transmitted to the aircraft.)

6.6 The display

A computer-stored list of conflicts is one thing. A display for the controller is another. As a 'reductio-ad-absurdum' imagine that the controller is faced by a list of call-sign pairs, time-of-start, time of end, minimum distance, type of conflict, etc. It would contain the necessary information, but, except when empty, would be totally unmanageable.

There are certain basic rules to aid in the design.

1 KISS - Keep It Simple, (Stupid)
2 FITS - Fit It Together,(Stupid)

These suggest that the display should be as simple as possible, needing only the minimum of manipulation. Existing transitional systems use many windows, some opening automatically, others on command. This is better than what went before, but it essentially copies bookwork, while ATC is more like car-driving than making entries in a ledger. (Imagine a car where you had to open three windows to turn a corner, then imagine trying to drive twelve cars simultaneously.)
6.6.1 Main display

As far as possible, all information should be presented on one screen and in one coherent picture.

We will assume that the best basic picture is a map of the current situation.

What therefore does the controller NEED to see of an aircraft?

1) Where is it?
2) What is it?
3) How fast is it?
4) Where is it going?
5) How high is it?
6) Is it climbing or descending?
7) Will it conflict - with whom - when?
8) Who else could get in the way?
9) What does it want to do?

The controller needs to see these things in a direct, intuitive way, (Figure 1) NOT as arbitrary symbols or numerical values (Figure 2). We put a symbol where the aircraft is (1). A Concorde is a very fast aircraft, a B747-400 is a very big fast aircraft and a Fokker F-27 is a small slow aircraft. We show aircraft as icons, whose size corresponds to the aircraft size (2), and whose wing-sweep corresponds to their speed (3). The direction of flight is shown by which way it is pointing (4). (The tailplane makes sure which end is which!) The Aircraft position is where the wings meet the fuselage.

Height has always been a problem on ATC displays. The three-digit code used at present is ergonomically squalid. Three-dimensional displays, beloved of engineers, simply do not work for
abstract displays, as anyone who knows about human vision (as opposed to camera optics) could have told them in the first place. However, most aircraft are cruising at pre-determined flight levels, and there is evidence (Lafon-Milon 1978,1981) that experienced controllers do not see a three-dimensional space, but a set of superimposed planes, at the standard cruising levels. Since these are reserved for traffic in alternating eastbound and westbound layers, we follow the European colour convention for strips, using shades of blue for Westbound and yellow for Eastbound cruising levels(5).

Climbing and descending aircraft have their bow and wings in the colour they are approaching, and stern and tail in the colour they are leaving (6). Since we have only an EGA colour display, we have only two Eastbound levels (Fl 330 in Yellow, and FL370 in Brown), and three Westbound levels (FL310 in (almost invisible) Blue, FL350 in Cyan and FL390 in Magenta).

6.6.2 Conflicts

Controllers are most interested in future conflicts. The CARD (Conflict And Risk Display) (Prosser et al 1991,Graham et al 1995), of which a rough image is provided in Figure 2, shows, for each conflict, a line representing the duration of the conflict, at a height corresponding to the severity of the conflict. Each conflict is numbered, and a table specifies the two aircraft involved in the conflict by their callsigns. Although this display is greatly appreciated by controllers, it is most useful when it is empty, since this relieves the controller of the nagging doubt that he may have missed a conflict. If a conflict is present, the controller must first identify the conflict number, then find that number in the list, to read the two call-signs involved. He must then find each of the two aircraft on the screen, estimate their speed and direction from their velocity vectors, and estimate their relative positions when they will be in conflict, before he can decide on a suitable manoeuvre. The system has already calculated exactly what will happen, but does not inform the controller.
We show future conflicts by linking the pairs of aircraft involved. We use lines that become more marked as the conflict approaches, and are coloured to correspond to the aircraft - which at the current time may be at different heights. This draws the eye to individual aircraft that may be in conflict with several others. Figure 3 shows the four conflicts among the same thirty aircraft as were shown in Figure 1.

6.6.3 Flight Profile

If we have chosen an aircraft as a suitable case for treatment, we must be able to examine its future trajectory, and any relevant potentially conflicting traffic. We can do this by presenting a height and time/distance plot along track (Figure 3) - the horizontal distance scale is identical to the plan display and dashes represent one minute of flying time. Blocks of solid colour show the times and heights at which other aircraft will be in conflict with this one. Hollow blocks show aircraft that will be separated only by height. Slanting blocks represent aircraft that will be climbing or descending. The colour of the blocks correspond to those of the aircraft at present. This display, by itself, is sufficient to resolve conflicts by height changes.

6.6.4 Relative Tracks

Figure 3 shows the future trajectory of the aircraft, which would be imposed on the normal main image as a solid green line. Dashed green lines show trajectories of height-separated aircraft, and solid green lines conflicting aircraft. These tracks end at the point of closest approach, which is linked by a solid (white for conflicting, green for height-separated) line to the target aircraft's corresponding position.
6.6.5 Control Intervention

It is important that the controller can choose which aircraft to examine. This should by a 'point-and-click' function, but QuickBASIC, in which this demonstrator is written, allows only keyboard input, and the author has not yet had time to program a pseudo-cursor. The controller can designate aircraft by number, or fall back on a predefined priority system (the most urgent conflict, the aircraft in most conflicts, the one which is not cruising, the one with furthest to go). Control orders can be constructed by using the keys as shown in Figure 3. A complete sequence of orders can be specified. for example, “S+H+++T+++F--T+++++R?” would mean "Increase speed ten knots. Turn right thirty degrees. In three minutes time, descend 40 flight levels. Maintain that level and heading until five minutes later, then resume normal navigation." The instruction "resume normal navigation" instructs the aircraft to proceed to its planned exit flight level, altering heading and speed to arrive at its original exit point exactly at the planned time. The final "?” instructs the system to try out the sequence, then present the image of the result. If the result is satisfactory it can be accepted. If not, a different manoeuvre can be tried out, or the trajectory of this aircraft left unchanged, and the other aircraft modified.

6.6.6 Intervention Methodology

The use of a key sequence is not an essential of this mode of control. The important aspects are that the controller can designate a series of manoeuvres in speed, height or bearing at future times, that he can use the system to return the aircraft to its required course, that he can check that his proposed sequence of actions will resolve the problems that occur, and that, having solved a problem (or problems) he can then forget about it.

6.6.7 Data Suppression

Finally (an innovation which will appal any controllers),the nineteen aircraft which will not be in conflict, and have horizontal separation from any that will be in conflict, have been suppressed in Figure 3. (This idea was first proposed by G. Maignan - personal communication). Worse, all aircraft which will not be in conflict can be suppressed - giving, once all conflicts have been resolved, the ultimate in calm displays. (It is tempting to put some form of marker where the 'hidden' aircraft are, but in practice, this leads to a chain reaction of worrying where they are going, at what level etc, which is as distracting as the original cluttered display.)
6.6.8 Further Development

Although this interface represents a radical departure from the traditional, it is not final. Some additional modifications have been made to a development version (DEMFAST).

- It is possible, for example, to provide a revised trajectory automatically after each input keystroke. Although this is impossibly slow on a '386' chip, a 100 MHZ Pentium gives immediate response, and allows an automatic 'Resume Normal Navigation' function.

- Given a better display, it would be possible to provide profiles for both aircraft in the most urgent conflict. This might make it easier to decide which one to manoeuvre, and save some decision time.

- A longer-term possibility would be to use a more modern immersive ‘pseudo-3D’ display, with appropriate display control and manipulation hardware to allow the controller to signal his intentions to the system by direct manipulation of three-dimensional trajectories. Preliminary investigations suggest that the correct choice of interface control is vital in this type of interface.

- In addition to the conflict-resolution oriented display described here, it would probably be necessary to have a 'monitoring and emergency' display which would report deviations from planned track, assigning significance of the observed deviations and estimating their consequences, and providing rapid pre-defined actions in emergencies. (for example, if a flight continued to climb after reaching its planned level, the system would find and display all aircraft that might be in conflict assuming the rogue would level at all higher levels, generate emergency instructions for any aircraft in immediate peril, and longer-term instructions for other aircraft to clear airspace around the problem.)

The demonstration program described here is not a complete ATC system. It does not provide coordination with adjacent controllers, or meteorological or other data. It would, however, be possible to embed this type of system in a more conventional one, allowing the controller to call up more detailed information to develop his understanding of the traffic and improve his solutions.
7. DATA LINK

This system differs from the current one in that it transfers all routine communication from the controller to the data-link. (Data-link systems already exist which are quite capable of handling this level of traffic with complete reliability, and some commercial aviation companies use such data links for their own purposes.)

Although this was not in the original scope of this study, there are several good operational and ergonomic reasons for the transfer of routine communication from human-human voice links to data-links.

7.1 Duplication

At present, and for the foreseeable future, controllers, if they give instructions by voice link to the aircraft, are obliged to repeat these instructions in a coded form to the ground-based computer. This duplication of communications, in differing cognitive modes, doubles the chance that error will creep into the system. Under time pressure, controllers abandon the data-input part of the transaction to concentrate on voice communication, so that the "computer picture" may differ from the "controllers’ picture” and, of course, both may differ from the real world. At present there is no form of cross-checking, so that the redundancy does not permit error detection or correction.

7.2 Speed

It takes considerably less time to input a coded order of this sort, particularly if each step is verified 'on-line', as in the improved version (DEMFAST) of the demonstration system, than it would to speak it, particularly since callsigns and read-backs are not required.

7.3 Reliability

Input of a pre-formatted message - probably using a mouse and screen-based controls rather than the primitive keyboard system described here - makes it impossible to make many of the 'human errors' currently generated in routine ATC communication. (Cushing 1994) It would eliminate the 'user-hostile' readback and verification currently nominally required, but often neglected. It would also eliminate the florid and dangerous 'macho' language sometimes employed in certain regions, as described in Cushing.

7.4 Language Neutrality

Because the data-link message would have a pre-determined code form, similar to that of the classic Nautical International Code of Signals, but based on an updated version of the ICAO Standard Language, it would have the same form at any place on earth or in airspace, regardless of the language employed by pilots or controllers.
7.5 Communication Flexibility

The coded messages produced in the ground system could be translated to a spoken equivalent, on the ground before transmission for checking, in the cockpit to warn the pilots of impending actions, and to provide the 'bulletin-board' valued by pilots. There is no reason why aircraft could not receive messages sent to other aircraft. It could even enhance this, since pilots could have their on-board system programmed to translate all ATC messages into their native language - eliminating the 'Zagreb' effect - where controller and a pilot conversed in a local language, so that a second aircraft was unaware of a height assignment that caused a fatal collision. If this were done, it would be as well to use a recognisably synthetic voice for the synthesised messages. A 'real human' voice on the frequency would then become an alerting device for all concerned, pilots and controllers alike.

7.6 Voice Link

It would not be advisable to abandon the direct voice link to the aircraft - although there is a good case for improving its quality - since emergency, social and other non-routine messages must still be provided for. (Voice-frequency data-link systems are in routine use in other fields. For example, a system of this type has been used for several years by a taxi-drivers' cooperative in a provincial town on a European off-shore island.) It is technically possible to provide an emergency override to prevent garrulous pilots or controllers from blocking the reception of emergency messages.

7.7 Local Storage

Digital messages can be stored in extremely compact form, so that pilots could have a 'say again' facility enabling them to have a message repeated until they understand it without the embarrassment of asking the controller for a repeat. Messages could also be printed or displayed on displays integrated with the Electronic Flight Information System.

7.8 Down-link

A final point is that a data-link system would, combined with a satellite navigation system, provide very accurate position and velocity data, with wind speeds and directions as a bonus.

It would also be possible to automatically transmit aircraft flight data parameters to the ground. Thus, the ground system could verify that an aircraft was starting a turn from the roll angle rather than waiting for the effect to show up in the aircraft's position. Sudden unexpected changes of flight attitude, rather than the disappearance of the flight from the radar, would automatically indicate an emergency.
8. CAPACITY ESTIMATION

Major changes, such as those suggested here, require adequate justification. In this case, the most important justification is that the control capacity of the revised interface is very high.

Capacity can be estimated empirically from observation of actual performance, or theoretically by measuring task completion times and estimation of reasonable workload levels.

8.1 Empirical Capacity Estimate

Using random traffic of the sort described above, it is easily possible to control the model's maximum capacity of forty aircraft simultaneously. (The QuickBASIC compiler is limited to the 640K memory of the primitive PC. This limits the model's capacity to 40 aircraft.) If each aircraft is present for 15 minutes, this corresponds to a capacity of 160 aircraft per hour at normal speed. This level of traffic can be handled with the system running at double speed, at least. Allowing for the estimate that conflicts should occur with a frequency proportional to the square of the number of aircraft present, then a realistic estimate of minimum capacity could be 220 flights per hour.

This is a rough initial estimate, and, of course, depends on the nature of the traffic. Unlike the present system, however, it appears that control is actually easier when most traffic is climbing or descending at entry or exit.

8.2 Theoretical capacity Estimate

The major task of the controller under the proposed system will be conflict resolution. Capacity would therefore depend on the number of conflicts to be resolved. Approximate time estimates for conflict resolution are about 15 seconds. The capacity problem then becomes a queuing theory problem, given the expected entry warning times, the entry rate and the service time, to estimate the probability that a conflict will not be solved before it starts.

A companion study on the frequency of conflicts in European airspace shows that the incidence of conflicts in point-to-point traffic is surprisingly low, given a choice of flight level depending on direction of flight, and that a simple planning algorithm can usually find a single conflict-free flight level from origin to destination, within one or two cruising levels of that originally requested. This (admittedly simplified) study suggests that one controller (or one team of two or three controllers) would be capable of handling all the conflict resolution tasks for European airspace.

8.3 Justification

An increase in capacity of this order appears too good to be true. However, it is based on a sweeping reduction in the routine workload required of the controller, mechanisation of the most time-consuming aspects of his task, and simplifying and accelerating the non-routine elements.
9. CONSEQUENCES

If it is possible to control traffic in random 'free-flight' in the manner described above, using extremely primitive hardware and software, it is interesting to estimate what this implies for the future system as a whole.

9.1 'Seamless Agreed Contract'

Ratcliffe (1996) discusses an investigation of the possibility of providing aircraft with a 'seamless agreed contract' or 'flight tube' from origin to destination - remarking that the idea has been put forward at intervals since 1964.

Ratcliffe employed a simplified computer model to estimate the probability that a path requested at random will conflict with another, assuming various levels of time separation to be required at crossing points. He shows that this is impractical with the current level of uncertainty for take-off time, which requires a time separation of the order of thirty minutes. However, he also shows that, given his simplifying assumptions, if sixteen upper airspace cruising levels were available, allocated according to heading at departure, then for 10,000 flights per day about 80% could expect to have their requested level, provided that a 2 minute clearance was adequate. This level of precision can now be reached when leaving the runway. (Ratcliffe remarks that it is unrealistic to expect the flight crew to enter the flight plan at that time, but that FANS-1 equipment could solve that problem.)

Ratcliffe also comments that: "With or without seamless clearance, it seems inconceivable that a team of controllers could form an adequate mental picture of an upper airspace containing 1000 aircraft in free flight."

If however, the requirement to form a mental picture is abandoned, the task becomes surprisingly practicable.

Ratcliffe concludes that a 'seamless contract' before take-off is at present impossible, but that "the technology required to implement the solution (...) is already in being; there would, however, be a considerable increase in the volume of data to be exchanged and the relationship between pilots, navigational planners and air traffic controllers will have to be extensively modified." (Ratcliffe's italics).

9.2 Semi-Seamless contract

If 80% of 10000 aircraft received their requested level, then 2,000 would not. (Over the whole of Europe over the whole of a day -assumed to amount to 16 working hours.) Ratcliffe assumes that these would be solved by negotiating alternative levels, but they could equally be treated by the equivalent of the current radar control, using speed variation and track deviations. About 125 conflicts per hour would need to be resolved. The notice available would vary from a minimum of the time from take-off to leaving the TMA to an hour for mid-flight en-route conflicts.
As a 'ball-park estimate', assuming that a conflict can be solved in an average of 15 seconds, then one controller would be 50% occupied by solving all the conflicts in European airspace. This is a staggering, ridiculous figure. In fact, there would be a good deal of other associated work, involved in monitoring the traffic or in responding to the automatic system's notification of deviations from planned flight paths. (Practically, of course, the system would plot optimal trajectories as great circle routes modified by current meteorological profiles. ) Moreover, the peaking of traffic in certain regions at certain times would require added effort.

It is however, a priori, feasible that a 'sectorless' system could be operated, where several controllers derived conflict solutions and rectified irregularities in close co-operation, maintaining the present satisfactory mutually-supportive social system, and allowing for the creation and transmission of craft expertise.

Ratcliffe noted that there were certain routes where there were no conflicting routes, so that a 'seamless clearance' at one flight level throughout could always be give. A further study may show that other routes can be organised to minimise conflicts by pre-defined en-route height changes. (Similar to the 'streaming' that good controllers employ at present.)

It should be possible to arrange that flights had 'default clearances' which would minimise the probability of conflict, particularly at the start of the flight.

A flight from one airport to another would be defined by the exit point from the first TMA, the entry point to the arrival TMA, and the time of lift-off from the runway. At that time the desired trajectory would be known, and the system could verify the clearance. Aircraft could reasonably expect to receive their full clearance to their destination before leaving the TMA, while still climbing.

9.3 Monitoring

The basic demonstrator realised here in an obsolete language on an obsolete machine could be extended to, for example, show aircraft that were not maintaining their planned trajectory, either by wandering slowly off-track, or by performing (or failing to perform) a definite manoeuvre. A data down-link would be able to report attitude or control-surface changes well before a conventional radar system can, and the system should be able to identify 'unplanned changes'. It should also be able to examine the consequences of, for example, a sudden unplanned change of flight level, and generate warnings and trajectory changes for other aircraft.

9.4 Safety-net

Finally, the system should contain a 'safety-net' which would automatically inject changes to maintain basic safety separation if the controllers were overloaded. This safety-net would concentrate on safety rather than efficiency. It could not, and should not attempt to provide service of the quality provided by human controllers. (It may be argued that ACAS is in fact exactly this system.)
9.5 Verification

Dr. Peter Evans at EEC has, or will shortly have, data on the upper airspace traffic for Europe for each day of May 1996. It would be possible to write a relatively simple program to estimate the number of conflicts that would have occurred to these flights under the 'free-flight' assumptions, the notice available, and probably the corresponding workload.

It might be possible to adapt the existing DEMFAST model, currently running with synthetic data, on a Pentium 100 Mhz, to take in this historic data. The problem of capacity should be soluble by a better programmer than I am.

In any case, some formal trials of the existing DEMON model should be made to prove the increase in solution speed.

9.6 Implementation

This system requires an accurate navigation system and a data-link aboard every aircraft. Most of the current generation of aircraft have the first, and the cost of the second would be relatively small.

At present, data-link technology has been stalled by the understandable reluctance of airlines operating on tight budgets to install equipment that gives no immediate financial or safety benefit to them, while ATC has not shown that it can use data-link to increase capacity or reduce ATC-related costs. This proposal could break this deadlock.

However, it represents a radical change from the present system. It would be unrealistic to expect to close down the traditional system at 11.59.59 on the 31 December 2000 and start a new system at 00.00.01 on 1 January 2001. The systems must co-exist, preferably in a manner that allows the new system to expand gradually to replace the other.

Where radar cover has never existed, the new system could be introduced directly. Although this covers about 85% of the world's surface, it does not include Europe.

In European airspace, it would probably be most practical to introduce this system in a literally top-down manner, starting with traffic above, say, FL370 and gradually lowering the bottom level until only lower airspace operated the old system. At some point, it would become clear that the new system was preferable to all.

Airlines with the necessary equipment will benefit immediately from more direct and economic routings. (To obtain full benefit from this system, upper airspace should be completely separated from existing historical constraints. Rather than 'Europe', the region should be, say, Latitude 30-75 N, Longitude 30W-60E.)

9.7 Social Consequences

The changes involved in this radical re-structuring may appear to controllers as 'de-skilling' their art and mystery, and might appear to short-sighted managers as an opportunity for massive staff reductions. It is vital that both these ideas should be discouraged. Controllers' skills may be changed, but they will continue to be absolutely necessary, and although some reduction may be possible in en-route staff, TMA, Approach, flow control and emergency services would remain necessary and even be increased.
10. CONCLUSIONS

10.1 The current ATC system is the product of unplanned evolution.

10.2 It is close to its limit of performance.

10.3 A radical revision according to accepted ergonomic principles has been proposed.

- Humans should be in control;
- Humans should do the tasks they enjoy and can do well;
- The task should be made to suit human mental capabilities;
- Mechanical routine should be mechanised;
- Irrelevant clutter should be swept away.

10.4 The use of modern data-link methods could increase safety and reduce communications congestion.

10.5 The use of digital data transmission and storage methods would enhance pilots' awareness of surrounding traffic, and eliminate language problems.

10.6 The revised system implies the use of direct 'free' routes to provide reduced costs and vastly increased capacity.

10.7 In principle, all European en-route airspace could be managed from one unit. Beacons, routes, sectors and most inter-centre boundaries could be discarded.

10.8 The revised system should not be regarded as 'de-skilling' and 'down-sizing' should be avoided.

ACKNOWLEDGEMENTS

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TRADUCTION EN LANGUE FRANÇAISE

SOMMAIRE

Une étude de l’interface du contrôleur aérien « en-route » avec le système ATC a mené à une considération plus large de la présentation et du maniement des informations ATC pour le contrôle en-route du trafic aérien.

La prise en compte initiale des « ergonomies de surface » a mené à une considération approfondie de la répartition adéquate des tâches entre le contrôleur et le système ainsi qu’à la distribution optimale du flux des informations, en utilisant la technologie actuellement disponible.

Ceci conduit à la proposition d’une révision radicale du processus de contrôle du trafic aérien en-route, dont les conséquences sont succinctement examinées.
1. INTRODUCTION

1.1 Avvertisement

Ce rapport traite d'un projet qui est définitivement hors du développement standardisé du contrôle aérien ainsi que défini dans les programmes officiels d’Eurocontrol, de l'Union Européenne et des autres organisations du contrôle aérien. En conséquence, le « disclaimer » officiel apparaissant en première page de chaque rapport du CEE est, dans le cas présent, mis en évidence et apparaît en caractères gras pour mieux le souligner.

Ce rapport ne reprend QUE les idées de l'auteur.
Il ne représente EN AUCUN CAS la politique de l'Agence

Bien que l’auteur ait tiré profit de discussions, depuis 25 ans, avec des contrôleurs du trafic aérien, des ergonomes et des chercheurs en sciences cognitives et en psychologie expérimentale, il n’est pas, n’a jamais été et ne sera jamais un contrôleur du trafic aérien. Les idées présentées dans le présent rapport sont donc personnelles et il est malheureusement conscient du fait qu’elles ne seront pas bienvenues par de nombreux contrôleurs du trafic aérien en activité.

Ce rapport commence avec la présente introduction.

Le Chapitre 2 contient un sommaire des origines et du développement du contrôle aérien.

Le Chapitre 3 est une description générale de la pratique ATC contemporaine.

Le Chapitre 4 décrit les principes fondamentaux de l’ATC.

Le Chapitre 5 constitue une allocation systématique des tâches au contrôleur ou à l'ordinateur basée sur des principes ergonomiques (facteurs humains).

Le Chapitre 6 est une reconstruction de l'interface contrôleur-système basée sur des principes ergonomiques et cognitifs, comprenant une démonstration dynamique.

Le Chapitre 7 commente l’utilisation de ‘data-link’ découlant du système, et considère quelques

Le Chapitre 8 estime la capacité du système ravisé. Il suggère que la capacité individuelle augmentée peut fortement réduire le nombre d’unités de contrôle requis.

Le Chapitre 9 commente certains aspects primordiaux de la réalisation d'un tel système.

Le Chapitre 10 est un sommaire des conclusions de ce rapport.
10. CONCLUSIONS

10.1 Le système contemporain de contrôle du trafic aérien est le produit d'une évolution non-

10.2 Il est proche de sa limite de performance.

10.3 Une révision radicale est proposée selon les principes admis en ergonomie.

- Les êtres humains doivent être aux commandes ;
- Les êtres humains doivent faire les tâches qu'ils aiment, et qu'ils font bien ;
- La tâche doit être compatible avec les possibilités mentales de l'humain ;
- Les activités de routine doivent être mécanisées ;
- Les encombrements hors de propos doivent être supprimés.

10.4 L'utilisation des méthodes modernes de 'data-link' peuvent augmenter la sécurité et réduire la congestion des communications.

10.5 L'utilisation des méthodes digitales de transmission et de stockage des données enrichira la conscience des pilotes du trafic environnant et éliminera des problèmes linguistiques.

10.6 Le système révisé implique l’utilisation des Free routes directes permettant de réduire les frais et d'augmenter fortement la capacité du système.

10.7 En principe, tout espace aérien européen «en route » peut être contrôlé à partir d'une seule unité. Les balises, routes, secteurs et la plupart des limites inter-centres peuvent être

10.8 Le système révisé ne doit pas être considéré comme une réduction de l'expertise et toute réduction de personnel est à éviter.