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Terminal area traffic management

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TERMINAL AREA TRAFFIC MANAGEMENT

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Abstract

The main theme in this report is the description of time-based traffic management procedures that have been proposed to increase the capacity of the air traffic system by the beginning of the next century. However, the report starts with a brief description of today's air traffic control systems. Their shortcomings are identified and the need for improved systems and procedures is discussed. The new technologies which will enable to overcome the limitations of the present communication, navigation and surveillance systems by providing higher quality and improved efficiency, are briefly discussed. Because terminal area management certainly is one of the most critical aspects of overall air traffic management, the main focus in this report is on this issue. Finally, current research efforts towards improved trajectory optimization and control for flight operations in an extended terminal area are described in some detail.

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ABBREVIATIONS

ABS	Aeronautical Broadcast Service
ACARS	Airborne Communication, Addressing and Reporting System
ACAS	Airborne Collision Avoidance System
ACC	Area Control (Center)
ADS	Automatic Dependent Surveillance
AFTN	Aeronautical Fixed Telecommunication Network
APP	Approach Control
ASDE	Airport Surface Detection Equipment
ATA	Assigned Time of Arrival
ATC	Air Traffic Control
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
ATN	Aeronautical Telecommunications Network
ATS	Air Traffic Services
CAS	Calibrated Airspeed
CDU	Command and Display Unit
CNS	Communication, Navigation, Surveillance
CTA	Control Area
CTAS	Center/TRACON Automation System
CTR	Control Zone
DH	Decision Height
DME	Distance Measuring Equipment
EFIS	Electronic Flight Instrument System
ETA	Estimated Time of Arrival
FAF	Final Approach Fix
FIR	Flight Information Region
FLIR	Forward Looking Infrared
FIS	Flight Information Service
FL	Flight Level
FMS	Flight Management System
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
HF	High Frequency
HUD	Head-Up Display
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
INS	Inertial Navigation System
IRS	Inertial Reference System
MLS	Microwave Landing System
MMI	Man-Machine Interface
RNAV	Area Navigation
RT	Radio-Telephony
RVR	Runway Visual Range
SSR	Secondary Surveillance Radar

STAR	Standard Arrival Route
STCA	Short Term Conflict Alert
TCAS	Traffic alert and Collision Avoidance System
TMA	Terminal Area
TWR	Tower
UTA	Upper Control Area
VFR	Visual Flight Rules
VHF	Very High Frequency
VMC	Visual Meteorological Conditions
VOR	Very High Frequency Omni-directional Range
ZOC	Zone of Convergence

1. INTRODUCTION

Due to the steadily increasing congestion in the air traffic system, air travel delays have become a major problem in recent years. Aircraft approaching the terminal area of a saturated airport are often forced to absorb delay in a fashion which is not very favorable in terms of fuel-economy (e.g., holdings). Moreover, flight operations in a congested terminal area generally result in a high workload for both pilots and air traffic controllers. Recent developments in the area of time-based traffic management hold promise for alleviating these problems. Assigning each arriving aircraft a landing time early during the flight not only permits to absorb delay in a more fuel-efficient manner (e.g. speed reduction), but also helps reducing the variability of the arrival traffic. The precision delivery capability provided by accurate time-based guidance allows the actual aircraft separations to be brought closer to the minimum required time separation between aircraft, thus increasing the system capacity. It has been widely recognized that in order to be able to exploit such time-based control procedures it is imperative not only to introduce advanced automation techniques in both airborne and ground systems, but also to develop an air/ground data link which allows an accurate and fast exchange of digital data between airborne and ground based systems, thus effectively integrating the information available in both systems.

The airborne component which synthesizes all relevant information associated with the present state of the aircraft is the Flight Management system (FMS). The development of the integrated Flight Management System, in which performance optimization and multi-sensor navigation and guidance have been combined, has led to considerable improvements in the onboard capability to plan, predict and execute optimized flight profiles with high precision, while significantly reducing the crew's workload. The FMS is therefore well suited for integration with Air Traffic Control (ATC).

On the ground side comparable technology is currently not available. In particular, the uncertainty in the information on both the actual and the planned trajectories seriously hampers the planning and conflict detection functions of the ground system.

Currently extensive research efforts are being undertaken to develop automation tools to support air traffic controllers in their planning, coordination and monitoring tasks, with the objective of increasing the efficiency of air traffic management (in terms of capacity and economy) and decreasing controller workload. Data links are being developed which allow the ground system to take full advantage of the capabilities of FMS and vice versa.

In future-ATM concepts it is envisaged that aircraft equipped with an advanced FMS featuring a four-dimensional (time-based) navigation capability, will "negotiate" their preferred trajectory with the ground system via the data link. The aircraft transmits via the data link to the ground system a desired four-dimensional trajectory. The ground system then performs 'collective optimization' to resolve conflicts between individual preferred trajectories. When no conflict exists the requested trajectory is approved, otherwise a set of time constraints will be transmitted and the process is repeated until a trajectory is found that allows the

aircraft to be safely and efficiently merged into the traffic flow. It is clear that if capacity is not a constraining factor, there is considerable 'freedom' for individual aircraft to optimize their own trajectories.

This report starts with a brief description of today's Air Traffic Control systems. Their shortcomings are identified and the need for improved systems and procedures is discussed. The main features of concepts that have been proposed as future air/ground integrated air traffic management systems will be described. The new technologies which will enable to overcome the shortcomings of the present communication, navigation and surveillance systems by providing higher quality and improved efficiency, will be briefly discussed. Because terminal area management certainly is one of the most critical aspects of overall air traffic management, the main focus in this report will be on this issue. Finally, current research efforts towards improved trajectory optimization and control for flight operations in an extended terminal area will be described in some detail.

2. DESCRIPTION OF PRESENT-DAY ATC

2.1 Airspace and route structure

Shortly after world war II, the International Civil Aviation Organization (ICAO) established rules and procedures for air navigation, as well as design specifications for the equipment to be used for this purpose. One of the more important air navigation services to be provided relates to Air Traffic Control (ATC), a service which is responsible for the "provision of a safe, orderly and expeditious flow of air traffic"⁽³²⁾. On the basis of ICAO guidelines, ATC is executed according to the same principles and methods in all ICAO Member States.

In order to be able to respond to specific problems on a regional basis, the world's airspace has been divided into 9 ICAO regions. Each of these 9 regions has in turn been subdivided into Flight Information Regions (FIR's). Within each FIR, the responsibility for the Air Traffic Control is delegated to the state which has the sovereignty over that particular part of the airspace.

The airspace organization within a FIR is determined by two elements: the airspace division and the route structure. Within each FIR, two categories of airspace can be distinguished, the controlled airspace and the uncontrolled airspace. Only within the controlled airspace ATC service is provided. The controlled airspace is further subdivided into Control Zones (CTR's) and Control Area's (CTA's). A CTR is generally a cylindrical shaped part of the airspace, approximately 10 NM in diameter, situated around one or more airports and extending upwards from the airport surface to a specified upper level (e.g. 3000 ft, see Fig. 1). A CTA is a large portion of airspace of a FIR and includes airways, Terminal Areas (TMA's) and Upper Control Areas (UTA's). An airway is a corridor of airspace, which defines an Air Traffic Service (ATS) route for en-route traffic. In the TMA's, which are usually considered separately from the CTA's, the transition of traffic takes place between the en-route phase (airway) to final approach (CTR) and from departure to the en-route phase (see Fig. 1). Also

defined in the CTA are the so-called holding areas, or stacks. In these stacks, arriving aircraft fly a race-track shaped holding pattern in order to absorb delays which can not be accommodated in another way. The UTA relates to a traffic area covering the upper airspace, i.e. the airspace above a certain flight level.

Fig. 1. Airspace structure in and around a Terminal Area.

To facilitate safe helicopter operations, special zones have been created (Helicopter traffic zones and Helicopter protection zones). In order to segregate military and civil air traffic, certain parts of the airspace may be restricted for civil flight operations (possibly on a time-shared basis). In areas where mixed airspace utilization is permitted, the civil traffic uses the ATS routes, while military ATC is responsible for maintaining safe separation between civil and military traffic.

An ATS route can be defined in a horizontal plane in terms of a series of reference points (determined by the location of radio navigation beacons), which are connected by straight line segments, and in a vertical plane in terms of a band of available flight levels. Several types of ATS routes can be distinguished, such as airways (en-route traffic), arrival and departure routes. A Standard Instrument Departure (SID) defines the route from a runway to an airway; a Standard Arrival Route (STAR) defines the route from an airway to the airport of destination. STAR's connect the en-route phase to the initial approach phase (see Fig. 2). The purpose of defining STAR's and SID's is threefold. First of all, arriving and departing traffic can be segregated, secondly, the need for communication between controllers and pilots is reduced and, thirdly, the flight paths can be shaped to provide the best possible noise abatement.

Fig. 2. Schematic representation of the different flight phases (Ref. 33).

2.2 ATC services and procedures

Since the beginning of ATC three distinct types of ATC services have evolved, corresponding to different types of controlled airspace, namely Area Control (ACC), Approach Control (APP) and Aerodrome Control (TWR: Tower).

Area Control provides service to traffic in the en-route airspace (CTA), while Approach control provides guidance and separation of approaching, overflying and departing aircraft in a TMA. In high density terminal areas, APP is usually split up into approach planning, which controls inbound traffic from the stacks via standard arrival procedures to the vector area, arrival control, which merges traffic from several directions with correct spacing onto final approach, usually by employing "radar vectoring procedures" (speed and heading commands), and departure control, which controls outbound traffic. Outbound traffic is generally directed to the en-route sectors via a SID procedure.

The Aerodrome Control service deals with both ground traffic on the maneuvering area (runways, taxiways, etc.) of an airport (Ground Control), as well as air traffic in the CTR, including aircraft which are landing on or taking-off from a runway (Tower Control).

The air traffic control procedures established by ICAO for the handling of air traffic relate to such aspects as responsibilities, available routes, separation criteria, coordination procedures between adjacent sectors, etc. Essentially, two types of control procedures exist, procedural control and radar control. Using procedural control the pilot informs ATC of the aircraft position and identity, either on request from ATC or when predefined conditions are met, such as passing a certain location or flight level. Due to the inaccuracy of these position reports and the unknown behavior of aircraft between subsequent reports, this method requires large separations. When radar control is used the controller is provided with a continually updated picture of the traffic situation, allowing the separation between aircraft to be reduced.

With respect to the execution of flights, two sets of flight rules can be distinguished, Visual Flight Rules (VFR) and Instrument Flight Rules (IFR). In the case that VFR rules apply, the responsibility for adequate separation lies with the flight-crew, according to the 'see-and-avoid' principle. However, when IFR rules apply, the responsibility for adequate separation rests with ATC (in controlled airspace). VFR may only be applied under Visual Meteorological Conditions (VMC), i.e. when certain well-defined conditions with respect to visibility from the cockpit are met⁽³²⁾. However, almost all commercial flights are conducted under IFR. For reasons of safety and efficiency, large parts of the controlled airspace are closed for VFR traffic. Aircraft operating under IFR are required to be equipped with an appropriate avionics package to be able to execute flights under poor visibility conditions.

The precision of following planned flight profiles with respect to route, altitude and time, the ability of ATC to determine and predict aircraft positions, and the reaction time needed by air traffic controllers and pilots to respond to potentially dangerous situations are important factors in the determination of safe values for the minimum distance requirements for separation between aircraft. These separation standards, among other factors, determine the maximum number of aircraft which can safely use a certain volume of airspace (airspace capacity) or

a runway (runway capacity) in a certain period of time.

Separation between aircraft is described in 3 dimensions, i.e., in vertical, lateral and longitudinal distances. Often the lateral and longitudinal separation standards are combined into a single horizontal separation standard.

Basically, for controlled airspace two separation standards exist, depending on the type of control procedure applied, namely, procedural separations, for airspace without radar coverage and for (procedural) transfer of control between ATC centers, and radar separations, for airspace with sufficient radar coverage. Procedural separation minima depend on the flight phase, the route structure and relative aircraft speeds. A rather elaborate set of rules exists for establishing the separation minima⁽³²⁾. In the vertical plane, for example, a separation of 1000ft below FL 290 and 2000ft above FL 290 is required. With respect to lateral separation a distinction has to be made between lateral spacing of aircraft and the spacing of routes. Currently applied dual routes may have less than the required lateral spacing. In that case, however, traffic is vertically separated by allocating specific flight levels to each route.

Radar separation standards only concern horizontal separations. The criteria are derived from surveillance accuracy, resolution and uncertain aircraft behavior. However, a lower limit of 3 NM in the TMA and 5 NM en-route has been established.

Beside the procedural and radar separation standards, additional standards exist, e.g. for aircraft landing or taking-off (the wake-vortex separation) and for approach operations under low visibility conditions.

The wake vortex, induced by aircraft as a consequence of generating lift, is a potential safety hazard for following aircraft. The intensity of an induced vortex is larger for heavier aircraft and increases at lower speeds. The potential risk is therefore larger for departing and landing aircraft than for en-route traffic. The required separation between two aircraft is determined by the weight class (heavy, large or light) of both aircraft. This is illustrated in Table 1. The separation criteria associated with wake vortex are generally larger than the radar separation criteria.

For final approach operations in low visibility conditions (CAT II and CAT III operations) longitudinal separations are increased (see Table 2).

Table 1. Wake Vortex Minimum Separation Distances (in NM; Heavy: 136,000 kg and above ; Light: below 7,000 kg ; Large: other).

Leading Aircraft Type	Trailing Aircraft Type		
	Heavy	Large	Light
Heavy	4	5	6
Large	3	3	4
Light	3	3	3

Table 2. ILS Operational Categories (DH: Decision Height ; RVR: Runway Visual Range).

Category	Decision height (ft)	Runway Visual Range (m)	Visibility (m)
I	$200 \leq \text{DH}$	$550 \leq \text{RVR}$	≥ 800
II	$100 \leq \text{DH} < 200$	$350 \leq \text{RVR} < 550$	-
III a	$0 \leq \text{DH} < 100$	$200 \leq \text{RVR} < 350$	-
b	$0 \leq \text{DH} < 50$	$50 \leq \text{RVR} < 200$	-
c	0	0	-

2.3 Communication, Navigation and Surveillance Systems

2.3.1 Introduction

Communication, Navigation and Surveillance (CNS) systems are essential elements in the provision of ATS, facilitating safe and efficient air transportation, especially in controlled air space. Communication systems enable air/ground communication between pilots and controllers, and ground communication between controllers. Navigation systems enable aircraft to navigate from the point of departure to the destination, by providing position and/or guidance information. Furthermore, ground-based navigation aids define the airspace structure by delineating ATS routes, fixing significant points and bounding special areas. Surveillance systems enable the observation and identification of aircraft, both on the ground and in the air. In this Section an overview is given of the currently used relevant on-board and ground-based systems for CNS in high-density airspace. A more comprehensive overview of CNS systems can be found in Ref. 32.

2.3.2 Communication Systems

Air/ground speech communication concerns the two-way transmission of spoken information between aeronautical ground and aircraft stations. The physical implementation is by means of radio telephony (RT), i.e. High Frequency (HF) and Very High Frequency (VHF) voice communication systems. For continental high-density and TMA traffic HF communication is of limited importance. General information, such as actual or forecast weather, is made available by the Aeronautical Broadcast Service to all airspace users on special radio channels, thus reducing RT communication.

For ground/ground speech communication between air traffic controllers in one ATC center or between controllers in adjacent centers, direct speech circuits have been installed based on existing telephone networks. These speech circuits are the primary means for the coordination of aircraft movements between the various elements of the ATS ground organization.

For ground/ground data communication between aeronautical fixed stations (ATC centers, etc.) a special network, the Aeronautical Fixed Telecommunications Network (AFTN) has been developed. In addition to the AFTN network, direct computer links and telephone networks are used for ground/ground data communication.

2.3.3 Navigation Systems

Navigation is the process of directing the movement of a vehicle from one point to another⁽⁶¹⁾. The navigation process provides the pilot (and/or the on-board flight control system) with information, permitting the aircraft to follow a planned flight trajectory and to comply with instructions from air traffic control. Navigation consists of two sub-processes, position determination and guidance. In the guidance sub-process, position information is used to guide aircraft along a required trajectory as accurately as possible. Navigation can thus be regarded as the process that determines the actual flight profile. The flight profile can be synthesized from three sub-profiles, namely, the horizontal flight profile (route), describing the trajectory in a horizontal plane (2 dimensions), the vertical flight profile, describing the vertical position coordinate along the horizontal flight profile (3rd dimension), and the speed profile, describing the magnitude of the speed vector along the 3-dimensional flight path, thus providing the relation between position and time (the 4th-dimension).

The information which is required to execute the navigation process is provided by various navigation aids. A distinction is made between dependent, station-referenced aids (the radio navaids), comprising point reference navaids and hyperbolic navaids, and independent, self-contained navaids. The station-referenced navaids, which have an airborne and a ground-based component, can be of the broadcast or of the transponder type. Transponder type navaids can serve a limited number of aircraft simultaneously, due to their active participation in the position fixing process by responding to interrogation by the airborne component. The broadcast type aids impose no limit on the number of aircraft to be served simultaneously.

Point-reference nav aids are navigation aids of which the ground-based component consists of only one (earth-fixed) beacon, which transmits a ground-to-air navigation signal. The most important point-reference nav aids currently used for civil aircraft navigation are the VOR and DME.

VOR, very High Frequency Omni-directional (Radio) Range, is the standard ICAO short-distance aid and at present the most important civil navigation system for continental en-route and TMA traffic. VOR, which is a broadcast type system, provides directional information, expressed in radials, of the aircraft relative to the VOR beacon. Being a line-of-sight system the VOR range is limited to approximately 250 NM.

The Distance Measuring Equipment (DME) is a transponder type radio nav aid. It is the standard ICAO system for precise navigation service, operated as a complement to VOR. A VOR/DME combination, whereby a DME is collocated with a VOR, provides distance and bearing information, which is sufficient for a position fix. The range of this line-of-sight system is approximately 250 NM. One DME station can accommodate at least 100 aircraft.

VOR and DME are typical short-range radio nav aids. For medium and long-range navigation, the non-ICAO standard hyperbolic systems LORAN-C, Omega and, to a lesser extent, DECCA are the primary radio nav aids. However, for flight operations within high-density continental and TMA airspace, which is extensively covered by short-range nav aids, the use of hyperbolic systems is of limited importance.

The Instrument Landing System (ILS) is a standard ICAO non-visual navigation aid for final approach and landing. ILS provides the aircraft with information to guide the aircraft to the landing runway. The ILS defines a straight line, extending from the touch-down point over the extended runway centerline at an angle of 2.5 to 3° with the horizontal plane. As mentioned earlier, three performance categories have been defined (CAT I, II and III), specifying the operational capabilities of the ILS system (including both airborne and ground-based components) in terms of approach visibility and decision heights (see Table 2).

Self-contained on-board navigation systems operate independently of radio beacons. They are thus insensitive to radio interference and can be applied globally and at any altitude. However, the navigation accuracy of these systems decreases with time, thus requiring regular updates of position information, a position fix, by a different navigation system. The most important self-contained navigation system for modern air transport aircraft is the Inertial Navigation System (INS). Based on ground-related aircraft acceleration measurements, an INS calculates the 3-dimensional position, as well as the ground speed along the track. The INS computer performs the position fixing calculations and is also used for storage of navigation waypoints and for computing guidance information to steer from waypoint to waypoint. A variant to the INS is the Inertial Reference System (IRS), an INS without the waypoint navigation computations. It merely provides position, heading, track, velocities, etc. to an area navigation system, which will be described later.

2.3.4 Surveillance Systems

For ATC, accurate and timely knowledge of aircraft position and identity is of prime importance. In order to obtain actual aircraft position and identity more accurately and frequently than is possible with periodical position reports transmitted via voice communication, a number of surveillance systems has been developed, including Primary Radar (PR), Secondary Surveillance Radar (SSR) and Airport Surface Detection Equipment (ASDE).

Primary radar transmits high power signals and detects actual reflection of those signals. Secondary Surveillance Radar needs less power, since an on-board transponder, on receipt of SSR interrogation pulses, transmits a reply, which is then detected by the ground system. Both radars provide the slant-range and azimuth of the aircraft. The advantage of the SSR is that information regarding aircraft identification (SSR mode A) and aircraft pressure altitude (SSR mode C) can be included in the transponder reply. Both systems have specific disadvantages⁽³²⁾ and for this reason a combination of primary and secondary radar is often used, in which case the SSR antenna is situated on top of the rotating primary and secondary radar. In current radar systems, the radar information is extensively transformed and filtered before it is presented on a radar screen. Airport Surface Detection Equipment is used to detect the position of aircraft and other objects (vehicles) on the ground and of aircraft flying in the vicinity of the airport.

2.4 Area Navigation and Flight Management Systems

Area Navigation Systems (RNAV) are navigation systems which allow the aircraft to fly any desired horizontal profile (within technical and operational constraints) without necessarily approaching or overflying radio navigation beacons, or even without being within their coverage (direct routes). In an RNAV system the position fixing component combines information from different aircraft sensors using at all times the best available set of information to provide the best possible navigation accuracy. Early RNAV systems were primarily based on INS and VOR/DME. Most current systems are based on IRS and dual or even multiple DME, to give DME/DME position or, in the absence of such information, a less accurate VOR/DME position. In areas with sufficient radio navaid coverage, the INS/IRS is used to smooth the radio navigation measurements and to cover short periods out of radio coverage.

The first RNAV systems only permitted accurate navigation in the horizontal plane (2-D RNAV). Modern systems, which are usually integrated within the Flight Management System (FMS), may also provide vertical navigation (3-D RNAV) and even time-based navigation (4-D RNAV).

The development of a complex airborne computing system such as the FMS, has been made possible by the advances in computing technology that have been realized in the last decade. As its name suggests, the FMS is not only responsible for navigation, but for all aspects of flight management^(36,55,59). Flight Management System technology was first developed in the early 1980's with the objective of reducing pilot workload. Indeed, the introduction of FMS, together with improvements in cockpit displays and monitoring systems, has allowed the transition from the three- to two-man crew cockpit.

Increasingly, Flight Management computers are becoming standard fit on present-day passenger aircraft. As a matter of fact, FMS has become an integral part of any new aircraft program, while avionic update programmes, which incorporate flight management computers, are available for older aircraft types. It is expected that by 1996, e.g. about half of the U.S. transport fleet will be equipped with an FMS⁽⁴⁸⁾.

Of the many features that a modern FMS offers, only those relevant to interaction with ATC will be discussed here, i.e., those features falling into the functional areas, navigation, flight planning, performance, guidance to the flight plan, predictions along the flight plan and display support. A functional description of a typical current generation 3-D FMS is presented in Figure 3.

Fig. 3. Typical current generation FMS functional arrangement (Ref. 36).

The navigation function provides the position and velocity determination, while continuously assessing the accuracy of the produced estimates. The selection which radio navigation aid the receivers in the aircraft shall be tuned to, is also performed by this function (autotuning).

The flight planning function supports the assembly and revision of the desired flight plan. Flight planning accepts and interprets pilot entries of flight plan data. These entries are in the form of a list of waypoints. Alternatively, a complete list of waypoints corresponding to a predefined route can be retrieved from the navigation data base. This navigation data base contains all current information required for operation in a specified geographic area, including waypoints, navigation aids, airports and runways, airways, terminal area procedures (SID's, STAR's) and Company Route structures (corresponding to normal airline routes).

The essential difference between an FMS and a conventional area navigation system lies in the ability of the FMS to optimize and control flight paths in a vertical plane. This optimization is based upon real-time measurements of actual flight conditions, as well as pilot-entered data. To support the performance function, the FMS contains a complete airframe and engine model, along with an atmospheric model. The key to vertical profile construction is a parameter called Cost Index (CI). This pilot-entered number relates the operator's direct hourly flying cost to the cost of fuel, to allow a tradeoff between the two. For example, a fuel-economic flight profile (corresponding to Maximum Specific Range operation) can be selected by entering a zero cost index. Thus, speed/altitude profiles can be employed that ensure the lowest possible (operator-defined) trip cost in day-to-day revenue service operations. In general, the lower the selected CI number the slower the resulting speed schedule and, consequently, the longer a flight will take. In a FMS capable of 4-D navigation (time control), the pilot can designate a required time of arrival at destination or at a specified waypoint. The 4-D navigation performance function then uses a quick-prediction algorithm to search for the cost index that produces an estimated time of arrival (ETA) that matches the required time of arrival. In addition to generating optimum profiles, FMS allows pilots to select non-standard speed/altitude profiles. Cost-optimal or pilot-selected flight profiles may require flying the aircraft at or near the limits of airplane or engine performance. Reliance upon a system such as the FMS, therefore requires assurance that the speed and thrust targets provided by the system will not exceed those limits, and that the systems flight planning computations will only offer performance options that are within the aircraft's capabilities.

Given the flight plan as defined by the pilot, and given the current estimate of aircraft position, The FMS is able to calculate lateral and vertical guidance commands which allow the aircraft to automatically capture and subsequently follow that route from take-off to ILS intercept⁽⁵⁹⁾. The FMS represents a flight plan as a sequence of connected legs. Each leg is defined by a lateral profile type and a terminator. Lateral profile types include great circle routes (courses), fixed tracks, fixed headings and DME arcs. In addition, there are some special flight plan leg combinations which can be activated as a single unit. These include holding patterns, procedure turns and parallel offset. Selecting the latter type allows the pilot to fly parallel to the predefined lateral flight path at a defined distance to the left or the right. This feature is incorporated to permit ATC to allocate fast and

slow aircraft on the same basic flight plan without one over-running the other. A terminator defines the end of a leg. Legs can be terminated at fixed way points, altitudes, course intercepts, DME distances, intersections of a VOR radial, and on command of the pilot. Several combinations of lateral profile types and leg terminators have been collected in a standardized "toolbox" of leg types, from which any desired profile can then be constructed⁽⁵⁾. If an active flight has not yet been acquired, the aircraft has to receive guidance from the FMS to capture the active leg of the flight plan. This automatic guidance can only be provided when the aircraft is on an interception course with the active leg. If this is not the case, the pilot has to either select a heading that will bring the aircraft on an interception course, or insert a "direct to" waypoint to make flight plan capture possible. Because leg types may have different lateral profiles and terminators, an elaborate set of rules is required for switching from one leg to another. By including such features as turn anticipation, efficient horizontal profiles can be constructed that can be accurately tracked.

On the basis of the entered flight plan, a vertical profile is assembled in a set of iterative refinement steps. For this purpose the lateral flight plan is divided into approximate flight phases, including the climb, cruise and (reversely computed) descent profile.

It is noted that the FMS usually contains only outer loop control and does not have direct access to the flight controls (inner loop). In performing the guidance function, the FMS provides commands to both the autopilot and the autothrottle system. For lateral guidance the interface with the autopilot is a roll command. The vertical guidance interface depends on the particular equipment fit of the aircraft. The vertical guidance commands provided to the system may include autopilot/autothrottle mode requests, vertical speed targets, altitude targets and speed targets (either CAS or Mach as appropriate). The way in which these guidance commands are actually used by the autopilot/autothrottle system depends on the flight phase.

A capability central to the operation of a FMS is the prediction of the down route situation. When the required information has been entered about the proposed route, the predictions algorithm can emulate the aircraft's four-dimensional track in space allowing to predict time of arrival, speed, altitude, fuel remaining, etc. at fixed waypoints along the flight plan and at the destination airport. In addition the predictions algorithm identifies additional "vertical" way-points such as top of climb, top of descent, and speed change points, that are a function of aircraft performance, environmental conditions and selected speeds. The predictions function also generates warning messages to the pilot if hazardous situations are detected. The value of the predictions produced by a FMS depends upon the accuracy of the information upon which it bases the estimates. There are indeed several uncertain factors which affect the fidelity of the predictions. For this reason, predictions need to be dynamically updated to allow for changes in the actual conditions. A major inherent source of inaccuracy in the predictions is the lack of up-to-date environmental information along the planned route. An FMS therefore makes certain assumptions about the environmental conditions. However, any additional environmental information (such as winds and temperatures) that becomes available can be entered in the FMS, allowing the flight planning estimates to be refined. The dynamically updated predictions are

particularly useful for assessing the effects of temporary or permanent modifications of the flight plan. In terms of computer throughput, the FMS prediction function clearly is one of the most demanding.

The primary display and entry unit of the FMS is the Control Display Unit (CDU). FMS also supports data transmission to the Electronic Flight Instrument System (EFIS). The EFIS navigation display provides a graphical presentation of the flight plan and the progress along the flight plan.

2.5 ATC objectives, tasks and the role of automation

The objectives of ATC are, as mentioned earlier, the provision of a safe, orderly and expeditious flow of air traffic. A number of basic tasks can be distinguished which are necessary to meet these objectives⁽³²⁾:

- **Planning:** This concerns the management (in the general sense) and optimization of air traffic. It comprises the planning/prediction of the trajectory of individual aircraft and the overall traffic situation. Included in this task are planning conflict detection and resolution;
- **Monitoring:** This concerns the monitoring of individual flight progress (to detect any non-compliance with the cleared flight profile), as well as the overall traffic situation (to detect any potential conflicts);
- **Control:** This concerns the preparation and execution of actions which have an immediate effect on the progress of one or more flights. This task includes the generation and issuance of clearance instruction messages and the coordination of flights between sectors.

With respect to the execution and support of the above mentioned tasks, a number of functions can be distinguished within an ATC center, which may be automated to various extent. In the evolution of Air Traffic Control, automation has mainly been limited to the gathering and storage of data, a limited automatic data update, and selective presentation of information to the Air Traffic Controller. This is illustrated in Figure 4, in which three successive generations of ATC systems are shown⁽³³⁾. Automation in ATC has primarily been aimed at better utilization of the limited information available on flight intention, as provided in the flight plan, and the position of aircraft as provided by current surveillance means. In the third generation ATC systems (see Figure 4), improved radar and digital computer systems have been introduced, allowing to integrate radar and flight plan data processing. In present-day ATC, the three central ATC tasks, planning, monitoring and control, are mainly executed by man. For those functions that have been (partially) automated, man and machine work in a complementary fashion, i.e. part of the task is executed by the computer, and part of the task is executed by man. In today's ATC systems, the following automated functions may exist:

- **Trajectory prediction:** This function is usually limited to ETA prediction for approach planning purposes.
- **Flight progress monitoring:** This function entails the detection of passage of a significant point, measurement of track to flight plan divergence and

- triggering of trajectory prediction if too large deviations are measured.
- **Short Term Conflict Alert (STCA):** A conflict detection function for conflicts up to 2 minutes ahead. STCA serves as a safety net, i.e., it is still the controllers function to detect and resolve (potential) conflicts as early as possible.
  - **Medium Term Planning Conflict Alert:** A conflict detection function for specific route intersection points for conflicts at approximately 10-15 minutes ahead.

Fig. 4. Three generations of ATC systems.

3. SHORTCOMINGS OF PRESENT-DAY ATC.

3.1 Introduction

In recent years the gap between the demand for air service and ATC capabilities has increased significantly. During the last decade, the airspace and runway capacity hardly increased (particularly in the U.S. and Europe), while the demand for air travel grew above expectations. The overall effect of this imbalance between demand and capacity growth has been a substantial increase in delays and the use of inefficient flight profiles, resulting in a reduced regularity and economy of flight operations. The shortcomings of present-day ATC to deal with this situation have been addressed in many publications^(32,51,86). For example, in Ref. 3 it is claimed that the shortcomings of present-day ATC in Europe amount to extra costs for the operators of over 4 billion U.S. dollars a year.

In order to provide a basis of understanding with respect to the consequences of the shortcomings of the ATC system for the airspace users in TMA airspace, it is necessary to first address the main parameters that characterize the system performance: capacity and efficiency. With respect to the latter, both ATC and flight efficiency will be considered. Secondly, the shortcomings of CNS systems and ATC automation are identified.

3.2 ATC capacity and efficiency

Today's ATC can be characterized as not being effective, i.e. the results of its operation are smaller than the required results. These results concern, besides safety, two major aspects, namely capacity and efficiency.

Capacity is the ability to accommodate demand. In terms of ATC, capacity is associated with the ability to accommodate a certain volume of air traffic per unit of time. When considering capacity, it is useful to make a distinction between the various elements of the ATC system. Usually the following three elements are distinguished, airspace capacity, runway capacity and control capacity.

For practical purposes, also a distinction is made between "theoretical" capacity and "practical" capacity^(23,32). The former, to which we will frequently refer to as capacity limit, corresponds to the maximum number of aircraft which can be accommodated in a given period of time, provided the aircraft arrive at evenly spaced intervals. The practical capacity is that level of capacity utilization which corresponds to a given acceptable level of (average) delay (see Figure 5).

Efficiency concerns the ability to use available resources with a minimum of waste. When looking at the performance of ATC, the ATC efficiency can be considered as the efficiency in the utilization of the available airspace capacity, runway capacity and control capacity. In fact, the ATC efficiency expresses the differences between theoretical and practical capacity.

The capacity of the airspace is determined by such factors as the possible presence of restricted airspace, the organization of the available airspace (e.g., the route structure), and the separation standards to be applied.

Fig. 5. Characteristic system performance parameters: practical capacity c_p and theoretical capacity c_t .
 (a) definitions,
 (b) qualitative effect of improvement measures.

The available capacity for each specific operating configuration of the runway(s) determines to a large extent the amount of traffic that can be handled by an airport at a given moment. At the airports, TMA traffic from various directions has to be merged, with sufficient spacing, onto one or more final approach paths towards the arrival runway(s). The practical capacity of an airport, and of a single runway, is determined by the structure of the airport and surrounding airspace (approach routes, etc.), the traffic composition, the applicable ATC rules, regulations and procedures and the meteorological conditions.

The actual wind speed and direction determine to a large extent the specific runway operating configuration. When crosswinds or tailwinds exceed certain values, that particular runway configuration becomes unavailable. Ceiling and visibility determine the need for landing aids and different levels of ATC procedures (separation standards) to maintain safe approach and departure operations. A runway can be used for arrivals only, for departures only, or for a combination of arriving and departing traffic. For an arrivals-only runway, the requirement that an aircraft has to have vacated the runway before the next aircraft is allowed to land is usually not a limiting factor for the runway capacity.

The control capacity concerns the volume of air traffic which can be handled by ATC or a specific control sector unit (sector capacity). Such a sector unit represents the basic component in the hierarchical ATC structure. Each sector controller team is responsible for the traffic in its volume of airspace, the penetrating routes and their intersections. It is clear that the mental workload of sector controllers largely depends on the density of the traffic in the sector⁽⁸¹⁾. Obviously, there is a limit to the number of aircraft one controller (team) can plan, monitor and control. However, controllers may have a higher or lower capacity to handle sector traffic, depending on their individual skills.

The control capacity is partly determined by the sectorization, i.e., the division of the airspace into geographic or functional control sectors. The control capacity is also determined by the level of automation and the required amount of air/ground and ground/ground communication (e.g., for handover procedures). Sector capacities may vary strongly when radar surveillance or communication equipment fails, and when severe weather phenomena occur.

Returning to the issue of delay, it should be clear that in order to avoid congestion in the air traffic system, aircraft must be delayed if the traffic flow rate exceeds the capacity limit of the "bottleneck element" of the system. However, delays occur even if the long-term average demand is less than the available capacity. Due to the variability of interarrival times, it may occur that short-term peaks in the arrival flow exceed the available capacity. Since the long-term average demand is less than the available capacity, the delays imposed in this mode of operation serve to smooth the short-term peaking in the arrival flow during busy periods. In ATC this short-term mode of operation is called "metering". The delays resulting from this mode of operation are generally small and some aircraft may not be delayed at all.

In order to minimize the extent and impact of delays that are unavoidable due to average demand exceeding capacity, the arrival flow is regulated by redistributing the demand over time and across the various elements of the ATC network. This mode of operation is called "flow control".

Several methods through which flow control can be exercised are in use, including:

- (i) Speed control in order to time properly the arrival of an aircraft at a waypoint or at a terminal area. En route speed control will generally amount to speed reduction since aircraft cruise already near their maximum speed.
- (ii) Rerouting, i.e., modifying the flight plan of selected aircraft in order to by-pass congested sectors.

- (iii) High-altitude holding and path-stretching in order to delay arrival at a congested terminal area and avoid more costly holding at low altitudes.
- (iv) Restructuring of airspace geometry, i.e., modifying airspace structures and procedures in order to redistribute ATC workload and flows.
- (iv) Controlling departure time, i.e., delaying the initiation of a flight in order to avoid more costly and less safe delay in the air. This pre-flight delay directive is also known as a "gate-hold" or "ground-hold".

While it is difficult to rigorously define control capacity, it is for most practical purposes possible to adequately define runway capacity in terms of separation standards, traffic mix and runway-delivery errors. One such basic capacity model based on IFR interarrival spacing is illustrated in Figure 6. In this model⁽¹⁸⁾ the scheduled interarrival time between two successive aircraft is:

$$T_{SIA} = T_S + T_B \quad (1)$$

with:

$$\begin{aligned} T_S &= d/V_T & \text{if } V_T \geq V_L \\ &= (d + o)/V & \text{if } V_T \leq V_L \end{aligned} \quad (2)$$

$$o = (h - d)(1 - V_T/V_L) \quad (3)$$

$$T_B = \Theta^{-1}(\alpha) \sigma_{IA} \quad (4)$$

$$\sigma_{IA}^2 = \sigma_{RD_L}^2 + \sigma_{RD_T}^2 \quad (5)$$

where:

- T_{SIA} scheduled interarrival time between two successive aircraft at the runway threshold
- T_S minimum permitted separation time, obtained by converting separation distance standard to time
- T_B buffer time added to minimum separation because of delivery uncertainty
- d separation distance standard (see Table 1)
- V_L approach speed of the lead aircraft
- V_T approach speed of the trailing aircraft
- h length of the common final path

- o increase in separation on the common final path if the lead aircraft is faster
- b buffer applied for separation assurance ($b = T_B V_T$)
- α missed approach rate
- σ_{IA} actual aircraft-pair runway interarrival-error standard deviation
- σ_{RD}^L runway delivery-error standard deviation of the lead aircraft
- σ_{RD}^T runway delivery-error standard deviation of the trailing aircraft

Fig. 6. Basic ATC capacity model (adapted from Ref. 18).

A delivery-error-dependent interarrival time buffer is added to the minimum permitted separation time on final approach to keep separation violations to a low probability level. This probability level is specified in terms of a wave-off rate α , which indicates the percentage of aircraft that have to execute a missed approach because of infringement of the minimum required separation standard. The value for the scheduled interarrival time of course depends on the weight category and the approach speed of the lead and trailing aircraft. Note that if the lead aircraft is faster than the trailing aircraft, the minimum separation occurs at the beginning of the common path. Since aircraft of different categories arrive randomly sequenced, the arrival capacity can be estimated as the reciprocal of the expected value of the actual interarrival time interval for a given traffic composition. It is noted that in order to convert a "distance" into a "time", the ground speed has to be used in Eqs. (2) and (3), rather than the air speed. In other words, the wind speed has to be accounted for.

The sensitivity of the runway arrival-rate to delivery precision has been investigated extensively, both in simulation studies and in operational field tests^(1,2,18,24,25,34,70). Figure 7, which is based on the results reported in Ref. 24, shows the runway arrival rate as a function of aircraft-pair interarrival-error standard deviation at the runway threshold for a traffic mix consisting of large and heavy aircraft only. For comparison, runway capacity is given in terms of single-aircraft delivery precision as well. Assuming a Gaussian distribution, the pair interarrival error σ is $\sqrt{2}$ times the σ of single-aircraft delivery error. Also, a second curve is included to show the effect of reduced separation standards.

Fig. 7. Impact of runway delivery error on capacity. 8.6% heavy aircraft and 91.4% large aircraft (adapted from Ref. 24).

As shown in Figure 7, the final delivery precision has a considerable effect on the runway arrival rate. However, the impact becomes even more pronounced as separations are reduced. As a point of reference, the delivery precision (interarrival-error standard deviation) of current manual control is about 18 sec^(18,24). Because of its significant effect on arrival acceptance rate, runway interarrival-error standard deviation is used as the measure to evaluate the system effects of several parameters.

One of the principal factors that increase the spread of the separation distribution at the runway threshold is the variability in final approach speed. There are several other factors that affect the runway delivery precision, including, pilot and controller response times, aircraft heading error, wind speed (error) and piloting procedures.

Realization of a more homogeneous traffic composition will definitely lead to an increase in runway capacity. It is recalled that the minimum permitted separation time T_s (see Eq.(2)) between two successive landings is a variable quantity. This variability is on the one hand the result of the minimum wake vortex separation distances that depend on the aircraft weight class, and on the other hand the result of the differences in the final approach speed. Thus, it may be possible to take advantage of the above variability by rearranging the landing order of aircraft to achieve a landing sequence that results in a more efficient use of the runway than can be obtained by applying the "First-Come-First-Served" (FCFS) strategy, which is currently used at most major airports. Methods to establish the landing order according to a certain strategy are commonly referred to as "sequencing" strategies. Although rearranging the landing sequence can reduce delays, it can not always be implemented. Position shifting of two in-trail aircraft generally requires one aircraft to overtake the other, resulting in an increase in controller workload. Obviously, position shifting can be allowed if it takes place before a position-shifted aircraft pair has merged on a common route.

Although determining an exact optimal sequence is theoretically possible by examining all possible sequences and then selecting the most favorable one, this is not a very practical approach. Enumerating all feasible combinations is extremely inefficient, because the required computational effort is a factorial function of the number of aircraft and is therefore beyond the capability of even the fastest computers currently used in an operational ATC environment. For this reason several sub-optimal approaches have been proposed, which generally consider a simplified, more tractable, problem that provides meaningful results within the computational limitations. Typically these approaches are based on Operations Research methods, such as dynamic programming and integer programming^(17,30,74,75,77,100). Since the existence of an optimal sequence is a direct consequence of the variability of the minimum permissible time interval, it is not surprising that two different types of sequencing strategies have emerged, weight-class sequencing and speed-class sequencing. The capacity gain that can be achieved when a speed-class sequencing strategy is used rather than a FCFS sequencing strategy, is illustrated graphically in Figure 8. Note that in Figure 8 all aircraft are assumed to belong to the same weight class. Also note that the minimum separation distance between two successive aircraft can occur at the start of the common path or at the runway threshold. Figure 8 also makes clear that it can be advantageous to segregate the arrival streams of turboprops (slow

aircraft) and jets (fast aircraft) and only to interleave these streams at a merge point which is selected as close as possible to the runway threshold. Figure 9 illustrates the difference between a weight-class sequencing strategy and the FCFS order, where it has been assumed that all aircraft have the same approach speed. Note that simply switching the order of a small and a heavy aircraft can already free up the equivalent of two landing slots. It can readily be observed that for both speed-class sequencing and weight-class sequencing, position shifting tends to bunch aircraft from the same class. Various studies^(18,64) have indicated that capacity gains averaging 4-6% are potentially available even without requiring overtakes and with a maximum shift of only two landing slots from the FCFS sequence.

Fig. 8. A comparison of speed-class-sequencing and FCFS-sequencing strategies.

A more homogeneous flow of traffic, i.e., a more constant number of movements per unit of time, will lead to an increase in ATC capacity and efficiency. Such improvements can be potentially realized by adjusting the traffic schedules such as to spread peak-hour traffic over the day. Unfortunately, such measures generally conflict with the interest of airlines, in particular those serving a hub-and-spoke route network. In a hub-and-spoke route network, which is gaining in importance as a result of deregulation in the air transport industry, all traffic originating at feeder airports is directed to one central airport (the hub). In order to reach the desired destination it is generally necessary for passengers to transfer to a connecting flight at the hub airport. Connecting flights can take place on a feeder route, which is generally served by small aircraft, or, when the destination is another hub airport, on a trunk line, which is generally served by large aircraft. To facilitate these connections, departures and arrivals are concentrated in so-called "banks" of flights. It can thus be concluded that, although very undesirable from an ATC perspective, the current trend is towards a less homogeneous flow.

Fig. 9. A comparison of weight-class-sequencing and FCFS-sequencing strategies.

3.3 Flight efficiency

It is evident that operators desire a flight profile that is completely unrestricted, i.e., an optimum horizontal profile (shortest route), an optimum vertical profile (unrestricted climb, cruise and descent), an optimum speed profile (no speed limitations) and no delays at departure or arrival. The flight efficiency is determined by the difference between the desired flight profile and the actual flight profile. As discussed earlier, operators generally prefer flight profiles that minimize operating cost. For such flight profiles, efficiency can be interpreted as the ratio between the theoretical minimum costs and the actual costs. Operators calculate their direct operating cost in terms of hourly flying cost plus the cost of fuel. However, when considering the costs of the overall transportation system, the implementation and operating costs of both air and ground systems should be taken into account.

The penalties on the efficiency of flight operations resulting from the shortcomings of present-day ATC can be largely attributed to three interdependent factors, namely non-optimal lateral profiles, non-optimal vertical flight profiles and delays. It must be noted that the "ideal" standards against which the actual flight profiles are compared, are based on the assumption that an aircraft has zero delay, flies the shortest route, and achieves the optimal vertical flight profile within the flight envelope of the aircraft, without taking into account any ATC constraints.

It is clear that metering and flow control may lead to an increased route length, however, other factors contribute to a non-optimal lateral profile as well. Current ATC systems only have a limited capability to accommodate direct routes, because trajectory predictions, data distribution, control procedures, etc., are based on a fixed route structure. As mentioned earlier, the fixed route structure (including departure and arrival routes) does not generally provide the shortest connection between the points of departure and destination.

Metering and flow control measures may also affect the optimality of vertical flight profiles^(24,39,57,64,72,91,104). Moreover, the optimality of vertical flight profiles may suffer from ATC requirements that are procedural in nature rather than tactical or strategic. For example, climb profiles after departure are specified as a part of a standard departure route with speed limitations at lower altitudes.

To illustrate the effect of speed control on flight efficiency, Figure 10 presents a typical time/fuel-burnoff relationship. The curve in Figure 10 has been obtained by evaluating a cruise stage with a length of 100 km, using the aircraft model of a Lockheed C-141 Starlifter jet transport⁽⁹⁷⁾. Each point on the curve in Figure 10 corresponds to a specific value of cruise speed for a given set of operating conditions (wind, temperature, aircraft gross weight, etc.). Moreover, each point on the curve also corresponds to a specific value of the cost index. To see this more clearly, refer to Figure 11 where it is shown that the cost-index CI, which was introduced in Section 2.5 to relate the cost of time to the cost of fuel, can be readily interpreted in terms of the slope of the tangent to the time/fuel-burnoff curve. The values of the cost index along the curve of Figure 10 are plotted as a function of the trip time in Figure 12. Also indicated in Figure 10 is the influence on the time/fuel-burnoff relationship of including a hold at the end of the cruise stage. Figure 10 clearly shows that if time of arrival is to be delayed, (for example, from t_1 to t_2), it is more advantageous to reduce cruise speed, rather

than continuing to fly fast and then spending the excess time flying a holding pattern. For this reason, time absorption through cruise speed reduction is often referred to as "linear holding"^(10,14). It is directly apparent from Figure 10 that the capability to facilitate delays using the linear holding technique is, unfortunately, rather limited. Obviously, the optimal holding speed corresponds to the cruise speed at which the fuel consumed per unit of time is minimal. Figure 10 also reveals that reducing the cruise speed below the optimal holding speed is clearly not advisable from a fuel-economy point of view.

Fig. 10. Typical time/fuel-burnoff relationship. 100 km cruise stage length.

Fig. 11. Interpretation of the cost index.

Fig. 12. The time/cost-index relationship corresponding to Fig. 10.

3.4 Shortcomings of current ATC system components

Many of the ATC deficiencies can be related to shortcomings of CNS systems. The CNS system capability may vary substantially per region, either as a result of varieties in equipment, or due to differences in the density of the air traffic. An assessment of characteristics and capabilities of the present CNS system in Western Europe leads to the following conclusions with respect to terminal area operation⁽⁸⁶⁾:

- (i) **Communication:** The quality and coverage of VHF air/ground communication systems is generally adequate. However, the VHF communication load is high. There is generally a lack of high-speed ground/ground data interchange and system interface capability. Limitations of voice communication, combined with the lack of air/ground data communication prohibits supporting automated systems in the air and on the ground.
- (ii) **Navigation:** VOR/DME navigation aids cover the existing route structure adequately.
- (iii) **Surveillance:** There is not sufficient radar coverage (primary and/or secondary radar). Moreover, automated systems related to surveillance are often incompatible.

Many of the shortcomings of today's ATC are related to incompatibility of ground based systems of different ATC centers, resulting from non-coordinated development of ATC systems on a national basis. This incompatibility concerns system hardware, procedures, level of automation, etc. and results, among other things, in strict handover procedures between adjacent centers to ensure safety and an acceptable controller workload. As a consequence, the capacity of the airspace is reduced.

With regard to the shortcomings of ATC systems two different aspects should be considered:

(1) Shortcomings of individual ATC systems: the lack of route flexibility has a large influence on the efficiency of flight operation. The inability to accommodate random (direct) routes is a direct consequence of the fact that many systems (and procedures) have been designed for the fixed route network only. Moreover, the ATC system performance is limited due to an often far from optimal division of responsibilities between various ATC services and units (sectorization, etc.). Current ground system capabilities do not permit the controller to make reliable and accurate trajectory predictions, which obviously significantly hampers the planning and conflict detection functions. The lack of air/ground data interchange prevents a full exploitation of the precise information available on-board aircraft. Due to the limited planning horizon, strategically oriented control and an associated increase in system capacity can not be facilitated.

(2) Shortcomings of inter-center ATC system cooperation: the shortcomings of cooperation between ATC systems in different centers are related to the fact that there exists a great variety of ATC systems, with varying levels of sophistication, and different operating concepts and procedures in adjacent states. For instance, within Western Europe there are 22 independent, national ATC systems involving some 42 en route control centers. Eastern European nations have expressed interest in tying their ATC systems into that of Western Europe, which obviously will add to the fragmentation if no appropriate measures are taken.

For a long time ATC has been able to meet its objectives of providing a safe and orderly flow of air traffic. As a result, the demand for economy of operation was to a large extent fulfilled automatically. However, the unexpected large increase of air traffic in recent years has resulted in a reduction of ATC's capability to meet its objective of expeditiousness. It has also resulted in less efficient flight operation, largely due to the fact that cockpit crews can not generally take advantage of their FMS optimization capability as a result of ATC instructions that frequently interrupt the planned trajectories. But not only flight efficiency will be impaired. Severe economic penalties may very well lead to a situation in which operators and individual pilots are tempted to change their operating policy from one of safety first to one which tends towards regularity first (meeting slot times).

From the observed shortcomings of present-day ATC and the expected growth of air traffic (even the most conservative forecasts show an increase of air traffic volume of more than 40% between 1985 and 2000⁽⁵⁾), it must be concluded that it is necessary and urgent to significantly improve the existing ATC situation in all its aspects.

4. FUTURE AIR TRAFFIC MANAGEMENT SYSTEMS

4.1 ATM objectives

From the description of present-day ATC and its major shortcomings, a number of potential improvements can be derived. However, many of these possible improvements can only be realized if they are implemented as part of an integrated system concept. For this reason, the ATC of the future is expected to evolve from the present situation by a combination of improved automation of ground systems, application of an automatic air/ground data link and integration of airborne and ground based systems. The expected benefits from such an integrated system approach include^(62,63):

- (i) Pilots and aircraft systems can obtain all required information on ATC system constraints and optimization criteria and can directly access the data bases of the ground systems via the data link.
- (ii) Controllers and ground systems can obtain better knowledge of pilot/aircraft behavior, in particular with respect to the planned and achieved trajectory. Aircraft state information can be made available to the controller/ground system to improve the quality of the surveillance information. As a result the integrity of the data that is common to air and ground systems will be improved as well.
- (iii) The communication workload of the controller is reduced by the use of a data link and consequently there will be an increase in the capability to handle traffic.
- (iv) Aircraft and the ground system can make use of up-to-date meteorological data.

It is clear that such an integrated system concept will allow a more strategic approach towards air traffic control, by planning air traffic movements ahead over a longer time horizon (typically 20-30 minutes) than is currently the case (typically a few minutes) so that potential conflicts can be detected and resolved before they arise. This future integrated control concept is commonly referred to as Air Traffic Management (ATM). In Ref. 51 Air Traffic Management is informally defined as:

"the term used to describe the total system, ground and air, needed to ensure the safe and efficient movement of aircraft, in all phases of operation. It covers airborne equipment (such as Flight Management Systems), the Air Traffic Control (ATC) systems, and in particular the procedures to integrate the two."

Besides ATC, the future ATM system concept also includes Air Traffic Flow Management (ATFM), and Airspace Management (ASM). ATM provides management and control of air traffic, both in the air and on the ground. ATM should also provide an optimum usage of the available airspace according to the requirements of the airspace user.

The main objectives of ATM can be summarized as, (i) maintaining or improving established levels of safety, (ii) improving airspace, runway and control capacity, and (iii) to improve flight efficiency. Clearly, the cost of implementation (of both airborne and ground based systems) is important and should be reasonable in relation to the expected benefits.

A practical aim of ATM is to regulate the flow of air traffic to or through capacitated elements of the ATC network in order to minimize congestion. In order to ensure effective Air Traffic Management it is necessary to achieve a balance between air traffic demand and ATC capacity. When at times traffic demand exceeds the available capacity, specific strategic or tactical ATM intervention will be required, depending on the time frame. Obviously, by applying strategically oriented control the need to exercise tactical control will be reduced.

4.2 Concepts and studies of Air Traffic Management

In the last two decades a significant effort has been devoted towards the development of new ATM concepts, which aim at matching ground based and airborne system capabilities. In an evolutionary way, these concepts should lead to a new ATC system which can accommodate the expected growth in the traffic volume and which provides much greater freedom for individual aircraft to operate in a cost-efficient manner, while maintaining at least the current level of safety. It is clear that proposed system concepts should allow for a smooth transition from the current to the new situation. The most relevant concept descriptions that have been produced include:

- (i) A Conceptual Model for a Future Integrated ATM System, produced by a GARTEUR Action Group^(51,52). The concept relies on the capability of modern aircraft to fly with precision trajectories in an air/ground data link environment. For this purpose, the Action Group has introduced the "Tubes in Space" concept, whereby ATC clearances will assume the form of a rigorously defined four-dimensional tube in space.
- (ii) The National Air Space (NAS) plan of the Federal Aviation Administration (FAA) of the USA⁽⁴⁹⁾. This plan, which is intended for application in the USA, also includes traffic management concepts which are to become operational in 1995 and beyond.
- (iii) The Future ATS System Concept description of the EUROCONTROL organization⁽⁵⁾. The EUROCONTROL organization was set up in 1960 with the objective to improve coordination of ATC between Western European countries. This concept is based on the idea of a "semi-open sky" in which the organization of airspace and navigation is based on random (direct) routes, supplemented by a basic network of published routes.
- (iv) The global CNS and ATM concept developed by the ICAO special committee on Future Air Navigation Systems (FANS)⁽⁶⁶⁾. This concept is intended for worldwide application and primarily focuses on satellite technology to complement or even replace terrestrial CNS facilities. An indication of the envisioned development of the ATM system is also provided.

- (v) The concept description produced by the Future European Air Traffic Services (FEATS) Concept Group⁽⁴⁵⁾. It applies to one particular ICAO region (Europe) and essentially builds on some of the above mentioned concepts, including the Future ATS System Concept Description and the FANS report.

The above mentioned concepts, most of which cover a time-span up to 2010/2015, are of a general nature and therefore need further refinement. Extensive research and development is required in order to be able to design and validate the various (sub)systems, functions and procedures. In order to establish a framework for the coordination and harmonized execution of ongoing and planned research activities on future ATM systems, a joint international program was initiated in 1989 under the umbrella of the EUROCONTROL organization, called "Programme of Harmonised Air Traffic Management Research in EUROCONTROL" (PHARE)^(62,63). The initial goal of this program is the development of an ATM demonstrator for 1992/93. It will feature research aircraft operating in an experimental environment provided by ATC simulators and will include data link facilities. In the validation phase which will extend up to 1995/96 the system will undergo extensive testing and evaluation using the results of the experimental work.

A complementary program launched by EUROCONTROL is "Enhanced Air Traffic Management and Mode S Implementation in Europe" (EASIE)^(62,63,76). The EASIE program encompasses both the development of the relevant automation support for the ATM ground system, as well as implementation of certain elements of the proposed Aeronautical Telecommunication Network (ATN). This automation of air/ground communication will constitute a major step forward in the integration of the FMS with ATC. The ATM system as defined by EASIE will be implemented on a geographical basis in phases determined by traffic density. Initial implementation will cover an area which includes Benelux, France, Portugal, Switzerland and the Southern UK. The area covered will be gradually extended to include adjacent areas with saturation problems.

Based on the proposed ATM concepts, scenario's are developed that provide guidelines for research on improved cooperation and integration of airborne (FMS) and ground-based systems, with the primary objective of improving the capacity and efficiency of the air transport system. Specific research areas include airspace and airport restructuring, the development and application of new and improved CNS systems, the revision of ATC services and procedures and the development of new and enhanced airborne and ground based system functions, including system integration aspects. These issues will be discussed in the remainder of this Chapter.

4.3 Airspace and airport restructuring

The airspace and airport structure to a large extent influence the capacity and efficiency of the ATC system as a whole. An increase in airspace capacity can be obtained directly by an increase in airspace availability, which can be effectuated by reducing the amount of reserved airspace, such as the restricted areas, or by applying a more flexible approach towards the utilization of such airspace, for example by allowing a mixed use of airspace by civil and military users. The latter will require a more extensive coordination between civil and military users.

Other options to increase capacity are to increase the number of (conventional) ATS routes, the number of direct routes and the number of runways. However, simply adding conventional (non-RNAV) ATS routes and runways is restricted by siting constraints and financial limitations. Furthermore, there is a limitation on the ability of present-day ATC to ensure separations at the increased number of intersections of airways that a significant increase in the number of routes would generate.

Environmental aspects play an increasing role, especially with respect to the location of runways and the definition of SID's. The use of RNAV routes is currently limited due the fact that present automated ATC systems are not capable of supporting direct routes. For this reason, direct routes can only be facilitated when the control workload is low. It should be realized that a concurrent extension of the number of routes and runways will significantly increase the complexity of the air traffic network, which will make the controller's task more difficult, possibly even resulting in a reduction in control capacity. On the other hand, improving the design of existing airports with respect to the layout of runways and taxiways may increase the capacity of a specific runway and of the airport as a whole.

There are certain measures which can significantly improve the ATC system, but can not easily be achieved because of their social-political implications. One such measure, which will increase runway capacity, is to alleviate the restrictions on night traffic that have been established for the purpose of noise abatement. The introduction of quieter aircraft may help justify reducing this type of restrictions. A matter of international politics concerns the adjustment of FIR boundaries. The current location of FIR boundaries often coincides with a nation's borders, which may not be the optimal location with respect to handover procedures and the span of control of ATC centers.

4.4 Improved CNS Systems

The limitations of current CNS systems are intrinsic to the systems themselves and to the means by which they are implemented. Therefore present ATC will not improve substantially, unless new system approaches are adopted⁽⁸⁶⁾. Current CNS developments, aiming at higher accuracy, better coverage and an efficient air/ground data exchange, include the introduction of the SSR mode S data link, the development of the Aeronautical Telecommunication Network (ATN), the use of satellite technology and the introduction of the Microwave Landing System.

As mentioned in Section 2.3, current SSR already includes a simple air/ground data link (Modes A and C). The new Mode S development of SSR creates the

possibility of a more comprehensive two-way air/ground data link for routing messages. However, Mode S is certainly not the only technique available to provide air/ground digital data exchange. A second generation VHF radio link called Aircraft Communication Addressing and Reporting System (ACARS) has already been in use for some time to allow airlines to keep track of their aircraft. In addition, the ICAO FANS Committee proposes satellite technology to meet future requirements for air/ground communications.

In response to the need of a system that supports the interoperable use of multiple data links, the concept of the Aeronautical Telecommunication Network (ATN) has been developed⁽⁷⁶⁾. ATN unites all present and possible future data links so as to appear as one system and decides which of the links is the most appropriate to use in a given situation.

Applications of satellite technology are certainly not limited to communications. As a matter of fact, satellite technology is already proving itself in the area's of navigation and automatic dependent surveillance (ADS) as well. Indeed, with satellite technology multiple users can be provided with accurate, continuous, worldwide and all-weather 3-D positioning and navigation. In the ADS application, aircraft will transmit data on their location and altitude, obtained from onboard measurements, automatically via a data link. It needs to be recognized that ADS does not detect navigation errors and the quality of the ADS data therefore strongly depends on the navigation accuracy. However, especially in oceanic areas where no radar coverage can be achieved, ADS may become a powerful surveillance tool. Also in areas where radar coverage does exist ADS data can be beneficially used to enhance the accuracy of the aircraft position information.

Space-based systems which are currently making a particular impact are the so-called Global Navigation Satellite Systems (GNSS), a generic term generally used to refer to a combination of the U.S. Global Positioning system (GPS) and the Russian-built GLONASS. More specifically, the projected GNSS constellation consists of 24 GPS satellites (including active spare satellites), with another 24 GLONASS satellites planned for deployment by the former USSR. Both the U.S. and the USSR have made their respective satellite navigation systems available free of charge to civil users well into the next century. What happens to satellite navigation for civil aircraft in terms of follow-on systems is yet unclear. However, what is clear is that a global transition to a satellite-based communication, navigation and surveillance network, as envisioned by the FANS committee will require international cooperation on an unprecedented scale, involving technical, legal and political matters alike.

Because of the data communication and surveillance capability of SSR Mode S and the fact that current radio navigation aids generally provide sufficient coverage for navigation, while voice communication is adequately performed via VHF-radio, the application of satellite communication and navigation in high-density continental en-route and TMA airspace is likely to play a limited role, at least in the time frame considered in the ATM concepts discussed here.

The currently used ILS will be gradually replaced by the Microwave Landing System (MLS) which will become the ICAO world-wide standard approach and landing aid in 1998^(37,67,82). Due to improved signal quality, the introduction of MLS will eliminate several inherent limitations of ILS. Moreover,

MLS enables new approach and TMA procedures due to the wide coverage in which precision guidance can be given. The greater flexibility in defining approach paths, including curved and segmented paths, and the potential of providing precision guidance during path interception, missed approaches and departures, is likely to have a significant impact on TMA and ATC procedures. If MLS is used as a CAT III landing aid, operations under low visibility will be improved, which may contribute to enhanced runway capacity. Multi-gate approach procedures and a reduction of the gate distance will also be supported by MLS.

It has to be mentioned that within the aerospace community some doubts exist concerning the need for MLS and a number of alternative (less costly) solutions has been proposed. One of these potential solutions, which would possibly also permit to fly curved-path approaches, concerns using ILS (whose antenna technology has significantly improved in recent years, eliminating some of the earlier shortcomings) in combination with a flight management system.

More recently, GNSS is viewed as the major potential competitor of MLS for instrument approach applications. To achieve the precision needed for terminal operations, it is proposed to develop an integrated system that combines GPS/INS, FMS computers and, possibly, enhanced vision devices such as head-up displays (HUD's) and forward looking infrared (FLIR) sensors. However, prospects of such a system to serve as a CAT II and CAT III cockpit-based landing aid will depend on GNSS system accuracy and integrity, as well as on the availability of a sufficient number of satellites. Availability is the probability that the system will provide service when needed. In practical terms this means that 3-D navigation solutions can be obtained only if a GPS receiver is able to "see" at least four satellites. For redundancy and reliability monitoring at least six satellites in good geometric relation to the aircraft are needed. Currently, the major integrity concern is for a monitoring and warning system to alert the pilots if the navigation accuracy of the system falls below the requirements. This problem is particularly acute for a pilot on an instrument approach. The accuracy of GPS for instrument approaches can be enhanced via a technique called Differential-GPS. Differential-GPS requires a GPS receiver to be installed at a ground station near an airport at a location which is exactly known. The GPS receiver is then used to measure the station position. The difference between the known position and the GPS computed location, which is caused by a variety of man-made and natural effects, is then transmitted via a data link to suitably equipped aircraft, allowing them to correct their own airborne receivers. Unfortunately, however, to date even Differential-GPS does not have the required accuracy (particularly in the vertical direction) to permit precision approaches. Since also the basic integrity and availability are not yet sufficient to meet even the least stringent CAT I requirements, it can be concluded that a significant development effort is still needed to make GPS a precision approach system. If MLS manages to prevail, it is likely that an integrated MLS/GPS system will emerge, in which signals from the two systems are combined to exploit the intrinsic advantages of each.

Improved CNS systems will contribute to the enhancement of ATC efficiency, primarily achieved through reductions in controller workload and improvements in delivery precision. However, the introduction of improved CNS systems will not have a direct effect on the capacity limit, except perhaps for MLS which may have a positive effect on the runway capacity during adverse weather

conditions.

4.5 Improved ATC services and procedures

When looking at the possibility to improve present ATC by optimizing its services and procedures, a number of alternatives should be considered. A measure which will have a considerable impact on airspace and airport capacity, is the reduction of the separation standards. The application of radar separation standards instead of procedural separations, has already increased the airspace capacity considerably. Further improvements can be obtained by reducing the separations between ATS routes, e.g. by relying on airborne RNAV capabilities. With respect to airport capacity, improvements have to be found in terms of a reduction of wake-vortex separation standards, or making those standards dependent on the actual meteorological conditions.

Flight profile planning, prediction and optimization will substantially benefit from improved meteorological information, concerning both the actual and the forecast situation. There are several possibilities to improve the situation. These possibilities include increasing the measurement update frequency, refining the measurement grid (the set of measurement locations), downlinking onboard measurement of wind speed, temperature etc., to the ground system and the use of improved meteo forecast models. In recent years significant progress has been made in the area of weather radars (both airborne and ground-based) which will also contribute to the provision of enhanced meteorological information.

An increase in the span of control of ATC centers can have a significant impact on the efficient utilization of airspace and runways. ATC which is presently tactically oriented can then adopt a more strategic approach towards planning and control of traffic. An increased span of control may require the adjustment of FIR boundaries, which may not be easily achieved due to political (sovereignty) considerations (Section 4.4).

An increase in the span of control does not necessarily imply an increased sector size. It even allows for smaller sectors, and hence for an increase in the number of sectors, resulting in an increase in overall control capacity. However, there is an optimum to the number of sectors, which is related to an increase in workload for air/ground communications and for handover of aircraft to adjacent sectors.

With respect to the European "patchwork" work of ATC centers, it is clear that better harmonization of ATC services and procedures, leading ultimately to a unified European ATC system, will significantly increase airspace capacity and efficiency of European ATC. Apart from developing common specifications for equipment, procedures and standards, harmonization objectives also include commonality in guidelines for selection, training and licensing in the European states.

4.6 Improvements and automation of ground system functions

Improvements of ATC with respect to the ground system functions will generally focus on enhanced automation. Since it has been generally recognized that the human mind is remarkably capable of rapidly adapting to changing

situations and grasping the implications of unforeseen events, the man-in-the-loop will remain essential, i.e., the controller and pilot will still take all decisions. However, when necessary, they will receive some form of computer generated decision support. In particular for the ground system this man-machine relationship philosophy represents a serious limitation on the level of automation that can be introduced. All system actions or system generated advisories must be in a form to allow controllers to fully assess and verify the functions performed by the computer. Only in the long term the role of the controller may evolve into that of an air traffic system manager, with a possibility for automated systems also to make decisions. However, even then controllers will retain their capability to intervene these automated functions whenever deemed necessary to achieve a safe, orderly and expeditious flow of air traffic.

The future ATM systems concept descriptions presented in Section 4.2 more or less share common ideas on automated support functions of the ground system. A future ground system will be built around a set of automation tools to assist the controller in his planning, coordination and monitoring tasks. A basic functional description of such a future ATM ground system is presented in Figure 13.

Fig. 13. Functional representation of the ATM system.

Although the description in Figure 13 is based on the system proposed by EASIE, the considered division into functional elements is fairly representative for most of the discussed future ATM system concepts:

- (1) **The man-machine interface:** the most sensitive and critical element in the new system will certainly be the interface between the controller and the ATM system. Appropriate display methods need to be developed that fully exploit the possibilities of the various controller aids and provide controllers optimum situational awareness. In addition, appropriate input devices need to be developed for data entry and for the interaction with the ATM functions. Other aspects to be considered will include but are not limited to, the development of criteria for filtering of data, the use of graphics for the display of conflict situations and advisories, and an appropriate allocation of communication tasks to voice or data link. Because the workload of the controller has to be maintained within acceptable limits, all the necessary precautions should be taken to cope with possible degradation in the automatic performance of other ATM ground system functions.
- (2) **Tracking and identification:** this automatic function provides the traffic situation as unambiguous tracks of identified aircraft and involves the periodic determination of aircraft position in space along with the associated speed vector. The surveillance function will generally be based on SSR Mode S radar tracking, however tracking can be improved for all phases of flight, but especially during maneuvers, by also exploiting the data link capability of Mode S to transmit additional aircraft information to the ground system. The extraction of aircraft identification is also a Mode S capability, however, Mode A will remain available for aircraft that do not have this feature.
- (3) **System plan/track correlation:** this function compares the flight tracks with system plans and attempts to provide correlation according to a set of criteria including identity and position. A system plan can be viewed as a 4-D description of a flight on the basis of the flight plan⁽⁷⁶⁾.
- (4) **Short Term Conflict Alert (STCA):** this automated function identifies pairs of aircraft which are likely to be in conflict within the next few minutes, and warns the controllers when such a critical situation arises. Relying on information from the surveillance system, the STCA function will serve as a ground based "safety net" only.
- (5) **Flight path monitoring:** this new function will compare the actual flight path flown by an aircraft with the approved and activated 4-D trajectory as produced by the traffic planning process. In the concept proposed by EASIE⁽⁷⁶⁾, the term "system profile" has been introduced to facilitate a more refined description of a planned 4-D trajectory. A system profile describes the 3-D position of an aircraft as a function of time. This position is at any given time surrounded by a 3-D "bubble" in which the aircraft should stay (see Figure 14). A system profile thus consists of a planned flight path as well as an assigned "tube" (formed by the bubble moving in time) around it. In the EASIE concept it is envisioned that the monitoring function will detect any non-compliance with the system profile which

is planned such that it is nominally free of conflicts. Moreover, appropriate warning messages will be issued in the event of an infringement of a tube boundary. Automated tools for systematic flight path monitoring during all phases of flight will enable the extensive use of parallel and direct routes, thus greatly increasing the airspace capacity, while keeping the controller workload within acceptable limits.

(6) **Trajectory prediction:** this function carries out the 4-D trajectory prediction of aircraft during all phases of flight. A trajectory prediction will be made based on the availability of the best information. This information is highly dependent on the particular avionics fit of the aircraft. Since the proposed future concepts are all based on the use of Area Navigation, it is assumed that the avionics fit will at least include a 2-D RNAV system. The most advanced avionics fit, however, will include a full 4-D FMS. For poorly equipped aircraft, the ground based prediction function will replicate the airborne prediction function to generate realistic trajectories. For aircraft equipped with a 4-D FMS, the FMS will be requested to provide the best estimate of the 4-D trajectory. The predicted trajectories consist of two parts, each part having its own time frame to cover both medium term and long term planning. The first part which is necessary to determine the system profile, will cover a time frame corresponding to that profile (typically 20 to 25 minutes). The second part covers the trajectory succeeding the first part and will be the basis for the system plan (long term flight plan). To facilitate the exchange of trajectory information the availability of an air/ground data link clearly is of primary importance.

(7) **Conflict search:** this function periodically examines the predicted flight paths of aircraft in order to identify potential conflicts and other proximity situations. The function works on the already approved profiles as well as on trajectory proposals under evaluation by the system planning function. It has to be realized that the ability to discriminate between conflict and non-conflict situations is largely determined by the accuracy of the trajectory predictions. The conflict detection function can therefore only work properly if the trajectory prediction function also works reliably and with a high level of performance.

(8) **System planning:** this very complex function plans and optimizes the traffic flow in a given airspace. The function defines a system profile and communicates it to the aircraft. Since system profiles should be free of conflicts up to a defined time horizon, potential conflicts need to be resolved during the planning phase, taking into account the aircraft limitations and constraints of the overall system. To this end, the planning function has to perform central coordination and collective optimization. Although the main emphasis of the optimization process will be on improving the capacity, undue penalties on economy should be avoided by assigning trajectories which are as close as possible to the preferred trajectories. To achieve this it is envisioned that 4-D FMS equipped aircraft will negotiate their preferred trajectories via the data link with the ATC ground system. Assuming the aircraft is in flight, this negotiation process is generally initiated when the controller requests a proposal from the pilot for an optimized 4-D trajectory computed using the FMS system and which satisfies all constraints. It is noted that con-

straints will be generally defined in terms of a sequence of waypoints and corresponding waypoint-types, which describe the nature of the constraint (height constraint, speed constraint, etc.). The ground system then checks the compatibility of the proposed trajectory with those of other aircraft. In order to avoid conflicts with already approved trajectories, the ground system may have to modify the proposed trajectory. If modifications to the requested profile are indeed required, the ground system will send revised constraints to the aircraft via the data link and the pilot will initiate another run of the profile generator. The trajectory negotiation process is continued until an agreement between pilot and controller has been achieved. In case of aircraft equipped with a 2-D RNAV system only, the ground component of the ATM system plans a trajectory generally based on trajectory data made available by the airline's flight preparation service.

Beyond the time horizon of the system profile, the traffic is planned by means of system plans. A system plan does not necessarily have to ensure a conflict-free situation, since due to the limited reliability of the system plans, it may sometimes be better to postpone conflict resolution until more certainty exists.

The traffic situation as presented by the planning function needs to be regularly updated in order to ensure a proper monitoring function, which attempts to detect any difference between the planned and the actual traffic situation. However, the system planning function is also activated as a result of events requiring an amendment to the current plan, such as the coordination of a new flight or changes in the meteorological conditions.

The system planning function will contribute significantly to an increase in the efficiency of airspace use and as a consequence the total system capacity. Automated planning functions that assist the controllers in short and long term control and planning may reduce the workload per aircraft, while simultaneously achieving more economical flight operations.

The future system will also need automated tools to organize the overall ground system for the management of flights. Such tools can be used, e.g. to allocate flights to sectors or controllers. To this end, tools are also needed to predict the workload within sectors and to organize communication and coordination procedures with neighboring centers. Another tool may assist the controller in task scheduling, i.e., to direct attention to the tasks that need to be executed at the appropriate times, so that unexpected events can be avoided.

The automated planning tools described here will be introduced in an evolutionary manner, such that the initial implementation will be for the last part of the en-route phase and the arrival phase. In a later stage of development, the planning of the whole en-route phase and ultimately the take-off and departure phase may also be implemented. It is not really surprising that these automated planning tools will be initially introduced in the arrival phase, considering the fact that about 60% of all airborne delays occur during this phase⁽¹⁷⁾. Several automated arrival management tools to help ATC controllers to plan, monitor and control the inbound flow of air traffic into the TMA have already been developed and tested, both in simulation and in field trials. In fact, some of these systems are currently in operation at a limited number of airports. A more detailed discussion of some important aspects of these tools is presented in Chapter 5.

Fig. 14. Movement of a "bubble" mapping out a 4-D tube in space.

4.7 Improvements and automation of airborne system functions

The large gap that exists between airborne and ground system capabilities has already been mentioned several times. It is clear that further improvement of specific FMS functions, in particular those related to performance management and area navigation, will not be effective, unless the ground system can accommodate the desired flight profiles as generated by the FMS. Although current FMS designs are already very mature in terms of crew operation automation, further enhancements will be needed to provide the capability to accurately plan and execute multiple-constraint 4-D profiles and to help the crew to better communicate with ATC.

In particular, the process of trajectory negotiation envisioned in future ATM concepts needs to be supported. Such a concept requires the development of new or improved airborne system functions, in particular those related to the planning and execution of a 4-D trajectory, the exchange of trajectory data using the air/ground data link, and the dynamic allocation of tasks between airborne and ground systems.

Using the description of an experimental FMS currently investigated in the framework of PHARE^(62,63) as a representative example of an advanced concept, the following main functional elements which need to be added or improved can be identified (see Figure 13):

(1) **Man-Machine interface:** this element needs to be enhanced to accommodate new and improved system functions, i.e. it has to provide the data link interface to the pilot, and a facility to input and display ATC constraints and 4-D trajectories. Current Control and Display Units (CDU) and Electronic Flight Instrument Systems (EFIS) need to be adapted for this purpose.

(2) **Constraint manager:** this function assembles all constraints in a constraint list in a chronological order. Aircraft operating restrictions which are not associated to a particular waypoint but which are defined for a particular phase of flight (e.g. a speed limit below a certain flight level within the TMA) are also included within the constraint list. Constraints can be constructed or modified by manual input of the pilot, by extracting constraint data from the database or by uplink from the ground system. With the constraint list completed the constraint management module may initiate the profile prediction process.

(3) **Profile prediction, navigation and outer-loop guidance:** this function determines on the basis of the requested flight plan, ATC constraints, mission objectives and meteorological conditions, the optimum trajectory. To request clearance, the pilot transmits the synthesized trajectory to the ATM ground system via the data link. If ATC does not approve of the proposed trajectory, a negotiation process is initiated as described in Section 4.6. However, if ATC does approve the intended trajectory, a maneuver space around the trajectory will be assigned and the resulting system profile (tube) will be transmitted to the aircraft via the data link. It is recalled that the system profile can be imagined as being formed by a "bubble" moving in time (see Figure 14). The pilot will evaluate the system profile and after having informed ATC, the now existing trajectory and corresponding tube may be activated in order to execute the flight. To allow for system errors and monitoring requirements, tolerances must be introduced so that the bubble actually features an internal structure composed of two concentric regions. The inner region is the maneuver space. The aircraft is authorized to optimize its own trajectory within this assigned space, but is not allowed to leave it. A performance buffer surrounds the maneuver space. The performance buffer thus determines the minimum separation between the planned trajectory and the constraint. The size of the buffer will correspond to the magnitude of navigation errors and Flight Technical Errors (FTE). The navigation error is the difference between the FMS produced estimate of the aircraft position in space and the actual position in space. Flight Technical Error is defined as the error that results when the pilot or the automatic flight control system attempt to match the actual (estimated) aircraft position with the desired position of the aircraft. It will be necessary to monitor the flight on-board the aircraft, in order to detect any drift away from the planned trajectory due to unforeseen circumstances such as unexpected wind conditions. If indeed a significant error is observed, sufficient time must still be available to direct the aircraft back into the maneuver space before a penetration of a bubble

boundary can take place. This leads to the requirement that in addition to providing margins to allow for navigation and Flight Technical Errors, the performance buffer should also include a margin to allow for monitoring. The overall size of the performance buffer will have to be established by suitable experimentation. Obviously, the dimensions of the maneuver space will depend on several factors, most notably on the density of the traffic flow in the area. Finally, the outer loop control directs the execution of the agreed trajectory by generating the commands for the flight control system.

An avionic system which is currently being introduced is the Airborne Collision Avoidance System (ACAS). An example of such a system is TCAS (Traffic alert and Collision Avoidance System). It merely serves as an airborne safety net and does not in any way increase the capacity nor the efficiency of the ATC system.

5. AUTOMATED ARRIVAL ASSISTANCE TOOLS

5.1 CTAS: a representative example

In view of the fact that most of the recently developed arrival assistance tools feature components that have a strong resemblance to each other, the discussion presented herein will primarily center on one representative example of such a system, called CTAS (Center/TRACON Automation System). CTAS^(27,28,29,43,54,73,75), which has been developed at NASA's Ames Research Center, has recently been selected by the FAA for field test implementation in the USA. Other well-known arrival management tools include Germany's COMPAS^(100,101), France's MAESTRO⁽⁵⁰⁾, U.K.'s TCSDG⁽⁶⁹⁾, the ZOC^(9,10,11,13,14) system developed by the EUROCONTROL organization, and several systems developed in the U.S., viz. TIMER⁽²⁴⁾ and TATCA⁽¹⁸⁾. Of interest is also the Dutch ASA (Automatic Slot Assignment System)⁽⁸⁾, which can be viewed as a forerunner of the above systems and which has been operational for more than a decade. An excellent overview, comparing the various tools, is presented in Ref. 78.

Commencing the management of arriving traffic already in the en-route airspace not only permits most of the delays to be absorbed using the most economic form of time control, namely speed control in cruise flight, it also allows to smooth the arrival stream by metering traffic into the terminal area at such a rate that the airport capacity is fully utilized without producing congestion or excessive gaps in the terminal airspace. For this reason, all mentioned automated arrival management tools attempt to exploit the benefits that can be achieved through a combination of efficient management of the arrival traffic and the accurate control of individual flights within an "extended terminal area".

Geographically, such an extended terminal area surrounds and includes the TMA of a major airport (and possibly some secondary airports as well) and may extend some 100 to 300 NM from the runways. Although the boundary of an extended TMA is indeed often specified in terms of airspace geometry, in a time-based traffic management approach it is more convenient to define this boundary as a time dependent quantity, a so-called "time horizon". However, it is

clear that a specified time horizon can be approximated in the spatial domain, by transforming a time interval into a corresponding distance.

Fig. 15. Scheduling regions for time-based arrival traffic management.

When the estimated time of arrival of a new inbound flight first falls within the so-called "horizon of control" (also referred to as "scheduling horizon"), the aircraft enters the process of arrival sequencing and scheduling (see Figure 15). This process involves the reordering of the arrival sequence (which is more or less random in terms of speed/weight classes) to obtain a landing order that is optimal according to some specified criterion (e.g., overall system delay), as well as the planning of landing times such that traffic approaching from various directions can be merged on the final approach path without conflicts and with optimal spacing. The target metering-fix times (at the terminal control boundary) corresponding to the assigned landing times are also determined. With the aircraft at the horizon of control, there is a range of earliest and latest landing times that the aircraft can achieve by varying its speed within the permissible range determined by performance and operational considerations. If the assigned landing time exceeds the latest landing time attainable through speed-control, the additional delay must be absorbed by either path stretching or holding in the en-route phase of operation. Ground-based trajectory predictions, obtained by integrating aircraft type specific point-mass equations of motion with the forecasted winds taken into account, are used to estimate the nominal landing times. Based on the trajectory predictions, computer-generated advisories concerning the selection of cruise and descent speed profiles and top-of-descent points are also given to the controller to help meet aircraft target landing times.

When the "freeze horizon" is encountered at an estimated fixed flight time from the metering fix, the schedules of arriving aircraft will no longer be subject to changes. Except for situations that require immediate controller intervention, a schedule remains frozen until the terminal control boundary has been reached.

At this boundary, adjustments to the target landing times and possibly even a limited reordering in the landing sequence, can be made to allow for the occurrence of unexpected schedule disturbing events or for time errors accumulated during the descent. This "rescheduling" process is not essentially different from the original arrival scheduling process, except that obviously there is less freedom to optimize the arrival sequence due to the fact that the "rescheduling window" is relatively narrow and close to the final approach fix. However, when appropriate assistance is given, most of the time aircraft will arrive into the TMA airspace with small time errors only. Consequently, rescheduling in the TMA region generally amounts to fine tuning the aircraft sequence and corresponding trajectories that were originally established at the scheduling horizon, thus allowing to meet the assigned landing times with limited uncertainty. Achieving precise spacing between aircraft on final approach ensures that landing rates will always be close to the capacity limit of the runway. It is noted that the planning of a trajectory within the TMA is based upon the nominal arrival path to be flown to the final approach fix. Any corrections to adjust timing within the narrow TMA airspace will be primarily executed by means of path stretching techniques. Path stretching techniques may include conventional fan or trombone type procedures (see Figure 16), but in CTAS also some more flexible path stretching techniques to delay or advance an aircraft are facilitated. In fact, in CTAS the controller has complete freedom to vector an aircraft away from the nominal route to an arbitrary point and heading in the arrival airspace. When flying off-route, the controller can be advised when to engage a preselected guidance mode in order to guide the

aircraft back onto the nominal route such that the final approach fix is reached at the desired time. Two different horizontal guidance modes are available in CTAS to allow capture paths to be synthesized in a flexible fashion. For each of the selected modes, appropriate guidance information will be displayed to the controller (including heading advisories).

A high degree of flexibility of the automation aids implemented in an operational system is imperative, if such a system is to prove effective in a real-world situation. In particular there is a need to be able to deal with unexpected situations such as missed approaches, pop-up traffic, and runway reconfigurations. In CTAS provisions have been made that allow controller to handle such situations effectively. For example, in case of a missed approach, a time slot needs to be opened up to allow the aircraft to be reinserted into the arrival sequence. In CTAS an automated function assists the controller to achieve this in such a way that the disruption of the overall traffic flow will be minimal.

Fig. 16. Fan and trombone type path stretching.

An important aspect in the design of an automated arrival traffic management system is the specification of the various time horizons. In particular, the scheduling horizon must be chosen sufficiently early in order to be able to handle most of the expected delays via speed control, while the freeze horizon should be selected sufficiently early (before descent clearances are issued) in order to avoid a high workload situation during descent which would result from the continual minor adjustments needed to meet the metering fix scheduled time. On the other hand, however, since time errors and schedule disturbing events are now not accounted for while the aircraft is in the region between the freeze horizon and the metering fix, the freeze horizon should not be chosen too early in order to ensure that aircraft can be delivered at the metering fix with an accuracy that is sufficient to avoid terminal area delays that exceed the combined terminal speed-control and path-stretching capabilities. Also the need to accommodate flights that originate from secondary airports within the extended TMA influences the selection of the various time horizons. In CTAS, the horizon parameters need to be established experimentally for each individual airport using realistic simulation and field tests.

In the development of an automated arrival management system such as CTAS, special attention has been given to the design of the man-machine interface. The lay-out of the controller-system interface is indeed of primary importance for the practicability and acceptance of automated system functions. Recent man-machine interface developments generally attempt to take advantage of the graphical and interactive capabilities offered by high performance workstations. Whenever possible, computer generated advisories are transformed into a graphical format such as to enhance rapid perception by the controllers. Graphical interfaces also provide the capability for controllers to interactively modify computer-generated proposals, thus ensuring that controllers retain full authority. In addition, graphical interfaces offer a convenient means for monitoring the overall traffic flow and for displaying conflict detection and resolution advisories. For the purpose of improved situational awareness, so-called timeline information displays have been introduced to supplement the conventional plan view displays. Figure 17 shows a typical example of such a timeline display. Displaying both the scheduled and the estimated time of arrival for each aircraft in the sequence allows controllers to keep track of time errors. In the controller interface of CTAS, multiple displays, as well as the advisories generated by the automation tools, can be combined on a single high resolution color monitor.

Current research efforts involving the CTAS system are directed towards the integration of airborne and ground-based components⁽⁵⁴⁾, with special emphasis on the profile negotiation process. The objective of these efforts is the creation of an integrated air/ground environment which not only leads to improved ATC efficiency, but which also allows pilots to take advantage of the unique capabilities of their aircraft. Clearly, the introduction of a digital data link will constitute a significant step forward in the creation of such an environment. Issues which are, or need to be addressed in the near future include, the specification of the trajectory data exchange in support of the air/ground negotiation, the allocation of the associated communication tasks between voice communication and data link, and the determination of the required accuracy for tracking a 4-D trajectory. With respect to the latter issue it is important to consider the effect on

the overall system of mixing 4-D FMS equipped and unequipped aircraft. Also the alternative methods for establishing the preferred aircraft trajectory need to be examined. Clearly, the airborne automated 4-D planning capability can be used for this purpose. Alternatively, the generation of preferred trajectories can be performed equally well on the ground given that critical performance data and constraints are known. Such ground-based generation of aircraft trajectory preferences may provide the additional benefit of providing trajectory optimization capability for unequipped aircraft.

Fig. 17. A CTAS time-line display for traffic flow monitoring (Ref. 78).

5.2 Comparison of system features

Although all mentioned automated arrival management tools have many features in common, also some important differences can be observed. These differences relate not only to the implementation of the various system functions, but also to the basic design philosophy itself. For example, all systems feature an on-line trajectory prediction function. However, two different methods for generating such predictions are currently in use. There are systems which, like CTAS, use point-mass equations of motion and numerical integration to build successive flight phases. On the other hand there are also systems that employ parametric performance models, which approximate the aircraft's behavior for all flight phases from empirically derived functions of characteristic parameters. The experiments that have been performed to validate these approaches, show that both approaches can provide the desired information with an acceptable level of accuracy.

However, also some more fundamental differences may exist, e.g., with regard to such issues as the interaction between man and machine. To illustrate this point, let us compare the CTAS system with the "Zone of Convergence" (ZOC) concept developed by EUROCONTROL^(11,13,14). One of the most important distinctions that can be made between ZOC and CTAS concerns the system/controller relationship. Both system are capable of modifying a "computer generated plan". However, unlike for the CTAS system, in the ZOC system amendments to the plan are mainly performed by the system itself, rather than by the controller. To facilitate such an approach, ZOC does not make use of the "frozen sequence concept", but rather performs "dynamic rescheduling". In this dynamic rescheduling process, all deviations from the flight plan, whether triggered by controllers or by pilots, are automatically accounted for in the advisories which are generated on the basis of the observed radar tracks. As a result virtually no controller inputs to the system are required. However, there are also certain disadvantages associated to this approach. In particular, unlike CTAS, the system does not seem to be optimally configured to derive substantial benefits from controller skills to improve the system performance or to flexibly respond to unexpected problems.

6. ADVANCED TRAJECTORY OPTIMIZATION TECHNIQUES

6.1 Historical background

Rising fuel costs and other economic factors spurred a considerable research effort towards the development of on-board algorithms for the computation of fuel-efficient flight trajectories during the 1970's. Of particular interest in this context is the work done by Erzberger et.al.⁽⁴²⁾, who used optimal control theory applied to a reduced-order "energy-state" system formulation to obtain an efficient real-time algorithm for computing vertical profiles that minimize the Direct Operating Cost (DOC) over a fixed range of flight, but with the arrival time unspecified. In this "energy-state" approach, specific energy, which is defined as the sum of potential and kinetic energy per unit of airplane weight, i.e.:

$$E = h + V^2/2g \quad , \quad (6)$$

is introduced to replace airspeed (or altitude) as a state variable. Moreover, an optimal trajectory is assumed to consist of three consecutive segments, namely a climb segment (during which energy increases monotonically), a cruise segment (during which energy remains constant) and a descent segment (during which energy decreases monotonically). For each of these three segments the optimum speed and throttle settings can be determined separately. For short ranges, the cruise segment disappears and the climb and descent segments are merged together. Figure 18 shows a typical family of flight paths, parameterized by the final range, computed using this algorithm⁽⁹⁷⁾. It is important to note that, if a cruise segment is present in the optimal trajectory, the actual altitude at which this cruise is flown, depends on the specified value of the cost index. Figure 19 shows the variation in the optimal altitude with the value of the cost index for a typical example.

The trajectories computed by the optimal control algorithm are characterized by continuously varying airspeeds during the climb and descent phases (see Figure 20). Also the throttle setting is a continuous function of time for the entire flight.

In current airline operational practice a much simpler control technique is used for the climb and descent flight phases, namely a constant Mach/CAS schedule technique. For the climb phase this implies a speed schedule of constant calibrated airspeed (CAS), transitioning to a constant Mach number. Similarly, the descent phase is commenced with a speed schedule of constant Mach number and subsequently a transition is made to constant CAS (see Figure 20). Usually, a climb is performed at maximum climb throttle setting and a descent at idle throttle setting. In response to the need for fuel efficient operation in an ATC environment, special attention has been given to the descent phase. In particular, the concept of "profile descent" was developed⁽²⁶⁾. This procedure allows pilots to plan for a fuel-conservative descent while accounting for the performance characteristics of the aircraft. The objective in this constant Mach/CAS procedure, which is executed in an idle-thrust clean configuration (with landing gear up, flaps zero and speed brakes retracted) is to achieve a near-continuous descent. Clearly, to accomplish this the top-of-descent point (the point where thrust should be reduced to flight idle to start the descent) should be carefully selected. Another important aspect of the profile descent is that Mach/CAS speed schedules are selected such as to produce near-minimum fuel usage. If no guidance information is available, flight crews have to rely on past experience and various rules of thumb to plan the trajectory and determine when to begin to descent. Depending upon the degree of sophistication of the rule-of-thumb, the pilot can also account for other factors such as airplane gross weight, wind and non-standard temperature effects. It is clear, however, that if the full potential of fuel savings is to be realized, onboard calculation of guidance information is essential. For this reason, the development of flight-management descent algorithms has received considerable attention^(20,39,57,64,72,89,103). Although they are computationally intensive, both the constant CAS/Mach technique and the optimal control technique can be implemented on airborne computers. Piloted simulation tests have shown that even the variable speed optimized trajectories

can be easily tracked⁽⁵⁰⁾. Figure 21 shows a comparison of the time/fuel-burnoff relationship for optimal control and constant Mach/CAS descent techniques, based on the results presented in Ref. 103. The fact that the fuel savings that can be obtained by applying optimal control is very modest, can be even better observed in Figure 22, where the relative fuel penalty has been plotted.

Fig. 18. A typical family of flight paths, parameterized by the final range.

Fig. 19. Typical variation in the optimal altitude with the value of the costindex.

Fig. 20. Optimal speed schedules corresponding to the trajectories of Fig. 18. Lines of constant CAS and constant Mach are shown as well.

Fig. 21. Fuel versus time comparison for optimal control and constant Mach/CAS techniques.

Fig. 22. Fuel penalty for constant Mach/CAS technique compared with optimal descent strategy (adapted from Ref. 103).

6.2 Current developments

In the 1980's, when the traffic density started to increase rapidly, it became apparent that the ATC procedures needed to cope with the resulting delays, severely limited the use of fuel-efficient descent profiles. Indeed, the need to efficiently handle the air traffic from a global point of view compromised flying optimized trajectories at the pilot's discretion. However, as discussed in this report, time-based (4-D) techniques have emerged that hold significant promise for both an increase in airport capacity as well as for improved fuel efficiency.

The first effort toward the computation 4-D trajectories based on the optimal control technique was made by Sorensen and Waters⁽⁸⁵⁾, who extended Erzberger's Energy-state approximation⁽⁴²⁾ to include an assigned time-of-arrival. In fact, they showed that the "time-fixed" fuel-optimization problem simply amounts to finding the cost index for which a corresponding "time-free" DOC-optimal trajectory arrives at the assigned time (cost index iteration). Calise applied singular perturbation theory to solve complex problems in flight performance optimization⁽²²⁾. Also regular perturbation techniques have been used for this purpose⁽⁹⁶⁾. Both techniques reduce the complexity of the trajectory optimization problem by splitting the original problem up into a series of much simpler problems, allowing to derive control solutions in the form of a state-feedback law. Chakravarty⁽²¹⁾ used singular perturbation techniques to develop an algorithm for computing 4-D optimal trajectories within an extended terminal area, using a similar "energy-state approximation" as employed by Erzberger. Most notable in his work is the "early descent" phenomenon, which may occur if at the boundary of the extended TMA the time-of-arrival is revised in order to absorb a delay. To absorb such a delay in an optimal fashion, the cost index needs to be lowered. It is recalled that a lower cost index generally implies a lower optimal cruise altitude (see Figure 19). The optimal descent concept proposed by Chakravarty requires an initial descent segment to match this with this lower cruise altitude. Figure 23 shows some typical trajectories over a range of 400 NM, based on results presented in Ref. 21. However, more recent research⁽⁹⁷⁾ indicates that this early descent concept has only limited practical value. In particular, it is shown that the distance between entry and metering fix needs to be considerable in order for the optimal trajectory to feature a cruise segment. Figure 24 compares long range flights for two different values of the cost index. Also shown is the optimal trajectory that results when at the entry fix, at the boundary of the extended TMA (at 500 km from destination), the cost index is revised from +12.5 N/s to -12.5 N/s. Clearly, the resulting optimal trajectory is characterized by a continuous descent.

In addition to research on optimal flight in the vertical plane, optimal trajectories in a horizontal plane have been studied extensively as well^(40,41). The main idea here is that a terminal area flight, which is essentially 3-D, can be decomposed into two principal subproblems: the vertical (longitudinal) maneuver, and the horizontal (lateral) maneuver. The assumption then is that these two subproblems can be treated as essentially independent of each other. For the horizontal problem, usually a minimum path-length criterion is used to generate trajectories consisting of straight lines and circular arcs. Moreover, special emphasis is generally given to the development of procedures that are amenable to fast on-line computer solutions that can be readily implemented in a guidance system.

Fig. 23. An example of "early descent" trajectories featuring a cruise segment (adapted from Ref. 21).

Fig. 24. An example of a continuous optimal descent trajectory.

To date, the synthesis of terminal area trajectories, based on the analysis of an integral 3-D problem formulation, has received very modest attention only^(74,97). This is somewhat surprising, since vertical and horizontal maneuvers, which are of comparable significance in influencing fuel consumption, often occur simultaneously on a terminal area flight path.

The most recent trend in trajectory optimization is towards the analysis of flight paths that are subjected to multiple constraints. An interesting effort in this direction was made by Jackson and Crouch⁽⁶⁰⁾, who proposed the so-called "Dynamic Interpolation" technique. This work aims at integrating FMS and MLS to provide guidance on a curved path onto the runway via specified approach waypoints. Such a discretely specified path has the advantage that the system controls may be segmented between waypoints, allowing the application of piecewise-continuous polynomials to define these controls. The system then computes the necessary steering commands the pilot or autopilot must follow to guide the aircraft through the designated points. Certain tolerances are allowed about the waypoints that the aircraft must fly within. The application of the proposed dynamic interpolation procedure to the 4-D aircraft trajectory optimization problem will allow the generation of aircraft controls that minimize a given cost function (e.g., aircraft acceleration, fuel consumption, early/late arrival time, etc.), while maintaining given constraints, such as waypoint interception, velocity constraints and path continuity requirements. An additional claimed advantage of dynamic interpolation over previous work is the coupling of horizontal and vertical motion into the optimization problem. Unfortunately, numerical results bear out that in many cases excessive speed and thrust requirements result, which are beyond the performance of today's commercial aircraft.

In Ref. 98 another approach is proposed to optimize trajectories featuring multiple constraints. This approach attempts to solve the aircraft trajectory optimization problem with the added complication that the aircraft has to remain within an assigned "tube in space" (system profile). For this purpose, a recently developed direct optimization technique is employed that uses cubic polynomials to represent state variables, linearly interpolates control variables and uses collocation to satisfy the differential equations⁽⁵⁶⁾. This representation essentially transforms the optimal control problem to a mathematical programming problem which is solved by sequential quadratic programming. The main advantage of this approach is that it is relatively easy to include path constraints in the optimization problem formulation. Moreover, preliminary results indicate that the method appears to be quite robust. Unfortunately, there are also some disadvantages associated to this approach, in particular its relatively high computational burden. However, recently new techniques have been proposed, such as sparse solution techniques⁽¹⁵⁾ and vector or parallel processing methods⁽¹⁶⁾, that hold great promise to substantially improve the computational efficiency of the direct optimization method, and which may eventually permit implementation of the method in a guidance system. Reference 98 also proposes another alternative approach, which appears to hold promise for application to system profile optimization, namely the finite element method⁽⁵⁸⁾.

7. CONCLUDING REMARKS

The discussion presented in this report has made clear that today's air traffic control does not permit the increase in capacity that is required to cope with the forecasted traffic demand. A number of measures that can be taken to improve the situation has been discussed. Although these potential improvements have been described as independent possibilities, in many cases full exploitation will not be possible, unless combined measures are taken. It is for this reason that future ATC concepts, which aim at increasing the capacity, are expected to evolve from the present situation through:

- improved automation of the ground systems,
- integrated application of airborne and ground systems, and
- application of air/ground data link,

resulting in a more strategically oriented approach to the control of air traffic, by allowing to plan optimized flight profiles that are free of conflicts over longer time horizons than is currently possible. Some of the main characteristics of this future concept, that has been termed Air Traffic Management, are new and improved CNS systems to provide accurate 4-D navigation and surveillance, improved handling and transfer of information between aircraft and ATC centers, the introduction of direct routes whenever possible, and further automation on the ground to assist in prediction, optimization and monitoring, together with effective man-machine communication. Clearly, the ATM system of the future should be developed in an evolutionary manner such that it remains compatible with existing systems and is capable to deal with a wide variation of traffic densities, avionics capabilities, etc.. Whenever possible the airborne and ground-based systems should exchange relevant information, such as accurate meteo forecasts and route clearances. The resulting advantages, fast response time and quality of information, will help to manage the air traffic, particularly in high-density terminal areas, by providing increased capacity as well as safer and more economic operation.

Unfortunately, there is little time left to take appropriate actions leading to the required increase in the capacity. In order to acquire the capability to manage the traffic demand foreseen for the beginning of the 21th century, it is important that all States and organizations concerned, recognize the need to coordinate activities as paramount for the success of the implementation of the envisioned integrated ATM system.

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