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Design of Automation Tools for Management of Descent Traffic

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ABBREVIATIONS

AAS	Advanced automation system
AI	Artificial intelligence
ARTCC	Air route traffic-control center, also simply referred to as the Center
ATC	Air traffic control
C	Cruise speed mode
D	Descent speed mode
DA	Descent advisor
DME	Distance measuring equipment
ERM	En route metering
FAA	Federal Aviation Administration
FAST	Final approach spacing tool
I	Inquiry mode
IAS	Indicated airspeed
ID	Identification
KIAS	Knots, indicated airspeed
n.mi.	Nautical miles
PVD	Plan-view display
RI	Route intercept mode of horizontal guidance
SP	Standard airline procedure descent profile
TMA	Traffic management advisor
TOD	Top of descent
TRACON	Terminal Radar Control (Facility)
VORTAC	Type of navigation station providing range and bearing
WC	Waypoint capture mode of horizontal guidance

SUMMARY

This paper describes the design of an automated air traffic control system based on a hierarchy of advisory tools for controllers. Compatibility of the tools with the human controller, a key objective of the design, is achieved by a judicious selection of tasks to be automated and careful attention to the design of the controller system interface. The design comprises three interconnected subsystems referred to as the Traffic Management Advisor, the Descent Advisor, and the Final Approach Spacing Tool. Each of these subsystems provides a collection of tools for specific controller positions and tasks. This paper focuses primarily on the Descent Advisor which provides automation tools for managing descent traffic. The algorithms, automation modes, and graphical interfaces incorporated in the design are described. Information generated by the Descent Advisor tools is integrated into a plan view traffic display consisting of a high-resolution color monitor. Estimated arrival times of aircraft are presented graphically on a time line, which is also used interactively in combination with a mouse input device to select and schedule arrival times. Other graphical markers indicate the location of the fuel-optimum top-of-descent point and the predicted separation distances of aircraft at a designated time-control point. Computer generated advisories provide speed and descent clearances which the controller can issue to aircraft to help them arrive at the feeder gate at the scheduled times or with specified separation distances. Two types of horizontal guidance modes, selectable by the controller, provide markers for managing the horizontal flightpaths of aircraft under various conditions. The entire system consisting of descent advisor algorithm, a library of aircraft performance models, national airspace system data bases, and interactive display software has been implemented on a workstation made by Sun Microsystems, Inc. It is planned to use this configuration in operational evaluations at an en route center.

INTRODUCTION

Although automated decision systems for air traffic control (ATC) have been investigated for at least two decades, attempts to implement these systems in the current ATC environment have largely failed. Among the reasons for this failure are obsolete ATC computers and displays, which are preventing the implementation of advanced concepts, and a tendency of developers to underestimate the complexity of automating even simple ATC functions.

Recently, the prospects for introducing higher levels of automation have improved because of two concurrent developments. First, a new generation of controller suites, incorporating color graphics workstation technology, together with new ATC host computers will remove many of the limitations impeding the implementing of automation concepts. The new controller suites, which will become operational in the mid 1990s, are the key element of the Federal Aviation Administration (FAA) Advanced Automation

Systems (AAS). Second, recent research has provided new insights into the appropriate role of automation in ATC and has yielded promising methods for designing such systems.

The system described in this paper builds upon ATC automation concepts and algorithms described in reference 1. Its main purpose is to provide a variety of computer-aided tools that can assist controllers in achieving safe, orderly, and expeditious movement of traffic into the terminal area. The criterion for designing these tools revolves around the principle of human-centered automation. In the context of ATC this principle requires developing tools that complement the skills of controllers without restricting their freedom to manage traffic manually. Such capability is achieved in the design described herein by providing various modes to assist the controller in solving specific ATC problems and by letting the controller decide when and how to use these tools.

The need for an effective controller-system interface imposes the most critical design constraint on air traffic control automation tools. To meet this constraint, the design of the interface makes extensive use of on-screen switches and menus selectable by manipulating a mouse or trackball. Such techniques improve the interface by minimizing the need for time-consuming and distracting keyboard entries. Also, computer-generated advisories are transformed, when possible, into a graphical format that enhances rapid perception of advisory information. The entire advisory system, including a plan-view display of traffic, has been implemented on a workstation made by Sun Microsystems.

It is planned to implement elements of this system at an en route center and to have controllers evaluate it without impacting the safety and efficiency of normal operations. In view of past failures, such operational testing is an essential step in validating automation concepts for air traffic control. Then, the FAA can confidently decide what elements of this system should be incorporated in the Advanced Automation System.

DESIGN GUIDELINES

Automation tools for ATC are defined here as systems with which controllers conduct informative as well as interesting dialogs that contribute to increased efficiency in performing their tasks. A successful dialogue consists of a rapid exchange of information using color graphics and possibly synthesized speech for system-to-human communications and a mouse, keyboard, touch-sensitive screen, and possibly a voice recognition system for human-to-system communications. This paper focuses on interactive color graphics and mouse input as the primary vehicle for system-human dialogue. As shall be explained, the graphics developed here are used to convey more complex information than is provided by aircraft tracks and alphanumeric lists displayed on current-generation ATC monitors.

In order to ensure desirable characteristics in the human-system interface and gain controller acceptance of automation tools a list of guidelines has been established, presented in table I.

TABLE I.– GUIDELINES FOR DESIGN OF AUTOMATED ATC SYSTEMS

DO NOT:	Automate unique skills or enjoyable tasks of controllers Automate complex or poorly understood tasks Automate in ways that reduce situational awareness Automate such that a system failure leaves controller with an impossible problem to solve
DO:	Automate to enrich controller's work environment Automate to increase situational awareness Automate to complement controller's skills Involve controllers from the start in selection and design of automation tasks

These guidelines are based in part on experience in other aerospace fields with successful examples of automated system designs. The system design described in the following sections represents an attempt to be faithful to these guidelines.

AUTOMATION SYSTEM CONCEPT

An automated system for ATC may be divided into three principal subsystems whose function involve sensing, planning and controlling. The sensing subsystem includes all of the components, including the ground radars, mode C transponders, and ground computers, that contribute to generating aircraft position tracks on ATC monitors. Since this subsystem is already highly refined in today's system, this paper concentrates on the design of the planning and controlling element of the automation system.

Figure 1 gives a diagrammatic representation of the proposed concept. Its key ground-based elements are the Traffic Management Advisor (TMA), the Descent Advisor (DA), and the Final Approach Spacing Tool (FAST). The functions of each element and the relationships between elements are discussed below.

The primary function of the TMA is to plan the most efficient landing order and to assign optimally spaced landing times to all arrivals. These time schedules are generated while aircraft are 150-200 n.mi. from the airport. The TMA algorithm plans these times such that traffic approaching from all directions will merge on the final approach without conflicts and with optimal spacing. The TMA also assists the Air Route Traffic Control Center (ARTCC) Traffic Manager in rerouting traffic from an overloaded sector to a lightly loaded one, a process known as gate balancing. Another function of the TMA is to assist the Center Traffic Manager in efficiently rerouting and rescheduling traffic in response to a runway reconfiguration or a weather disturbance. In general, the functions of the TMA involve assisting the Center Traffic Manager in coordinating and controlling the traffic flow between Centers, between sectors within a Center, and between the Center and the Terminal Radar Approach (TRACON) Facility. Moreover, the TMA must permit the Center Traffic Manager to specify critical flow control parameters such as runway acceptance rate and to override computer generated decisions manually.

At a Center, the controller positions requiring the highest skills and mental workload are those handling descent traffic. These positions are responsible for producing an orderly flow of traffic into the TRACON. The Descent Advisor (DA) is intended to provide controllers in these positions with flexible tools to implement the traffic plan generated by the TMA.

The DAs, which are implemented at the various descent control positions, are driven by the output of the TMA. The design of each DA takes into account the airspace structure and ATC procedures of each specific arrival sector. For simplicity, only two DAs are shown in figure 1, but in general there can be four or more, at least one for each gate feeding traffic into the TRACON.

For each aircraft passing through an arrival sector and heading toward an arrival gate, the DA receives the specified gate arrival time from the TMA. Then, the DA algorithm transforms these arrival times into various types of advisories which controllers can use to keep aircraft on time. The advisories provide continuously updated information for managing the cruise and descent trajectories of aircraft in space and time. If this concept is implemented in today's environment, the controller would have to issue the advisories by voice, but in the near future it will be more efficient to issue them via the proposed ground to air data link.

The TRACON controllers take over control of traffic at the feeder gates. They merge the traffic converging on the final approach path while making sure that aircraft are properly spaced. If the Center controllers have delivered aircraft at the gates on time using the DA tools, the TRACON controllers ordinarily will need to make only small corrections in the relative positions of aircraft to achieve the desired spacing. The Final Approach Spacing Tool (FAST) assists the controller in making these corrections with high accuracy and a minimum number of heading vectors and speed clearances. Achieving precise spacing between aircraft on final approach ensures that landing rates will always be close to the theoretical capacity of the runway.

Another type of tool designed for the TRACON controller is the Tactical Advisor. This tool helps the controller to replan traffic quickly in response to several special situations, such as missed approaches, runway changes, and unexpected conflicts.

CENTER CONTROLLER PROCEDURES FOR MANAGING DESCENT TRAFFIC

An analysis of controller procedures for managing descent traffic provides important insight and motivation for designing the descent advisor system. Hence these procedures are briefly reviewed in preparation for describing the system in the next section.

Typically, arrivals enter the airspace of the ARTCC that is feeding traffic to a major destination airport at least 200 n.mi. from the airport. Initially, the arrival traffic continues along established jet routes at cruise speed and altitude. Center controllers direct the traffic to points in space called feeder gates, typically located about 30 n.mi. from the airport at 10,000 ft above ground level. Some airports utilize as many as four such gates or corner posts which approximately form a rectangle, with the airport at the center. At the gates, the Center controllers hand the traffic over to the Terminal Radar Control Facility (TRACON) for final sequencing to the runway.

A critical task for the Center controller is to ensure that the streams of randomly spaced aircraft are merged into a properly ordered and spaced single stream as the traffic arrives at the gates. They accomplish this by issuing a series of speed and altitude clearances and heading vectors.

Traffic over the gates is spaced either on the basis of distance or time. The choice of spacing distance depends on the level of traffic and other factors, but is typically 10 n.mi. Under the time spacing criterion, arrivals are separated either by a specified time interval such as three minutes or, alternatively, are delivered at a specified clock time. Clock time over the gate as a spacing strategy is used primarily when En Route Metering (ERM) is in effect. ERM is a program installed on Center host computers. Certain Centers such as the Denver Center rely on ERM during periods of heavy traffic to allocate delays and coordinate flow at the feeder gates.

Two types of strategies are commonly used to control spacing. In one type controllers keep aircraft on their standard arrival routes as long as possible and control spacing with speed clearances before and during the descent. This strategy is appropriate for low and medium traffic conditions. In the second type, controllers take aircraft off their standard arrival routes while still at cruise altitude and then issue a series of heading vectors to control the spacing. This is the strategy of choice during heavy traffic.

Although accurately controlling the spacing at the gates is their primary objective, controllers also try to keep aircraft on fuel-efficient profile descents whenever possible by issuing appropriate descent clearances. Another factor that complicates the spacing control task is the necessity to compensate for strong variations in ground speed during the descent as a result of altitude-dependent winds and atmospheric effects. The management of descent traffic under these complex conditions is a difficult task that only experienced controllers with exceptional skill can perform efficiently. Thus, these tasks offer a timely opportunity for the development of automation tools.

GRAPHIC INTERFACE DESIGN FOR DESCENT ADVISOR AUTOMATION TOOLS

In essence, management of arrival traffic in the Center airspace involves predicting and controlling the spatial and time relationships of aircraft at the feeder gates. With currently used manual procedures, controllers are able to visualize evolving traffic situations 5-10 min into the future, depending on skill and circumstances. The DA increases this prediction time horizon to at least 25 min in most situations, thus giving the controller more time to organize traffic flow efficiently.

The analytical foundation for the DA is a collection of numerical algorithms for accurately predicting and controlling aircraft trajectories in space and time, referred to as four-dimensional guidance. Although four-dimensional guidance was originally developed for on-board flight management systems, it also provides a powerful framework for solving analogous problems in ATC automation. The design of a four-dimensional descent advisor algorithm was reported in a series of papers (refs. 1-3). It was shown in these papers that with descent clearances generated by this algorithm, pilots could control their arrival time at a feeder gate to an accuracy of ±20 sec. Such accuracy is significantly higher than is achieved in current operations and provides the basis for increasing the efficiency of the ATC system. One major challenge of applying this algorithm in an ATC environment lies in the design of an efficient interface between the controller and the algorithm. An equally important challenge is designing sufficient flexibility into the DA so that controllers can adapt it effortlessly to handle the types of traffic management problems previously described.

The design of the interface builds upon the environment available in a modern engineering workstation. Thus, the interface uses a mouse or track ball as the primary device to enter information and special color graphics to output information. However, the mouse is the preferred device in this application because it is less cumbersome to use than a trackball for entering certain types of information.

Integrated Controller Display

The controller interface combines on a single high resolution color monitor both the traditional plan-view display of aircraft tracks as well as advisories generated by the automation tools. Furthermore, the monitor screen is used to display the complete menu of automation tools available for selection by the controller. The main problem in implementing this concept referred to as an integrated controller display is organizing the information on the screen so as to minimize confusion and avoid display clutter. An alternative to an integrated controller display is a separate monitor for displaying advisory information. However, this approach has the disadvantage of requiring the controller to shift his attention and viewing direction from one monitor to the other, possibly causing distraction and loss of concentration during crucial moments.

In a sense, an integrated controller display is somewhat analogous to a heads-up-display (HUD) installed in modern aircraft cockpits. A HUD superimposes flight director information on the out-the-window visual scene, a technique that is favored by most pilots.

The integrated-controller-display concept is illustrated in a series of photographs of the monitor screen (figs. 2-5). These photographs provide the basis for describing the graphic interfaces in this paper. They illustrate the detailed implementation of this concept for an arrival area at the Denver Center. Specifically, the pictures show a plan-view map of the airspace through which arrival traffic flows toward the Drako feeder gate, one of four such gates feeding traffic to Denver Stapleton International Airport. The Drako point can be found near the right lower corner of the display. Blue lines indicate standard arrival routes leading to Drako. In general, the color blue designates information relating to the automation tools. Other air routes and boundary markers used by controllers are shown in white, and the white broken circular arcs are 25-n.mi. range circles centered at Drako. Except for the color coding, this type of information is identical to that found on existing plan view display (PVD) monitors at the Denver Center. The display can be reconfigured by keyboard input to show the airspace and traffic at any of the other sectors.

Aircraft positions, identification (ID) tags and associated data blocks are drawn in green. The data blocks are organized in standard format, with the first line showing mode c altitude in hundreds of feet followed by cleared altitude, and with the second line showing a controller code and the ground speed in knots.

The next sections describe in detail the graphical artifacts and automation modes comprising the DA tools.

Time Line

The graduated blue scale on the left side of the screen is the so-called time line, whose purpose is to show graphically the future time relationships of aircraft at a designated time control waypoint. In the figures, the Drako feeder gate at the Denver Center has been selected as that point. The scale covers a time range of about 30 min, with future time increasing toward the top in one minute increments. The corresponding hour on the scale can be inferred from the current time shown just below the time line. During operation the controller observes the time line scale sliding steadily toward the bottom of the display. At the point where the downward sliding scale runs into the blue margin line, future time becomes current time.

The time line concept is a natural by-product of four-dimensional guidance theory, which underlies the accurate estimation of arrival time. It was used in a slightly different format as part of an AI based scheduling system for ATC flow management (ref. 4). It also plays a key role in the ATC planning system, COMPASS, developed in Germany (ref. 5).

When aircraft destined for Denver first enter the airspace of the sector feeding traffic to the Drako feeder gate, the DA algorithm computes an estimate of arrival time at the gate. In this computation the algorithm assumes the aircraft will continue to fly at cruise speed and altitude along the planned arrival route to the point of descent and then follow a standard profile descent at idle to the altitude specified at Drako. This type of descent trajectory will also be referred to as a standard procedure profile (SP). The predicted arrival times and the corresponding aircraft ID tags are then posted on the right-hand side of the time line. The arrival times are updated approximately every two minutes by using as input to the DA algorithm the latest available position, velocity, altitude, and route information.

After learning to interpret the information on the time line, the controller can use it to quickly assess the traffic situation at the gate up to 30 min into the future. Furthermore, he or she can gauge the exact effect of speed clearances and heading vectors by observing the periodic updates of predicted arrival times posted on the time line.

Descent Clearance Advisors

In addition to providing the feeder gate arrival times on the time line, the DA algorithms can also provide assistance in solving the traffic management problems previously reviewed. To invoke the DA algorithms, the controller must first select one or more aircraft of interest and then designate his selections to the computer by an action referred to as "selecting" an aircraft. An aircraft is selected by moving the mouse pointer to the position marker of a chosen aircraft, a small green diamond, and depressing (clicking) the left mouse button. If the pointer is within the acceptance aperture—a small region containing the diamond when the button is clicked—the color of the aircraft and all information associated with it on the screen turns from green to yellow. Similarly, a selected aircraft is deselected by clicking on its position marker, thereby changing its color back to green. For operational and computational reasons the number of selected aircraft should be kept to no more than three.

Selecting an aircraft causes two panels (also known as windows) to pop up on the screen (fig. 3). The Mode Select Panel near the bottom of the screen provides a menu of labeled "buttons" for selecting advisory modes and display options. The functions of these modes will be explained in the next section. At the top of the screen, the DA Panel displays profile descent information generated by the DA algorithm.

If an aircraft is selected for the first time, the DA Panel displays profile parameters for the most recently computed standard procedure (SP) profile. Each line in the panel provides the following information: Aircraft identification; type of profile (SP); DME range in nautical miles of the top of descent (TOD) from a nearby station (Denver VORTAC in this case); the target descent altitude at the time control point (Drako) in hundreds of feet; the jet arrival route designation; the arrival time at the time control point. All of this information is computed specifically for the type and weight of the arriving aircraft as well as for the current estimate of the wind profile. The lines in the panel are ordered by predicted arrival times with the latest times at the top. This ordering is consistent with the sequence shown in the time line.

A significant attribute of the system design is its refresh feature. Approximately every 10 sec the DA algorithm automatically recomputes the descent profiles and the predicted arrival times of all selected aircraft. The profiles of the other aircraft continue to be updated every 2 min. Thus, the information on the time line and in the DA panel adapts continuously (at a 10-sec rate for selected aircraft) to changes in aircraft position, altitude, heading, and airspeed. In addition to increasing the accuracy and timeliness of the information, this adaptive capability can be exploited by a knowledgeable controller to solve various traffic management problems.

Time Range Bar

When an aircraft is selected, a yellow vertical bar with brackets at the ends is displayed next to the time line at the predicted arrival time of the aircraft. The time range enclosed by the brackets indicates the maximum variation of arrival time achievable through speed profile management along a fixed arrival route. In particular, the brackets point at the maximum and minimum arrival times obtained by flying the aircraft along its minimum and maximum speed envelopes, respectively. It follows from the definition of the bracket times that the predicted times for the SP profile must fall between or on the brackets. This is seen to be the case in figures 3 and 4. Overlapping brackets, as in figure 3, can occur when the predicted arrival times of two selected aircraft are sufficiently close to each other. If this causes an ambiguity in reading the bracket position, it can be resolved by briefly deselecting one aircraft.

Top of Descent Marker

From aircraft performance studies it is well known that the location of the top of descent point for a fuel efficient descent trajectory depends significantly on the choice of the descent speed profile as well as on many other factors. Therefore, showing its location on the plan view display (PVD) can give the controller useful cues for the efficient management of descent traffic. Its location on the PVD is indicated with a small purple marker which is labeled with the appropriate aircraft ID (see fig. 3).

The location of the TOD marker should normally be at least several miles in front of the aircraft position at the time the descent clearance is issued. However, if the TOD and position markers appear to coincide, it indicates that the aircraft is either at or has already passed the optimum point of descent. In this situation the DA algorithm uses a mid-descent logic for generating speed profiles, as explained in a later section. As long as this logic can still find a feasible descent profile during the profile refresh cycles, the TOD marker will be seen to track the position marker. The colocation of these markers alerts the controller that the opportunity to initiate a descent along the currently predicted horizontal path is about to disappear, unless the aircraft is already flying a descent profile. If this loss of descent opportunity occurs, it is indicated by the simultaneous disappearance of the TOD marker and the profile information in the DA Clearance Panel for the affected aircraft. The controller can remedy this situation by stretching the horizontal rate of the aircraft until the lost information reappears. The primary use of this marker is as a visual indicator to help the controller in judging the distance remaining to the TOD point, and in properly timing the issuance of the descent clearance. Also, the markers can assist the controller in monitoring the descents in mountainous terrain and in detecting potential conflicts with descending traffic.

Distance Spacing Markers

Distance spacing markers give a graphical representation of the future spatial relationship of traffic converging on a time control point. Their positions on the screen are always based on the descent profile parameters currently displayed in the DA Clearance Panel.

The markers are made visible on the PVD by clicking on the spacing button in the Mode Select Panel. They consist of small blue dots with leader lines pointing to an aircraft identification tag and a number representing the distance in nautical miles to the time control point (Drako) (fig. 3). The location of the first marker is determined by finding the first of the selected aircraft, referred to as the leading aircraft, to arrive at the time control point. The marker for the leading aircraft is then placed at this point, with the distance variable set to 0.0. Markers for all other selected aircraft are placed at locations corresponding to the time that the leading aircraft arrives at the time control point. Thus, the markers show the constellation of selected aircraft positions relative to the first aircraft arriving at the time control point. They play an analogous role in the spatial domain as the arrival time markers do in the time domain.

The combination of time line and spacing markers provides controllers with integrated graphic tools for visualizing the future relationship of aircraft at a point in space. These graphic tools are easier to understand and more interesting for controllers to use than are the lists and tables found in the current operational ATC system.

Arrival Time Selection and Advisories

An on-screen, interactive procedure is used for selecting arrival times and generating arrival time advisories. It is intended to be used primarily as a stand-alone manual mode. A more automated mode used in conjunction with an automatic scheduler is described in the next section.

The first step in the procedure is to "select" an aircraft of interest and to watch for the time range bar to appear on the time line. The appearance of the bar indicates that the system is ready to accept a time command, and its length gives the time range available for selection. The aircraft ID tag located to the left of the time range bar serves both as a cursor for selecting a time and as a command input device for the DA algorithm. When an aircraft first enters the arrival area, the location of the cursor ID tag is initialized to the predicted time for the SP profile. Thus, both tags are initially located at the same point on the time line.

The cursor tag can be relocated by moving the mouse pointer on top of the tag, holding down the left mouse button, and dragging it with the mouse to any point on the time line. A capture of the cursor tag by the mouse pointer is indicated by a change in color of the tag from yellow to white when the left mouse button is held down.

The decisive moment for acceptance of a time command occurs when the mouse button is released. At that moment, the cursor position becomes the commanded time that is fed into the DA algorithm. If the cursor position is outside the time range brackets, the time of the nearest bracket is instead chosen as the commanded time.

After the DA algorithm has finished its profile calculation (in about 3 sec time) the new descent parameters are read into the DA Clearance Panel. At that time, the profile mode designator is changed from SP to I, where I stands for "Inquiry." Also, the predicted arrival time and its associated ID tag are relocated to the new position on the time line. This process was accomplished for PA 001 in figure 4. The "inquiry" designation indicates that the profile shown is the DA's response to the controller's "what if" question. The clearance corresponding to the inquiry profile has not been issued to the aircraft, which continues on its previous profile.

The process of selecting new arrival times and generating the corresponding descent clearances can be repeated any number of times. Each time a new clearance is generated, the TOD and spacing markers are also updated. Thus, the controller can quickly assess the effect of different time commands on the trajectory and its relationship to other traffic, prior to issuing any clearance to the aircraft.

As before, the DA algorithm automatically refreshes the profile and corresponding descent clearance approximately every 10 sec. At each refresh cycle, the algorithm reads the location of the cursor tag as well as the current aircraft state. It is also possible to return to the original SP profile type by clicking on the "Show SP" button in the Mode Select Panel.

When the controller has settled on a desired arrival time and has decided to issue the displayed descent clearance to the aircraft, he can lock in the profile and clearance by clicking on the associated arrival-time ID tag located to the right of the time range bar. This action simultaneously freezes the current profile and clearance, stops the cyclic refreshing of the profile and changes the profile type designation from I to DA. It also places a * symbol next to the arrival time tag. This locked profile mode is illustrated by TA 321 and AA 404 in figure 4. In order to prevent the locked profile from being changed inadvertently, the cursor tag of the aircraft with the locked profile is rendered inactive. However, the locked DA state can be cancelled if necessary and the aircraft returned to the I state by clicking again on the starred tag. When the aircraft with a locked profile, such as AA 404 shown in figure 4, is deselected, the * remains visible, thereby providing a marker to remind the controller that the aircraft had previously been issued a profile descent clearance. Furthermore, the locked clearance can be redisplayed by reselecting the appropriate aircraft.

Meeting Gate Times Sent by Traffic Management Advisor

In the traffic management concept described earlier, optimum landing times are generated by an automatic scheduler, which resides in the TMA. The scheduler assigns landing times that merge the traffic flow, conflict free, from all four feeder gates while ensuring that the aircraft spacing requirements on final approach are observed. After the landing times have been generated, the scheduler converts them to arrival times at the appropriate feeder gate by taking into account the difference in flight time between touchdown and the gate. Then, the TMA sends these times to the appropriate DA located at the controller position that is feeding traffic to a gate. The DA tools and procedures described in the preceding section are applied here to assist the controller in generating advisories for meeting these scheduled times.

The controller selects the automatic scheduler, referred to as the TM mode, by a keyboard command. In this mode, the green cursor, which was used in the preceding section to input a time command manually, is removed from the time line. In its place, a blue cursor appears at the time determined by the automatic scheduler for each aircraft. Also, since the blue cursor is a commanded value from the TMA, it cannot be picked up and moved by the mouse to a different time. However, the controller can still assign his own gate times by returning to the manual mode of the preceding section and then dragging the cursor, as before. To obtain advisory clearances for meeting the gate time, the controller selects the appropriate aircraft by clicking either on the aircraft position indicator as before or, alternatively, on the blue cursor ID tag. Then, the DA algorithm enters the inquiry profile mode (instead of the SP profile mode, as before), and begins generating profiles and advisories for the selected aircraft. If the cursor position falls within the time range bar, the speed and descent advisories shown in the DA panel correspond to permissible aircraft trajectories that will cause the aircraft to arrive at the scheduled gate time. The controller can lock any currently displayed clearance he finds acceptable by clicking on the predicted arrival time tag on the time line. He can also redisplay and revise the clearance by applying previously described procedures.

Spacing Advisories

Two advisory modes are available for generating descent clearances that meet specified spacing distances at the feeder gate (or time control point). The two modes are invoked by clicking on one or the other of the buttons labeled SEP_ONE and SEP_TWO in the Mode Select Panel.

Before using either mode, the controller must choose a desired spacing distance in nautical miles and enter it via the keyboard. The current value of 10 n.mi. shown in figures 3 and 4 is displayed in the Mode Select Panel to the right of the SEP_TWO button. Another requirement for activating these modes is that exactly two aircraft must be in the selected state. As a rule, the controller should pick two consecutively arriving aircraft that are 15 to 25 min of flight time from the feeder gate. The arrival time sequence displayed on the time line and the spacing markers provide information to help the controller choose an appropriate pair.

After selecting a pair of aircraft and observing that the spacing markers predict a spacing sufficiently different from the specified value, the controller can choose one or the other of the two spacing modes to assist in achieving the desired spacing.

The SEP_ONE mode should be chosen if only the speed profile of the trailing aircraft can be modified to change the spacing, while the speed profile of the leading aircraft must remain unchanged. Clicking on SEP_ONE causes the DA algorithm to search for a speed profile for the trailing aircraft such that the resulting spacing distance will match the specified value as closely as possible. After the DA algorithm has completed the calculation in a few seconds, the new clearance is posted in the DA Clearance Panel and the spacing markers are updated. Also, the profile mode indicators are changed from SP to I. As for all SP and I profile types, the DA algorithm refreshes the profile and its corresponding clearance in a 10-sec cycle, each time using updated aircraft state information. The clearance for PA 001 and the corresponding spacing distance between PA 001 and TA 321 obtained by invoking SEP_ONE is shown in figure 4. The spacing distance of 11.4 n.mi. is within the allowed error tolerance of the specified spacing distance of 10 n.mi.

If the spacing distance achieved with SEP_ONE is inadequate, the controller can invoke the SEP_TWO mode. This mode gives the DA algorithm the freedom to change the speed profiles of both trailing and leading aircraft. As in the SEP_ONE mode, the DA algorithm first attempts to achieve the specified spacing by changing only the trailing-aircraft speed profile. If this attempt fails, the DA algorithm then changes the speed profile of the leading aircraft in an effort to achieve the desired spacing.

The controller must decide which of the two modes to use based on an assessment of the prevailing traffic situation in his sector. For example, he would probably decide not to use the SEP_TWO mode if he previously had issued a descent clearance to the leading aircraft or if the leading aircraft is itself in trail and at a minimum spacing distance behind another aircraft.

If the controller judges the spacing distances acceptable, he would then proceed to issue the appropriate clearance(s) to the aircraft. At that point, he should lock in the profiles and clearances by clicking on the "ok" button in the Mode Select Panel. This action terminates the cyclic refreshing of the profiles and freezes the currently displayed clearance. As was the case for the Time Control Advisories, locking the profiles changes the profile type indicator from I to DA and places a * symbol after the arrival-time-prediction tag. The profiles can be unlocked by previously described procedures.

The final transaction in using these two modes is to deselect the pair of aircraft. Then the controller can concentrate on identifying and picking another pair of aircraft whose spacing needs to be controlled.

HORIZONTAL GUIDANCE MODES

In the preceding explanation of descent profiles and automation tools, the crucial problem of constructing efficient horizontal paths for the aircraft was not addressed. In the previously discussed examples, the aircraft were all flying along standard jet routes. Here the methods used to construct the horizontal profiles are defined for both on-route and off-route situations.

Construction of a horizontal path always begins at the current position and heading of the aircraft and terminates at the time control point. It is a prerequisite for the subsequent synthesis of the descent profile. The controller has a choice of two horizontal guidance modes, referred to as Route Intercept (RI) and Waypoint Capture (WC). They are selected by clicking on the appropriately labeled button in the Mode Select Panel.

Route Intercept (RI) Mode

This mode operates in conjunction with the set of standard jet arrival routes converging on the time control point. The routes recognized by the DA algorithm in the Drako feeder gate approach sectors are those drawn in blue on the PVD. They have a corridor width of ±4 n.mi. relative to its center line. Other feeder gates have their own set of standard arrival routes.

In calculating a profile, the DA algorithm first determines if the aircraft position falls within a corridor of one of the standard routes and if its course is within 45° of the route direction at its current location. If the aircraft passes these two tests, the DA algorithm then uses its on-route logic to construct the horizontal path. This is done by concatenating all standard arrival route segments traversed when moving from the current aircraft position to the time control point. It includes circular arc segments to transition smoothly from one segment to another where a change in course occurs at junction points.

If the aircraft fails at least one of these tests, the DA algorithm declares it off-course and invokes the RI logic. This logic, illustrated in figure 5, seeks to create a route intercept segment connecting the current aircraft position to a point on a standard route segment. First, the algorithm generates a directed line, called the aircraft course vector, which emanates from the current position and points in the direction of the aircraft course over the ground. Then it searches for points of interception of the course vector with standard route segments. As a rule, the first point of interception found establishes where the aircraft joins the standard route. Next, the logic creates a new route by concatenating the route intercept segment with the segments of standard route traversed between the route intercept point and the time control point. From here on, the DA algorithm generates speed and altitude profiles in exactly the same manner as if the new route were a standard route. One exception to the rule of choosing the first point of interception arises when that point falls 25 n.mi. or less in front of a junction point and a second point of interception occurs on the downstream side of the junction point. In this case, the route intercept logic chooses a path to the second interception point. There are other exceptional cases incorporated in the RI logic, but a description of these is deferred to a future publication. Here it suffices to say that the exact conditions of capture are highly dependent both on the geometry of the route structure and the established controller procedures in an arrival sector.

Route intercept points are indicated on the PVD by white markers with attached aircraft identification tags. The RI profiles shown for the two selected aircraft in figure 6 illustrate both a regular RI point for CO102 and an exceptional case for TWA61. The first RI point for TW61 on its current heading was found to be closer than the minimum allowed distance (25 n.mi.) from the junction of routes J56 and J170. Hence, the second RI point located between the junction point and Drako was the one selected by the algorithm.

The RI logic combined with the automatic refresh of profiles provides considerable flexibility for solving arrival time and spacing problems that require off-route vectoring. This flexibility derives from the fact that changes in heading between refresh cycles reflect in migration of the RI point and therefore in changes of the predicted arrival time. The controller can use this characteristic to expand the arrival time range beyond what is available by speed control alone. For example, in figure 6, the spacing at Drako between TWA61 and CO102, can be adjusted by a heading change of CO102. A change to the left will move the RI point upstream on the intercepted segment, thus delaying its arrival at Drako. At the same time it also causes the downward motion of the time range bar to slow down or even migrate up the time line. One way for a controller to take advantage of this capability is to make gross changes in arrival time first with vectoring and then to make fine adjustments with speed clearances.

Waypoint Capture (WC) Mode

This mode provides advisories for predicting and controlling the arrival time of aircraft during off-route vectoring. It uses only the aircraft initial position and course and the time control waypoint position in generating the horizontal path. Therefore, it differs from the RI mode in that it does not depend on knowledge of standard arrival routes for its calculations.

The horizontal path synthesized in this mode consists of an initial circular arc turn starting at the current position and course followed by a straight flight segment leading directly to the time control point. The path is computed such that the end of the circular arc turn is tangent to the straight flight segment. The geometry of this construction is illustrated in figure 7. The algorithm determines the radius of the turn from the airspeed, wind speed, and maximum allowable bank angle. Furthermore, the direction of the turn toward the time control point is chosen so that the total length of the path is minimized. In order to compensate for computational delays and to allow for controller response time, the algorithm also moves the start of the turn at each computational cycle a distance equivalent to 15 sec of flight time ahead of the current aircraft position. Once this logic has determined the parameters of the path, the DA algorithm synthesizes the speed and altitude profiles in exactly the same way as in the RI mode.

As in other modes, the DA algorithm refreshes the waypoint capture profile in approximately a 10-sec cycle using updated aircraft state information.

A white marker indicates the end of the circular arc and the beginning of the straight line segment on the PVD. A number next to the marker gives the magnetic heading in degrees, of the straight line segment leading to the time control point (fig. 8).

The most sophisticated application of this mode is in advising the controller when an off-route aircraft should be vectored toward the time control point in order to capture a time slot. This includes solving the related problem of when to break out of a holding pattern to capture a time slot.

In such applications, the general procedure is to vector an aircraft initially on a 30° to 90° heading away from a direct course to the time control point. In figure 8, CO102 is heading in the proper direction for using this mode. As the aircraft continues on this course with the DA algorithm generating a sequence of waypoint capture profiles, the motion of the time range bar will slow down relative to that of the time line scale, indicating increasing delays. The greater the angle between the aircraft heading and the direct course to the time control point, the faster the delay will increase. When a specified arrival time on the time scale passes near the middle of the time range bar, the optimum time has been reached for the controller to issue the WC heading advisory shown on the PVD. This places the aircraft on a path to arrive approximately at the specified time. If the residual time error is excessive after the aircraft has executed the heading vector, the controller can zero out that error using the time control advisories described in an earlier section. It is recognized that this procedure (as well as others described above) will be made more automated in future refinements of this tool. However, by initially providing the tool in this form, the controller retains maximum flexibility, and thus can tailor its use more easily to a variety of specific traffic situations.

SPEED PROFILE MODES

Three modes representing different constraints on generating speed profiles for time control have been implemented on the DA algorithm. They can be selected by clicking on a speed-profile-mode button located in the Mode Select Panel. Repeated clicks of the button causes each of the modes to be selected in succession. The names of the modes, in the order in which they are selected, are Descent (DA), Cruise-plus-Descent (C+D), and Cruise (C). The characteristics of each mode are described below.

Descent Speed Mode

In this mode the DA algorithm achieves a specified arrival time by iterating on the descent speed profile only. Thus, while the aircraft is at cruise altitude the cruise Mach number/indicated airspeed (IAS) is not controlled by the algorithm. However, at each cyclic refresh of the profile, the cruise speed used as an initial condition by the algorithm is updated with information received from the National Airspace System Host Computer.

For each aircraft type, the speed range available for time control is specified by the maximum descent Mach number, the maximum descent IAS and the minimum descent IAS. For a 727 these limits have been chosen as Mach 0.84, 350 KIAS, and 230 KIAS, respectively.

In addition to providing time control, the DA algorithm also ensures that the descent profile is optimally fuel efficient. It achieves this first by choosing the TOD point so as to minimize powered flight at low altitude, and second by generating altitude-speed profiles that permit idle thrust flight throughout the descent. The types of profiles are similar to those generated by advanced flight management systems.

The idle thrust condition produces an interdependence of the speed and altitude profiles. That is, for each speed profile there is a unique altitude profile that can be flown at idle thrust with the aircraft in the clean configuration (no flaps and speed brakes). This interdependency changes the TOD point whenever the speed profile changes. Furthermore, the altitude profile and TOD point also depend on aircraft performance parameters and winds. For example, the location of the TOD point can move 25 n.mi. or more when the speed profile is changed from the fastest to the slowest descent speed.

The best time to invoke this mode is while an aircraft is in cruise and still some distance from the TOD point. However, the algorithm also provides speed advisories after the aircraft has passed the TOD point or while the aircraft is descending. The part of the DA algorithm handling these situations is called mid-descent logic. If an aircraft has moved passed the optimum TOD point or is already in descent, this logic first computes the constant descent angle required to reach the desired altitude of the time control point from its current position. Then it determines the speed range within which the aircraft can fly at this descent angle and still be able to decelerate to a specified final speed. In this step, the use of speed brakes is permitted in any part of the descent. The speed range obtained will grow smaller as the angle of descent increases. Eventually, as the angle of descent reaches a critical value, the speed range shrinks to zero and the DA algorithm fails to generate a feasible profile.

Cruise Speed Mode

In this mode the DA algorithm iterates only on the cruise speed segment in order to achieve a specified spacing or arrival time. For the descent portion of the flight, the algorithm always assumes the airline SP profile. The limits on the cruise speed envelope used in this mode consist of a maximum cruise Mach number, which depends on weight, altitude, and temperature, and a minimum cruise indicated airspeed. Both limits depend on aircraft type and engine model. Figure 9 shows plots of Mach numbers, IAS, and altitude as a function of range for the maximum, minimum, and nominal cruise speeds.

The cruise speed advisory (CS) appears in the DA Clearance Panel as the first item after the aircraft identification in figure 6. It consists of a desired cruise Mach number or, if the aircraft is cruising below 28,000 ft, a desired indicated airspeed in knots.

In order to compensate for controller and pilot delays in executing a cruise speed advisory, the DA algorithm also includes a 15-sec delay in the start time of cruise speed changes, measured from the aircraft position at the time of calculation. This delay compensation combined with the periodic refresh of the profiles and clearances every 10 sec helps to reduce time errors in executing the cruise speed advisory.

This mode should be used early in arrival sequencing when an aircraft is at least 50 n.mi. from the top of descent point. At a smaller distance, the available time range is too small to be useful in arrival time control. By using cruise speed control only, the controller can complete most of the repositioning of an aircraft necessary to achieve a specified arrival time before the aircraft begins its descent. Since the descent profiles in this mode are all based on standard procedure types, the speed differential between in-trail descending aircraft is likely to be small. This has the advantage of minimizing the occurrence of overtakes and thereby helps reduce the controller's effort in monitoring the descent traffic.

Cruise-Plus-Descent Speed Mode

This mode provides the greatest possible time range by allowing the DA algorithm to control both the cruise speed and the descent speed profiles. The speed limits that determine the extreme values of the time range are generally identical to those used in the other two speed-control modes. An exception to this rule is the maximum Mach number in descent which in this case is set equal to the maximum cruise Mach number. This assumption sacrifices a small amount of time range but has the advantage of simplifying both the algorithm and, as will be shown below, the specification of the speed clearances.

In generating a cruise-plus-descent speed profile, the algorithm first attempts to meet the specified arrival time by cruise speed control only. If the attempt succeeds, the profiles generated are similar to those in the cruise speed mode. If the attempt fails, cruise speed will have reached one of its limits without achieving the specified arrival time. Descent speed control is then initiated with the cruise speed set from the limit value. Another condition imposed on the descent speed profile is that the Mach number of the constant Mach descent segment, if one is necessary, be the same as the Mach number in cruise. This condition limits the number of the speed clearance parameters that the controller has to issue to two, which is the same as for the other two modes.

When an aircraft is less than 25 n.mi. from the TOD point of the SP profile, the algorithm reverts to descent speed control only. Plots of Mach number, IAS, and altitude as a function of range for maximum, minimum and nominal speed profiles in cruise and descent are given figure 10.

COMPUTATION OF PROFILE TRACKING ERRORS

As explained in a preceding section, the controller normally "locks" a profile immediately after issuing an aircraft the clearances displayed in the DA clearance panel. Locking the profile sends a signal to the DA algorithm to cease generating new profiles and initiate tracking the locked profile. The profile tracking process consists of computation of errors in time, lateral position, and altitude between the current position of the aircraft and the locked profile.

As the first step in computing these errors, the error tracking algorithm determines if the current aircraft position lies within a three-dimensional corridor centered around the locked profile. In the horizontal plane, the corridor extends 4 n.mi. on each side of the center of the locked profile, while in the vertical plane it extends 1000 ft above and below the altitude of the locked profile. These corridor dimensions can be changed for different conditions. Where the horizontal path consists of a circular turn segment, such as in a transition between two straight line segments, the corridor takes the shape of an annulus (fig. 11). If the current aircraft position is found to be outside this corridor, the aircraft is considered to be off track, and the rest of the error computations are skipped.

If the aircraft is within the route corridor, the error computation algorithm first projects the actual aircraft position onto the path of the locked profile in order to locate a projected position (see fig. 11). Then it determines the increment or decrement in current time needed to bring the locked profile position into coincidence with the projected position. An increment in time corresponds to early arrival (negative time error) and a decrement to late arrival (positive time error). The time error, in seconds, is displayed in the DA panel to the right of the locked profile arrival time. In figure 4, TA 321 has accumulated a time error of 3 sec (late) relative to its locked (DA) profile. The time error is also incorporated in the position of the predicted arrival time along the time line via algebraic addition of the time error to the locked profile arrival time. Thus, even when the locked clearance is no longer displayed in the DA clearance panel, the controller can still monitor the time error by comparing the blue scheduled time (or the green cursor position, as the case may be) with the predicted arrival time.

In the current implementation, the last computed time error in the DA panel is appended with a question mark, if the current aircraft position lies outside the route corridor. Similarly, a question mark is also placed after the corresponding predicted arrival time ID tag on the time line. The error computations are repeated approximately every 20 sec.

CONCLUDING REMARKS

The human-centered automation concept described in this paper deliberately places the automation tools in a subordinated position relative to that of the human controller, who will remain the cornerstone of the air traffic control process in the foreseeable future. The controller selects the automation levels and functions in response to specific traffic management problems. He or she can combine his own procedures and decisions with computer generated advisories by choosing tools that complement his own control techniques. At one end of the spectrum of computer assistance, the controller can use the tools in a passive mode to gain insight into the effect of the planned actions. At the other end of the spectrum, he or she can use the tools actively by issuing the computer generated clearances to the aircraft.

The descent advisor tools described in this paper are primarily designed for use by center controllers in managing descents into the terminal control area. Other tools under development will optimize flow management and generate scheduling information that must be distributed to all descent controller positions. While these other tools are essential elements of the overall automation concept outlined early in the paper, they cannot be fully exploited until the Descent Advisor tools are available to controllers to assist them in executing schedules accurately and with low workload. Therefore, the Descent Advisor constitutes the basic building block of more automated air traffic control systems.

The interactive graphic interface is probably the most innovative as well as the most critical design feature of the Descent Advisor. It was designed by building upon the user environment incorporated in certain types of high performance engineering workstations. That this workstation technology can be so easily adapted to the needs of air traffic control automation is remarkable and fortunate for progress in this area.

Controller acceptance of this interface, more than any other issue, will determine the viability of this concept. Here, real time simulations are the main avenue for evaluating controller response, for refining the interface and for developing user procedures. Ultimately, however, only tests with live traffic can establish the effectiveness of the interface with a high level of confidence. Such tests with live traffic, considered an essential step in the development of an advanced automation system, are planned to begin at the Denver Center in early 1990.

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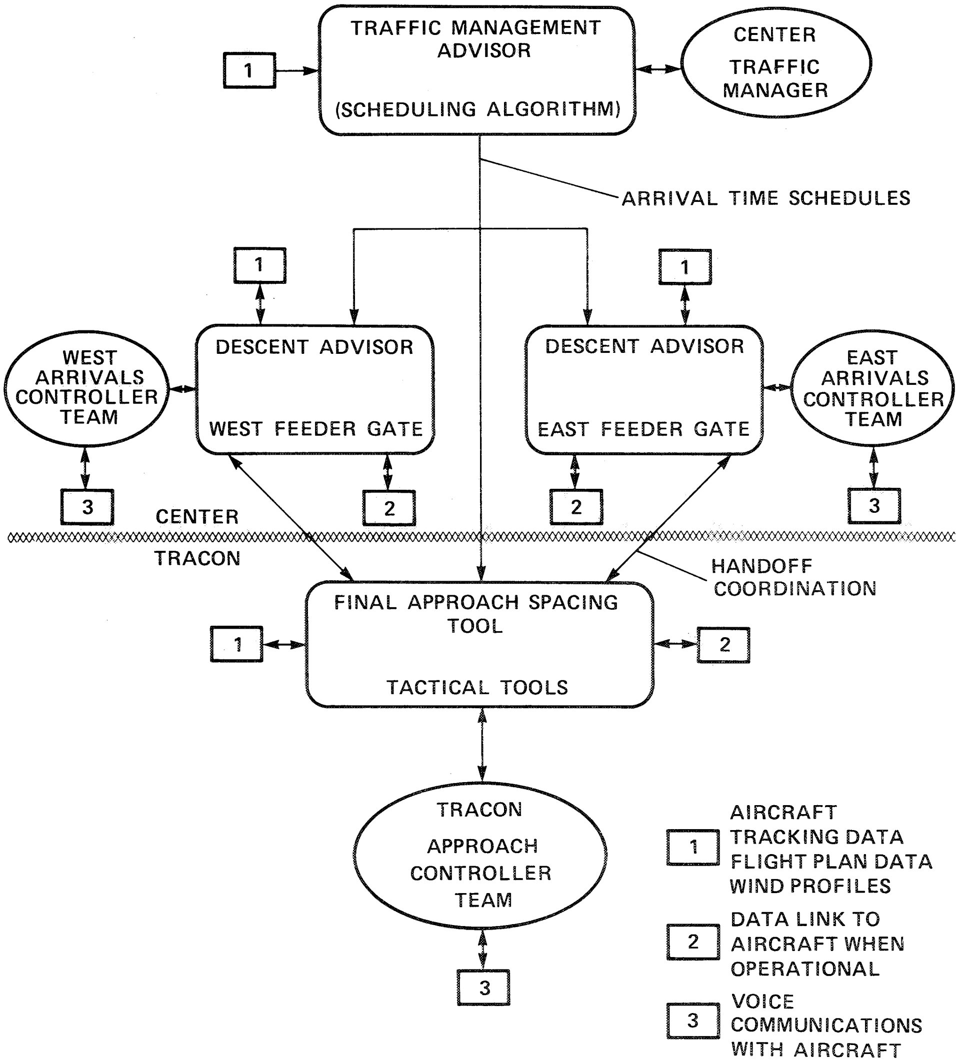

Figure 1.– Automation concept and hierarchy of automation tools.

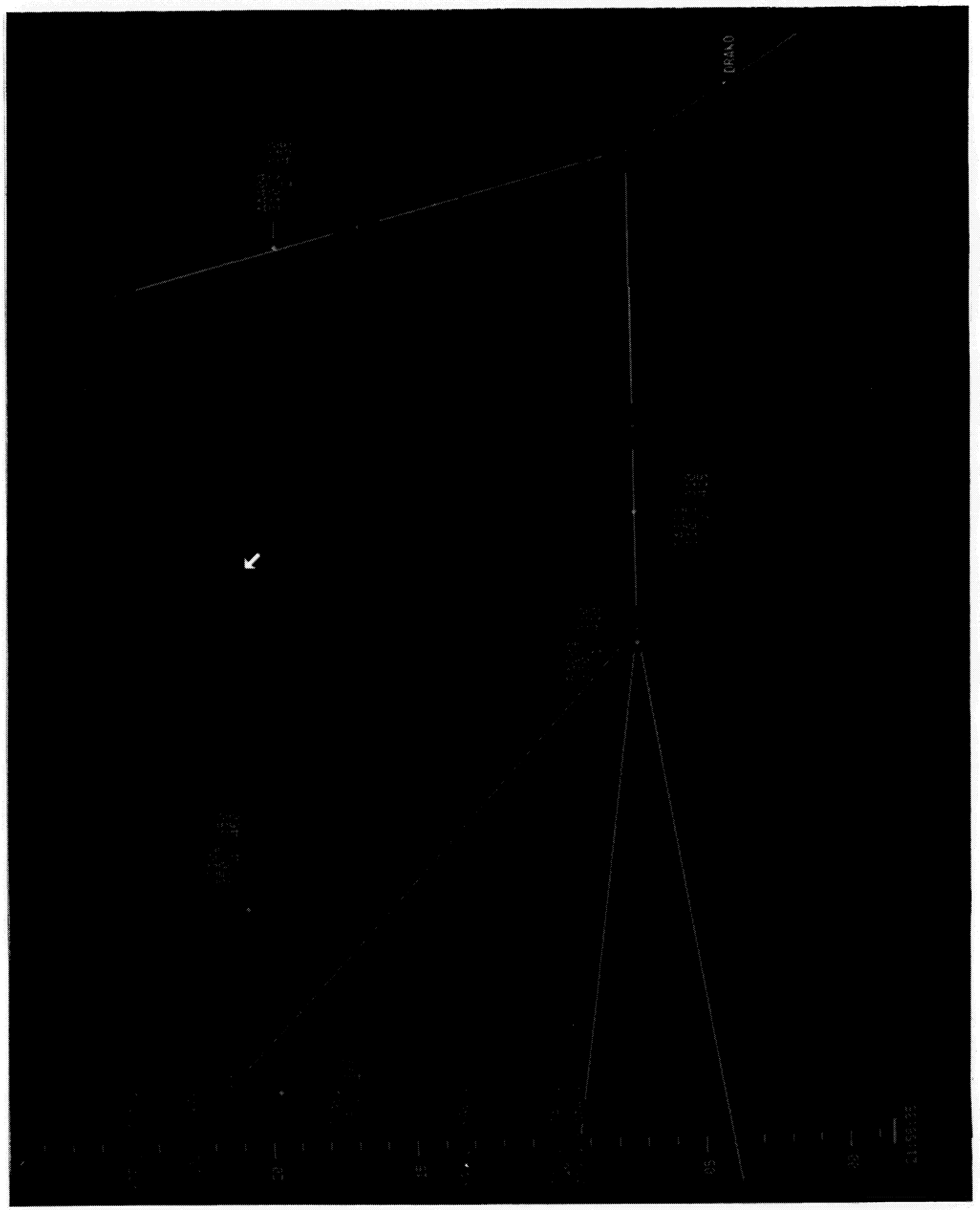

Figure 2.– Integrated controller display with time line.

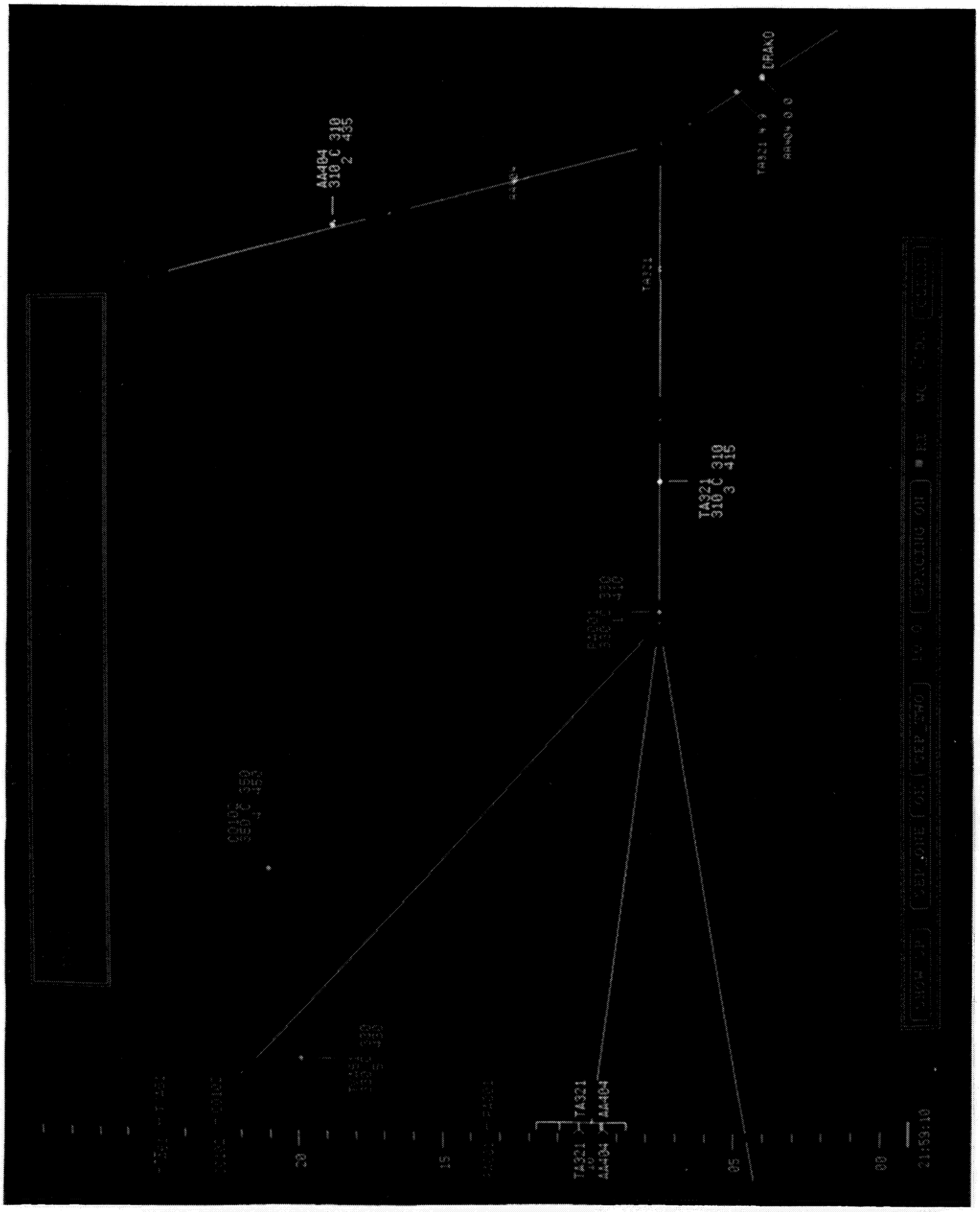

Figure 3.– Integrated controller display showing two selected aircraft in SP profile mode, and spacing advisories.

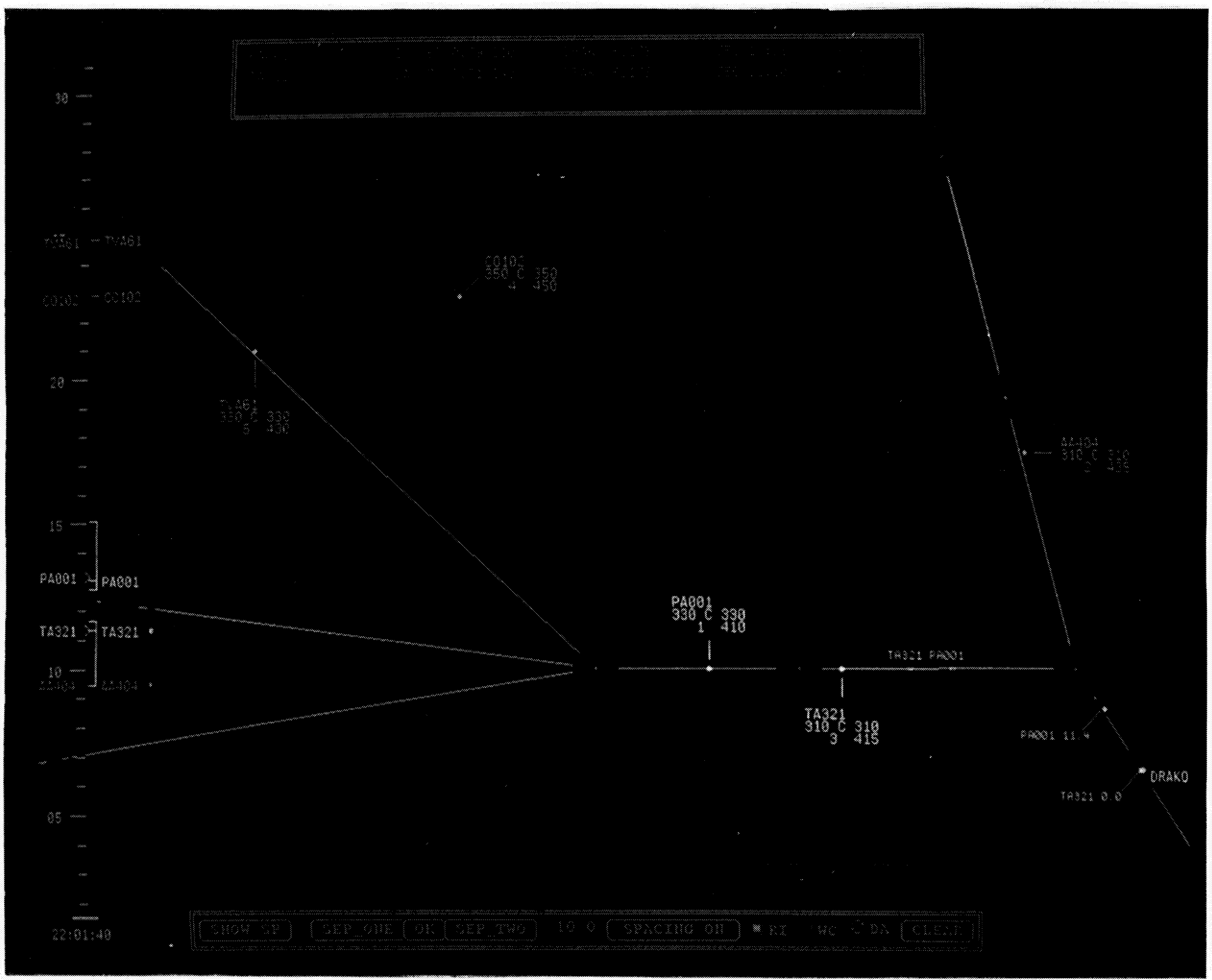

Figure 4.– Integrated controller display with spacing advisories.

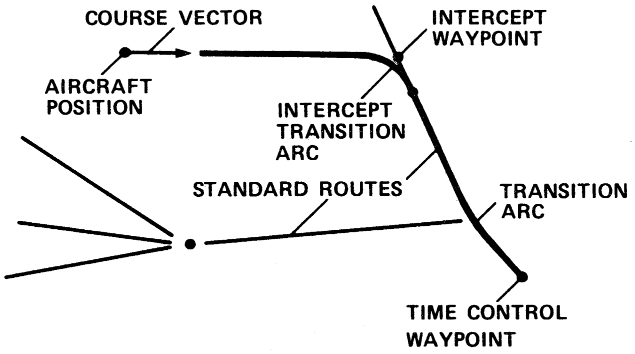

Figure 5.– Sketch of route intercept guidance.

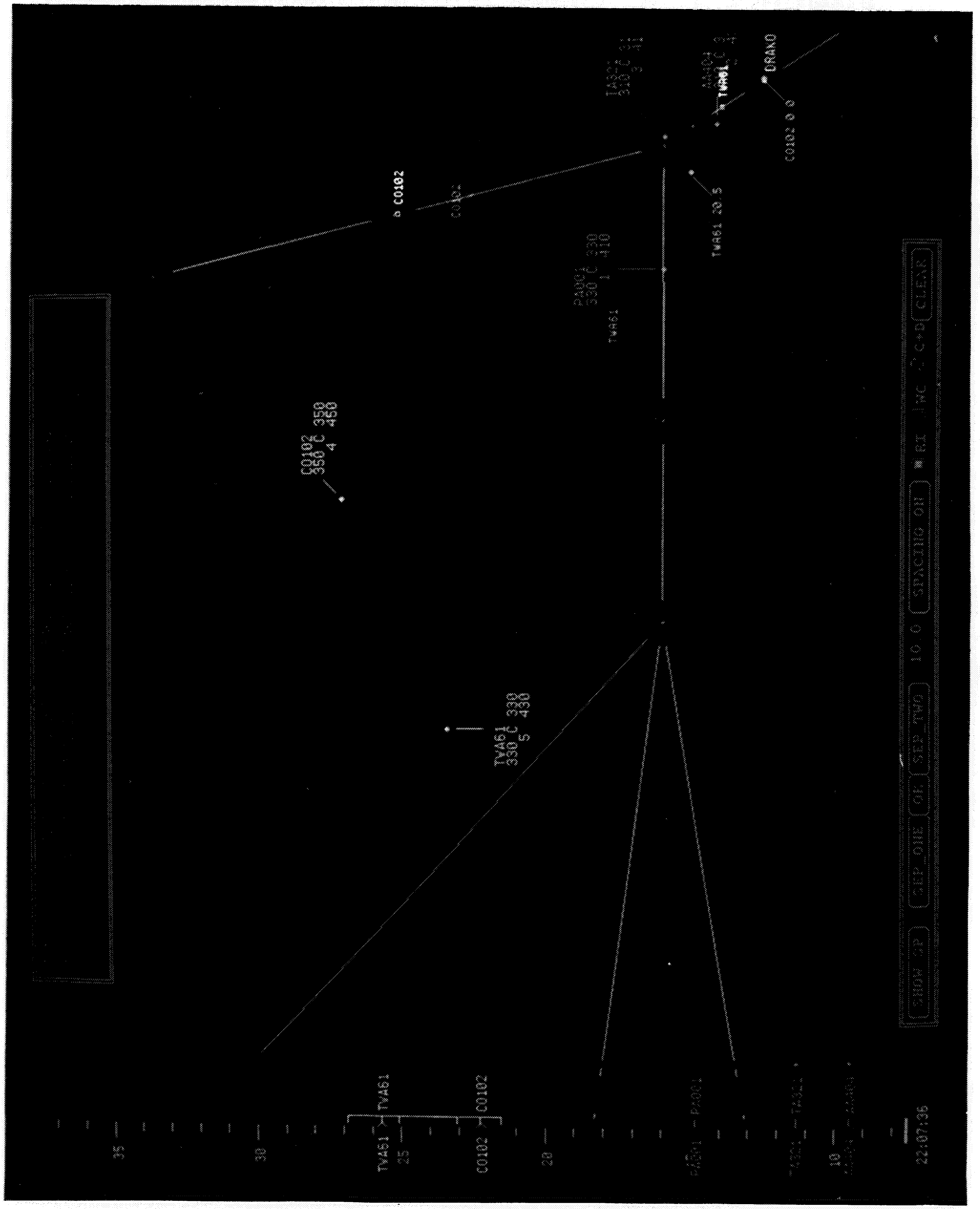

Figure 6.– Integrated controller display illustrating route intercept guidance and cruise speed advisories.

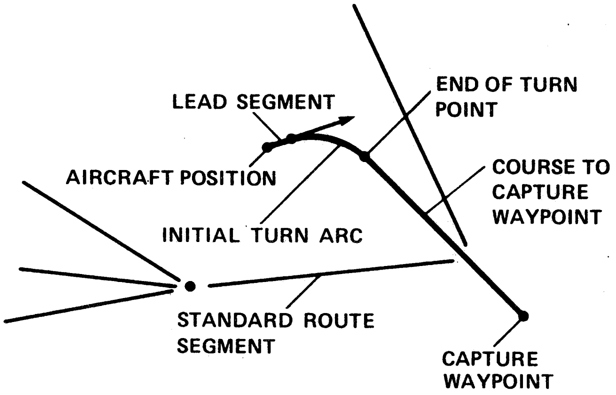

Figure 7.– Sketch of waypoint capture guidance.

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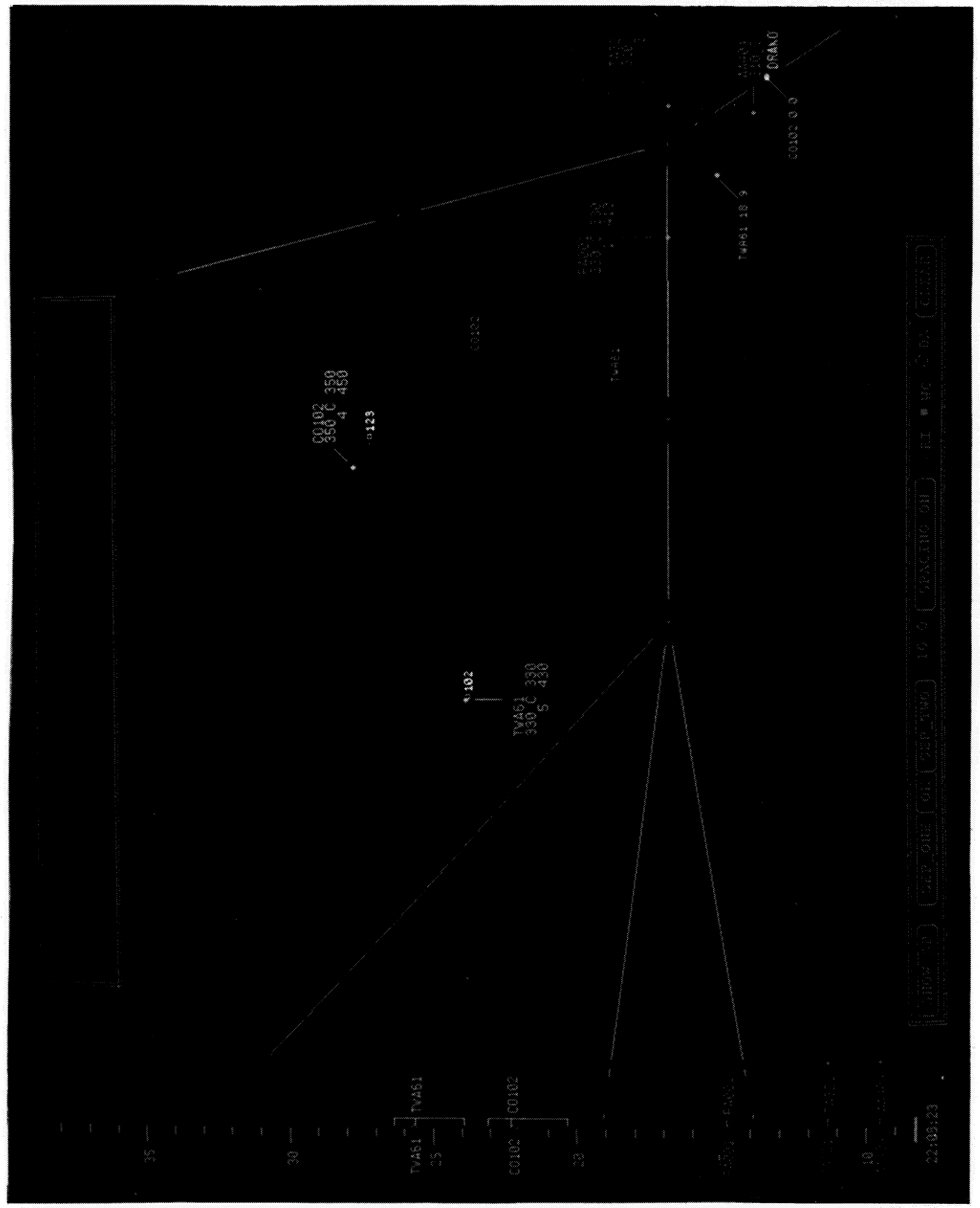

Figure 8.– Integrated controller display illustrating waypoint capture guidance to Drako.

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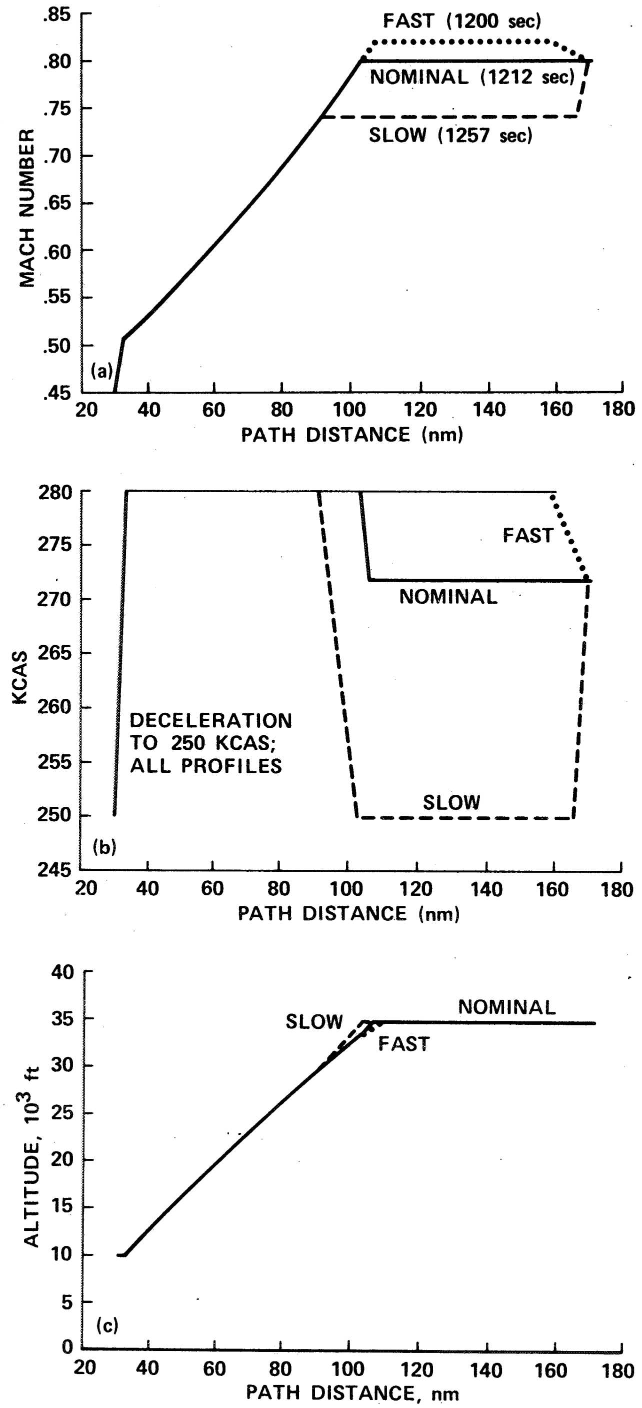

Figure 9.– Cruise-only speed and altitude profiles. (a) Mach number. (b) KCAS. (c) Altitude.

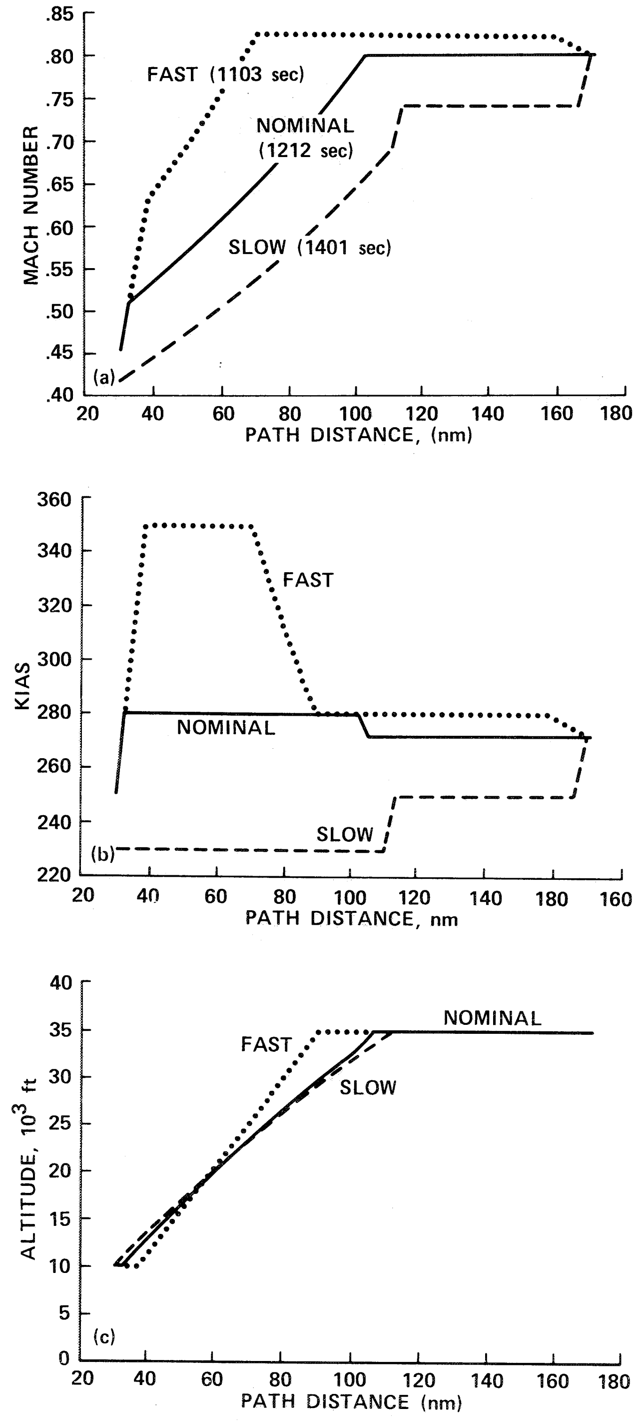

Figure 10.– Cruise-descent speed and altitude profiles. (a) Mach number. (b) KIAS. (c) Altitude.

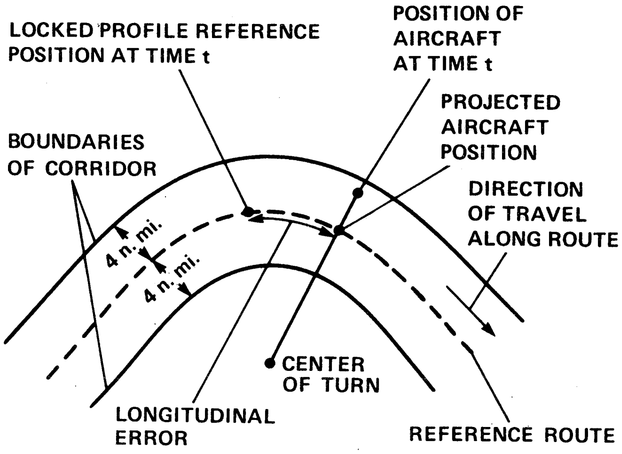

Figure 11.– Definition of profile corridor and computation of time error.

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16. Abstract

This paper describes the design of an automated air traffic control system based on a hierarchy of advisory tools for controllers. Compatibility of the tools with the human controller, a key objective of the design, is achieved by a judicious selection of tasks to be automated and careful attention to the design of the controller system interface. The design comprises three interconnected subsystems referred to as the Traffic Management Advisor, the Descent Advisor, and the Final Approach Spacing Tool. Each of these subsystems provides a collection of tools for specific controller positions and tasks. This paper focuses primarily on the Descent Advisor which provides automation tools for managing descent traffic. The algorithms, automation modes, and graphical interfaces incorporated in the design are described. Information generated by the Descent Advisor tools is integrated into a plan view traffic display consisting of a high-resolution color monitor. Estimated arrival times of aircraft are presented graphically on a time line, which is also used interactively in combination with a mouse input device to select and schedule arrival times. Other graphical markers indicate the location of the fuel-optimum top-of-descent point and the predicted separation distances of aircraft at a designated time-control point. Computer generated advisories provide speed and descent clearances which the controller can issue to aircraft to help them arrive at the feeder gate at the scheduled times or with specified separation distances. Two types of horizontal guidance modes, selectable by the controller, provide markers for managing the horizontal flightpaths of aircraft under various conditions. The entire system consisting of descent advisor algorithm, a library of aircraft performance models, national airspace system data bases, and interactive display software has been implemented on a workstation made by Sun Microsystems, Inc. It is planned to use this configuration in operational evaluations at an en route center.

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