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STUDY OF AIRCRAFT-CENTERED NAVIGATION, GUIDANCE, AND TRAFFIC SITUATION SYSTEM CONCEPT FOR TERMINAL-AREA OPERATION

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16. Abstract

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SUMMARY

A concept for automating the control of air traffic in the terminal area in which the primary man-machine interface is in the cockpit is described. The ground and airborne inputs required for implementing this concept are discussed. Digital data link requirements of 10 000 bits per second are explained. A particular implementation of this concept including a sequencing and separation algorithm which generates flight paths and implements a "natural order" landing sequence is presented. Onboard computer/display avionics utilizing a traffic situation display is described. A preliminary simulation of this concept has been developed which includes a simple, efficient sequencing algorithm and a complete aircraft dynamics model. This simulated jet transport was flown through automated terminal-area traffic situations by pilots using relatively sophisticated displays, and pilot performance and observations are discussed.

INTRODUCTION

Present-day equipment and controller procedures at aircraft terminals are not meeting future – and, at many terminals, present – requirements for expeditious aircraft landings (refs. 1, 2, and 3). Advances in digital computer hardware and the systems methodology required to design effective software offer the possibility of large-scale automation of the terminal-area air traffic control system. This automation is being introduced into the system as a direct aid to the controller (for example, the Automated Radar Terminal System (ARTS III)) in order to reduce controller information processing workload. However, no comparable provision is being implemented to alleviate the controller communications workload, although plans to expand the presently proposed radio beacon system digital data link would permit much information to be transmitted directly from ground computers to the cockpit.

The existence of an automated high-bit-rate data link could not only significantly reduce controller communications workload, but could also further reduce the controller workload associated with formulating aircraft control commands in order that aircraft follow computer-generated flight paths along computer-generated time lines. This workload reduction could be accomplished by allowing the aircraft pilot to interact directly with the ground computer system. One approach to this interaction is the pilot's use of an aircraft situation display, which is formated by the ground computer and transmitted over the data link and contains measured aircraft positions, computer-desired aircraft positions, and supporting alphanumeric data. The display would allow the pilot to verify the data qualitatively with onboard equipment and execute a four-dimensional computer-generated flight path. He could also monitor the relative positions of other aircraft as they execute computer-generated flight paths. This process would occur nominally without direct participation of the ground controller. The function of the ground controller would be to insure the correctness of the computer-generated flight paths, monitor the execution of the flight paths, and participate during emergencies by direct communication with aircraft and with full control over the ground computer and peripheral equipment.

The objective of this study is to examine an automated terminal-area air traffic control concept in which the primary man-machine interface is in the cockpit. A simple, efficient sequencing and separation algorithm was synthesized and mechanized in a real-time digital simulation which was used to evaluate pilot performance by using several computer-generated cockpit displays. This effort has resulted in preliminary sizing of the data link and onboard digital computer.

This report comprises two sections: The first describes the general system concept, and the second details a simulation of a particular application of this concept.

SYMBOLS

A	arrival
D	departure
E	expected value
k	landing slot number
L	probability of delayed aircraft, limit of arrival-to-departure ratio
M	limited number of delaying aircraft
m	number of delaying aircraft

N	number of possible classes of aircraft
n	aircraft class, number of aircraft
$P(n)$	probability of class n arrival
$P(n,T)$	probability of n arriving aircraft in time interval T
T	time interval, sec
V	aircraft speed, knots
V_1	entry speed, knots
V_2	speed prior to outer marker, knots
x	map coordinate, positive east with respect to O'Hare terminal, n. mi.
y	map coordinate, positive north with respect to O'Hare terminal, n. mi.
Δt_A	arrival spacing interval, sec
Δt_D	departure spacing interval, sec
η_A	runway arrival efficiency
λ	expected aircraft arrival rate

Subscript:

max	maximum

Abbreviations:

A/C	aircraft
ARTS III	Automated Radar Terminal System
ATC	air traffic control

ATCRBS	air traffic control radar beacon system
CDC	Control Data Corporation
COMP	computer
CRT	cathode-ray tube
CTOL	conventional take-off and landing
DME	distance measuring equipment
EADI	electronic attitude direction indicator
IFD	integrated flight director
ILS	instrument landing system
INSTR	instrumentation
MLS	microwave instrument landing system
NAV	navigation
VOR	very high frequency omnirange

SYSTEM CONCEPT

The basic concept discussed in this report is that of orienting the automation taking place in the terminal-area air traffic control system directly toward the users of the services, namely the aircraft pilots. An implementation of this concept is shown in figure 1. It utilizes a terminal-area computer which generates flight paths with traffic sequencing and separation according to a programed strategy, a ground-aircraft data link, and a cockpit display showing actual and computer-desired aircraft positions overlayed on a terminal-area video map with supporting alphanumeric information (fig. 2). This concept does not require a controller as an active participant to control aircraft in the system under nominal conditions. The controller functions in a parallel mode to operate and monitor the ground computer systems and insure that the computer-generated flight paths sent to and executed by the pilots are providing sufficient separation and efficient sequencing. If a failure occurs in some portion of the aircraft ATC avionics, the controller concentrates on controlling the aircraft using the radio voice link and/or the radio beacon systems (ATCRBS). During failure of some portion of the ground system, a set of emergency instructions previously loaded by the ground system as part of its normal set of display instructions is presented to the pilot for execution until backup ground procedures and equipment become available.

Implementation of this concept also requires that accurate aircraft locations and altitudes be fed to the computer. As shown in figure 1, these inputs can be generated in one of the following three ways or any combination of these:

1. By using the existing ATCRBS
2. By using aircraft-derived navigation information sent to the ground over the data link
3. By using the planned microwave instrument landing system (MLS) to determine the position and altitude onboard and then sending the position and altitude over the data link

Ground-determined and onboard-determined aircraft positions are compared for failure detection and then mixed in the computer by using estimation, filtering, and smoothing techniques.

After transmission of these data to the aircraft, a small onboard computer processes the information and displays aircraft and map features near the aircraft position. The onboard computer also formats the computer-desired position of the aircraft and all desired flight-director information required to execute the computer-desired flight path. Major advantages associated with this system are:

1. Increased system capacity as a result of accurate execution of computer-generated flight paths and reduced time dispersion at touchdown
2. Increased pilot awareness of local traffic situation and upcoming events
3. Increased flexibility, since the pilot can maneuver the aircraft laterally to avoid weather if local traffic permits and if the flight-path end points and time line can be maintained

The accuracy with which aircraft can follow computer-generated flight paths along time lines and land at precise sequencing times determines, to a large degree, the sequencing and separation intervals used in the computer algorithms and, therefore, the ultimate capacity of any automated terminal-area system. Thus, each aircraft in the system must be supplied with a large amount of computer-determined information to enable the pilot to execute a flight path accurately. This information gives the pilot increased flexibility in compensating for system uncertainties. Much of this information is of little interest to the ground controller monitoring the system, since his concern is the outcome of the flight-path execution process, rather than the details of how they are being executed. Also, the quantity of computer-determined information requiring transmission may exceed that which a human can efficiently process and make judgments on, not to mention participate in its actual transmission. These reasons form the rationale for the pilot-oriented approach toward automation discussed in this report.

System Operational Procedures

The nominal set of pilot actions expected to be involved in using this system for landing is presented as a context for the detailed discussion of system elements that follows. The pilot initiates interaction with the ground computer by setting the aircraft data link frequency at a standard frequency for the particular terminal. The pilot also sets his radio (voice link) at a specific frequency allocated for emergency instructions from the terminal area should they be necessary. The pilot then selects a terminal-area entry mode using an alphanumeric keyboard on a cockpit display and thus informs the terminal-area computer that he wishes to land. This action is necessary since desirable entry locations may be farther from the terminal than the terminal-area radar range. Transmission of onboard-determined position and altitude, aircraft and display identification, and aircraft status (normal or emergency) begins. The ground computer then includes the aircraft in its situation display format, given that enroute radar (or, if possible, terminal-area radar) and onboard-determined position correlate. It also informs the pilot, via the display, to call for the appropriate sector display. The pilot then uses the alphanumeric keyboard to change from the entry mode to the verification mode and to call for the appropriate sector. He verifies his position and altitude as shown on the display using onboard navigation equipment and comparing visual landmarks with those shown on the display video map overlay. Having confirmed the computer estimate of his position, the pilot verifies the relative positions of other aircraft local to his aircraft using the display to locate these aircraft visually or with onboard radar. Anything not verified is reported to the ground by voice link.

Having verified his position and thus computer initialization, the pilot informs the computer by changing the display mode to the approach mode. This action allows the aircraft data to enter the ground computer sequencing algorithm. The sequencing algorithm determines aircraft touchdown time and then determines a flight path for the aircraft which insures separation. This flight path is presented to the pilot as a series of computer-desired positions with supporting alphanumeric information. The pilot executes this flight path by observing the position of his aircraft relative to the computer-desired position shown on the display. He also monitors his position relative to terrain and to other aircraft as presented on the display and checks this presentation against possible visual sightings and onboard navigation equipment. The approach mode allows for delay and merging of common-class aircraft until they are within the bounds of the scanning microwave instrument landing system (MLS).

When the aircraft comes within the MLS bounds, the pilot changes the display mode to MLS. The onboard avionics terminates navigation equipment (VOR, DME) computation and transmission of aircraft position and possibly initiates MLS computation and transmission of position. The pilot also changes voice-link frequency to MLS controller frequency. He then verifies the continuity of his actual position as shown on the display and begins his descent from the merging altitude to touchdown, using the display to insure touchdown and runway exit at the correct time and location.

Flight-Path Generation

The primary function of the ground computer in this system is to generate aircraft flight paths which insure separation of aircraft in the air and allow sequencing of aircraft at touchdown and at runway exit. These flight paths are functions of aircraft position, type, and performance characteristics; runway and terminal geometry; and terminal-area routing as a function of terrain, population areas, noise abatement procedures, and aircraft vortices. The flight paths are modified by any detected emergencies or equipment failures. The function of the ground controller is to operate this computer system, verify its proper functioning, and participate during emergencies or equipment failures. The ground computer can either format the flight paths and send them over the data link as a series of computer-desired aircraft positions or send parameters from which an aircraft computer can format identical flight paths. The ground computer does not format speed and heading commands but relies on the pilot or his onboard avionics to fly the aircraft to match the computer-desired position with the actual position as a function of time.

Measured aircraft positions and altitudes are required computer inputs. In this system ground tracking data via the radio beacon system and onboard-determined position and altitude sent to the ground over the data link are compared for equipment failure detection and then mixed in the computer by using smoothing, filtering, and estimation algorithms. These estimated aircraft positions are compared to determine the relative positions and altitudes of each aircraft with respect to all other aircraft. This monitoring algorithm can inform the ground controllers and the aircraft pilots involved when two or more aircraft are operating too closely. A collision-avoidance algorithm may be included in the ground computer subroutines and called when a close situation is detected.

Estimated and computer-desired aircraft positions and altitudes are also compared, and the differences are used to change the display format – increased deviation requires more information to be displayed. When the deviation between the estimated and computer-desired aircraft position or altitude exceeds a standard set for each aircraft class, the aircraft is classified as an intruder. An aircraft which enters the terminal-area air space without making proper contact with the ground is also classified as an intruder. When an aircraft is classified as an intruder, the ground controller attempts to contact the aircraft via the voice link. If this contact is made, the ground controller assists the pilot in overcoming the difficulty. If no contact can be made with the aircraft, intruder-avoidance algorithms are required within the computer to reroute aircraft local to the intruder. These algorithms estimate the future flight path of the intruder, determine those aircraft whose normal flight paths bring them within unacceptable proximity to the intruder, and reroute these identified aircraft.

SIMULATION DESCRIPTION

A preliminary digital computer simulation has been developed to investigate overall operational aspects of the automated pilot-oriented ATC concept. The basic simulation objectives are to mechanize this concept and to check basic pilot interactions with the automated system. The simulation includes a simple, efficient sequencing algorithm, a complete aircraft dynamics model, and relatively sophisticated computer-generated pilot displays. Emphasis is placed on demonstrating the concept rather than on analyzing the complete system operation; therefore, effects such as measurement and equipment errors, atmospheric winds, and emergency procedures are not included. The rest of this report deals with the sequencing algorithm, flight profiles, and pilot displays evolved during this preliminary study of the pilot-oriented ATC concept.

Sequencing Algorithm and Flight Profiles

For the simulation study, computer-desired flight paths are determined automatically from only the entry route, aircraft class, and runway touchdown time. The runway touchdown time is the single output from a sequencing and separation algorithm (appendix A). Thus, implementation of a minimum-data-link system requires the selective transmission of only this parameter to individual aircraft, with onboard computation of the flight path according to standard approach procedures. This flight path then assures separation if all aircraft maintain the time lines on their flight paths. Results indicate that time-line maintenance is not a significant problem with the displays provided in the simulation used during this study.

Natural-order sequence.- The sequencing and separation algorithms are configured to accept the "natural order" of incoming aircraft of different performance characteristics (primarily speed) within limits dictated mainly by safety (>50-second range, >3 n. mi. lateral, >300 meters (1000 ft) altitude). The natural order is defined as the landing sequence that would occur if aircraft of different performance were allowed to fly approaches with no delay, assuming no requirement for separation. The order of a 1-hour sample of arriving aircraft for saturated runway conditions, for which the expected rate of arrival (72 planes/hr) is equal to runway acceptance rate, is shown in column 2 of table 1. Each aircraft belongs to one of three possible performance classes (table 2), where higher performance indices n indicate higher operating speeds. The data in column 2 of table 1 were generated by using the assumptions for a random process that are the basis for the Poisson distribution and were chosen from many such sets because the realized number of arrivals nearly equaled the expected number for the hour. The probabilities of entry of the classes and the time from entry to touchdown are assumed to be equal for all classes. This avoids the disadvantages to fast planes caused by entry points of equal distance.

Runway spacing delay.- Obviously, aircraft may not be landed as shown in column 2 of table 1, since common occupancy of the runway would occur. Thus, an initial task for the sequencing and separation algorithms is to introduce time separation at touchdown. Column 3 of table 1 shows the random traffic input sample of column 2 with a 50-second separation at touchdown. This process introduces delay whenever two or more arriving aircraft could occupy the same landing slot. This type of delay is unavoidable for any terminal-area sequencing algorithm which has the capability only to delay aircraft. The minimum time criterion (no speedup required) is selected to simplify the algorithm; therefore the aircraft fly at the nominal maximum speed dictated by safety. The expected value of this delay as a function of time is shown in figure 3 for various percentages of the saturation acceptance rate. If the algorithm is allowed to increase aircraft speed above the nominal operating speed (up to the maximum speed dictated by safety), the aircraft nominal operating speed will be lower than the maximum allowable. This would be equivalent to assuming that the natural-order sequence had inherent delay. The data of figure 3 were calculated according to the equations of appendix B. It is interesting to note how quickly the delay for an arrival will increase with time, even when the expected value for arrival rate equals or is less than runway capacity. In figure 3 the delay after only 1 hour of operation at capacity is shown to be greater than 5 minutes. The average number of arrivals for these 20 runs for the hour was 70.8. The standard deviation of system delay time was 4.8 minutes.

Departure introduction.- The landing sequence of column 3 of table 1 would be acceptable if all aircraft flew identical velocity profiles and if the effects of wake turbulence, particularly on smaller aircraft, were negligible. One procedure that tends to reduce these effects is the insertion of at least one departure between two arrivals whenever the earlier arrival is a faster and presumably larger aircraft. This procedure groups arrivals (column 4 of table 1) into ascending speed sequences with departures interspersed between sequences. This method inherently increases separation along any common final approach. It also allows for the introduction of departures with no more delay for arriving aircraft than that attributable to the obvious and required loss of some percentage of a landing slot. For the simulation it is assumed that the insertion of a departure requires at least one-half the time increment of a landing. An arbitrary arrival-to-departure ratio for a given runway is obtained by increasing the number of departures inserted in this manner. This procedure has the obvious limit, assuming full runway utilization, that occurs when there are not enough departures to insert into the departure slots. Equations which describe these limits are developed in appendix C.

Figure 4 shows the arrival-to-departure limit L plotted as a function of the arrival probability of class 3 (highest speed) aircraft for various class 1 probabilities. This limit L can also be interpreted as the average number of arrivals that became grouped in ascending speed-class order. The locus of the plots illustrates the minimum limit of 3 that occurs when the arrival probabilities of each class are equal. In figure 5 are plots of runway arrival efficiency η_A as a function of class 3 arrival probability for three values of departure-to-arrival spacing ratio. Class 1 and 2 probabilities are assumed to be equal.

Full runway utilization occurs whenever sufficient departures are available. A minimum arrival efficiency of 75 percent occurs at the equal-probability point ($P(1) = P(2) = P(3) = 1/3$) for equal departure and arrival spacing.

Approach-path merging.- Lateral and/or altitude separation must be provided to allow high-speed aircraft with early landing slots to pass slower aircraft. For example, in the simulation three speed classes are assumed; each class is separated by at least 300 meters (1000 ft) of altitude at any common point along an arrival route to allow for passing. Any restriction of this passing capability will add delay to the system. However, the arrival routes must merge at some point to allow a common, straight flight path prior to landing. The previously described procedure of separating arrivals into ascending speed sequences separated by departures increases aircraft separation, and thus the allowable length of common approach. This separation is to such an extent that variable glide slopes can be used to merge arrivals. Figure 6 shows the ranges, altitudes, and glide slopes used in the simulation for glide-slope arrival merging for the three aircraft classes (designated by n). Lateral separation along the arrival routes or the straight final approach is not included in the computer-calculated flight paths but is considered to be a pilot decision. This capability allows the pilot to avoid weather along the arrival route and to meet his requirements for the straight final approach.

Figures 7, 8, and 9 illustrate worst case separation which occurs for the sequences . . . 3D1 . . ., . . . 3D2 . . ., . . . 2D1 . . ., respectively (where 3D1 indicates class 3 aircraft, departure, class 1 aircraft), and for the speed profiles assumed in the simulation. These speed profiles are summarized in table 2. These figures illustrate the increased separation achieved by increasing the departure spacing interval Δt_D from

25 seconds (two departures per arrival interval) to 50 seconds (one departure per arrival interval).

Delay introduction.- The capability to introduce an arbitrary delay for any arrival and to do so with complete independence from other arrivals is required for expeditious implementation of the natural-order landing sequence. One method of accomplishing this is to separate aircraft into common speed-profile classes, separate these classes by altitude along arrival routes, and then use speed control and flight-path extension to achieve delay. Two methods of introducing delay along a given arrival route for common speed-profile aircraft were used in the simulation studies and are illustrated in figures 10 and 11 and described in appendix A. The first method (fig. 10) allows the introduction of continuous delay by flight-path extension and was used in the simulation algorithms as an additional delay to the limited delay achieved by early speed reduction. This type of delay can be accomplished at a single altitude and thus allows a large number of aircraft classes (finer division of aircraft into common speed-profile classes) to be "stacked" along a given route. However, the lateral space required is twice that of the second method of flight-path extension (fig. 11). This method of delay introduction allows the flight-path extension to proceed to 90° turns (fig. 11(d)), at which point further delay requires a complete loop (fig. 11(e)). The step increase in delay time is accommodated by a step decrease in the speed delay flown. This allows continuous delay capability but reduces the possible division of aircraft into common speed-profile classes, since altitude separation is required for a given class. It also requires that aircraft enter the system at sufficient range to allow compensation for the step increase in delay when the complete loop is flown.

Description of Pilot's Situation Display

The approach to direct interaction between pilot and ground computer used in the simulation is the use of digitally generated displays such as the aircraft situation display of figure 2. The main system advantage of this display is the reduced total data transmission required since common data are shared by local aircraft. A typical system requires ground format and transmission of the actual and computer-desired positions of all aircraft in the terminal area, with alphanumeric tags, overlayed on a terminal-area map. These data are transmitted at a single frequency determined by a bit rate of approximately 10 000 bits per second for 200 aircraft with one update every 4 seconds. This bit rate provides position information with 3-meter (10-ft) resolution within a 200- by 200-n. mi. sector, 3-meter (10-ft) altitude resolution, and 200 map features to the same resolution with 10 percent information overhead. It should be noted that even with position resolution of 3 meters (10 ft), the data-link size is reasonable.

The pilot's display is centered on the measured position of the aircraft. It presents a plan view of the computer-desired position of the aircraft and projected flight path to landing and actual positions of other aircraft overlayed on a video map of the terminal area. The situation display is oriented "heading up" so that the entire display turns with the aircraft, and therefore, the pilot has an out-the-window (inside-out) view. The computer-desired position is represented by the inverted V-shaped symbol, and each aircraft is represented by an arrowhead symbol. The nose of the symbol represents the estimated position, and the direction of the arrowhead indicates heading. The correct relative position is alinement of the nose of the aircraft symbol with the time line of the symbol for the computer-desired position. Aircraft flight number (call letters), altitude in tens of feet above the runway, and ground speed in tens of knots make up the ARTS III type label adjacent to the aircraft symbol.

The video map information consists of landmarks and navigation aids in the terminal area (table 3). Navigation aids are represented by triangular symbols labeled with their three-letter code (fig. 12). Landmarks such as the terminal runway system (Chicago O'Hare International Airport), other local airport runway systems (MXT, Midway), and the shoreline of Lake Michigan are displayed for the pilot's convenience. In the final-approach pattern, the locations of high elevation points, with height indicated in feet, may be displayed on option (fig. 13(a)). Another optional display is the range mark aid, consisting of the marks depicting longitudinal and lateral range in nautical miles (fig. 13(b)). The entire situation display has zoom capability with a radius of 5 to 60 n. mi. Aircraft within range are not necessarily displayed if altitude differences are greater than a pilot-selected limit; thus a vertical-range display capability is allowed.

The aircraft may maneuver to the right or left of the computer-desired position to avoid weather, if local air traffic permits, but must maintain proper altitude and correct position relative to the time line. The time error in seconds is contained in the center of the display.

The traffic situation display offers the following advantages:

1. Allows the pilot to avoid weather or turbulence conditions if local traffic permits while maintaining his sequence (time line) position

2. Gives the pilot relative positions of local aircraft (currently a secondary controller function)

3. Serves as an aid to navigation by indicating positions of landmarks

4. Allows the pilot to check functional operation of automated equipment

5. Provides the pilot with more background information when an emergency develops

Description of integrated flight director.- Simulation runs were conducted principally with six conventional instruments (fig. 14) containing "zero reader" altitude and directional flight-director steering, with time-line error being read from the situation display. In order to reduce required eye travel, an integrated flight director (IFD) was developed along similar lines as the electronic attitude direction indicator (EADI) currently being examined by the industry.

Figures 15 and 16 illustrate the IFD. In figure 16 the double outer lines show raw altitude error (high or low) and lateral position error (left or right). This raw error information may come either from an ILS beam or be derived from computer-desired position data received from the ground computer. In the region between the two circles, a heading-error indicator moves with respect to a fixed pointer. The computer-desired heading is derived from two or more successive computer-desired position coordinates to provide the reference for this indicator. Also in this region, the pitch and roll aircraft attitude is graphically displayed in an eight-ball-type format. The flight-director steering information is contained within the inner circle of the IFD. The upper number represents the time error in seconds (accurate to 0.1 second) with respect to the aircraft time line. The lower number represents the velocity error with respect to a computer-desired reference velocity, which may also be derived from two or more successive position coordinates. Pitch and roll steering information is provided by the "horizontal tail" symbol which moves in the vertical plane and the outer lines which roll with respect to the horizontal reference. The roll steering information is given without scaling so that leveling these indicators will produce the desired turn rate.

The down-link message column of figure 15 presents a summary of the information being formated on the digital data link for transmission to the ground computer. This is an option available to the pilot for verification purposes, both with his onboard instrumentation and with information actually being received by the ground. A similar verification capability exists for up-link information.

In the simulation operation, with the CRT equipment time shared, a display update rate of only three to four updates per second was achieved. The entire display was updated at this rate, which proved to be adequate for all functions except the IFD steering information. This update rate did not provide sufficiently smooth steering information for more complex tasks such as turns and particularly during the final-approach operations. Because of the system restrictions of the real-time simulation setup, it was not possible to determine minimum acceptable update rates for the steering information.

Simulation implementation.- The automated terminal air-traffic control system is simulated on the Control Data series 6600 computer system at the Langley Research Center. The simulation is programed to operate in a real-time mode for studies of pilot interaction with the automated ATC system or to operate in fast time for analyses of system operation. The simulation software is comprised of the same basic elements as the actual system, as indicated by the simplified block diagram of figure 17. This schematic shows the system elements which are represented by various simulation software subroutines and by hardware. The ground-aircraft radio beacon system and ATC data links are indicated in the figure but are not simulated.

The simulation is controlled from the program control station, shown in figure 18. This location includes a data entry and simulation mode control console, an on-line typewriter, several 8-channel strip chart recorders for data output, and the CRT display console, which is used for the computer-generated cockpit or ground controller displays associated with the automated ATC system. Since the CRT cannot be mounted in a simulator cockpit, the pilot seat and controls, shown in figure 19, are mounted on a mobile base, which rolls up to the CRT console. This setup provides the cockpit environment for these preliminary studies of cockpit ATC display requirements. The simulation described herein is used to study ATC system interactions and to develop requirements for onboard ATC displays, and will be used to develop more sophisticated simulation programs and hardware for automated ATC system flight evaluations.

Simulation hardware.- The hardware used in the automated air-traffic control system simulation consists of a general-purpose CRT display unit and a pilot seat with aircraft controls mounted on a movable base (fig. 19). The display equipment is a CDC 250 Series CRT display system with approximately 25 cm by 25 cm (10 in. by 10 in.) of screen area available for display. The CRT system configuration and computer link are shown schematically in figure 20. In this system time and memory of each display controller are shared by three CRT units and an on-line hardcopier. The controller memory consists of 8192 words of 24 bits each. Each 24-bit word is an instruction to the display logic to draw vectors or write characters on the CRT screen. The 6600 computer uses 60-bit words, and therefore the 24-bit display instructions are packed and stored by control memory as five 24-bit words per two 60-bit words. The control processor instructions are routed across the data channel and stored in sequential locations in the controller memory. The instructions in the controller memory are repeatedly executed by the controller logic; therefore a particular picture is repeatedly drawn on the CRT. The refresh rate is fast enough so that, in most cases, the display on the CRT appears to be at a constant level.

To produce the apparent real time CRT displays for the cockpit or traffic controller stations, the simulation program updates the display instructions as rapidly as they can be accepted by the peripheral and controller equipment and data channels. With normal system loading, the lag between central memory and CRT display averages about 1/4 second. This means that for the pilot's display, where new CRT instructions from the central memory are updated only at 4-second intervals, these random CRT lags cause slight variations in the actual display update times.

The pilot seat, cockpit controls, and instrumentation shown in figure 19 represent the basic equipment available in a commercial transport cockpit. The input and output of these devices are sequenced directly and do not exhibit the lag associated with the CRT unit. Six basic aircraft instruments are included (fig. 14): altimeter, airspeed indicator, heading indicator, vertical-speed indicator, rate-of-turn indicator, and an eight ball with flight-director indicators. A two-axis side-arm controller is used for aircraft pitch and roll control, rudder pedals control yaw. Throttle and flap setting levers are provided, and microswitch buttons are available for mode control of the CRT display and the flight-director steering commands.

Simulation software.- The computer program for ATC system simulation is composed of two basic parts: the ATC system ground computer and an aircraft and its associated avionics, as indicated in figure 17. The ATC ground computer part, containing the sequencing and separation algorithms and on-line monitoring routines, does not require real-time synchronization, and when used alone for system analyses, is usually run in fast time. However, since the aircraft dynamics and avionics part links to the cockpit controls and displays, it must maintain real-time synchronization, and therefore, for piloted aircraft studies, the entire simulation must be run in real time. As previously mentioned, the simulation program is modular in that various elements or subroutines represent different parts of the ATC system. The two basic parts will be discussed separately, the ground computer software routines first and then the simulated aircraft and its associated avionics.

Ground computer software.- The ground computer routines perform two functions: on-line monitoring of aircraft positions and status, and occasional calculations required by special conditions such as sequencing of new aircraft. Again, display and data link output functions which are tied to the cockpit are real time in that they require updates at regular intervals and therefore are synchronized with time. All other calculations must be performed on an "as available" basis and be fitted in between the required real-time operations in a time-sharing mode. The simulation program is set up in this manner, with all on-line functions being performed in the main program, with the exception of routines to generate the fixed terminal-area maps required for the displays.

All aircraft under ATC system control, with the exception of the simulated aircraft flown from the cockpit, are assumed to be in the position desired by the ground computer. The times at which the aircraft shift from one portion of the trajectory or one maneuver to another are determined and defined by simulated ground computer software when the aircraft come under system control. The main program contains the equations for desired aircraft positions as functions of time. The program solves for the position of one aircraft per iteration, because of time considerations, and then stores that position for comparison with the positions determined by the radar or radio beacon system and updated at 4-second intervals. The computer output to the controller and data link would be based on these comparisons and updated measured data. In the simulation case, the computer-desired positions at the output time are used.

The controller's situation display (fig. 21) and the plot of flight path against time (fig. 22), used for system analysis purposes, are generated from the aircraft position data. The terminal-area maps in figures 21 and 22, which indicate landmarks such as the airport runway and navigation aids and controller operational cues such as flight corridors and range markers, are generated by subroutine CHICAGO. The controller's display includes provisions for manually slewing the display and zooming in on points of interest by using potentiometer controls. Another potentiometer is used to vary the simulation time increment so that particular events may be analyzed in real time or time may be reversed for restudy of an event.

The main program also contains the system mode controls, provisions for insertion of additional aircraft of a selected type on a selected route, and initialization loops for both the ATC system and the simulated aircraft. The system itself may be initialized and loaded in two ways. The aircraft type and route numbers may be individually selected and manually inserted under system control. A second option permits the selection of a system acceptance or aircraft arrival rate in planes per hour and the total number of aircraft desired. The individual aircraft type, route numbers, and arrival times are randomly selected to be delivered to the system at the specified arrival rate. Weightings can be imposed on the aircraft type selection to produce any desired traffic mix.

The simulated aircraft may also be initialized in several ways. The first is simply to initialize the aircraft with the conditions of any aircraft already under system control. The second is to introduce the simulated aircraft at any point along any route and let the sequencing and separation algorithm (NEWAC) schedule the landing in the traffic presently under system control. The third, and probably most important, initialization for piloted aircraft display studies, involves specifying a landing traffic load (aircraft occupying every landing slot, every other slot, etc.), selecting this traffic randomly, and initializing the simulated aircraft at any flight condition, which may include errors in position and time. This initialization technique is particularly useful in evaluating critical maneuvers or conditions and in providing the pilot with a realistic traffic situation display. In all cases, when the aircraft is initialized, a trim circuit in a hold mode is initiated to allow the pilot to adjust his trim and throttle settings for the flight conditions specified.

Simulated aircraft.- The simulated aircraft model used for the ATC system evaluation and pilot display studies is representative of large commercial jet transports. This type of aircraft was selected as being typical of the traffic coming under ATC system control. Other types and classes of aircraft may be readily incorporated by simply changing the aircraft characteristics which are stored as data. The aircraft dynamics equations and aerodynamic coefficient calculations are in general form (ref. 4) and are included in subroutine ATC707. Engine thrust is interpolated from thrust curves stored as a function of throttle setting. A four-pass Runge-Kutta integration scheme with a computing interval of 0.0625 second is used to solve the aircraft dynamics equations. The resulting position and attitude information is used in generating the simulated aircraft situation and flight-director displays.

Display software.- The remaining information on the situation display includes the positions of other air traffic. In the simulation the position coordinates are assumed to be received over the ATC system data link and the symbols generated by the aircraft avionics. The onboard avionic software is represented by subroutine PILDIS. This routine receives the data generated by the ground computer and transmitted over the data link, performs several simple calculations, and generates the CRT display commands. The estimated actual position of the simulated aircraft is subtracted from the coordinates for the other traffic in order to center the situation display on the actual position of the simulated aircraft. The desired position of the simulated aircraft is also plotted on this display. Ground computer outputs such as speed, heading, and altitude for the simulated aircraft are used to generate the flight-director display and alphanumeric reference information on the display. Fixed landmarks in the terminal area such as runway and navigation aids, which are loaded into the aircraft avionics when the aircraft enters ATC system control, are also drawn on the situation display. Momentary switch controls are used to zoom the situation display, with the range marks being plotted at integer multiples of one-quarter of the lateral range at the limits of the plotting area.

Since the display software represents the routines for the onboard control computer, particular attention has been given to programing techniques for the pilot displays. The display software should be optimized with respect to time and memory, and programing techniques such as the use of scaled fixed-point arithmetic should be incorporated. These routines should then be implemented on a smaller general-purpose digital computer and eventually to an onboard digital computer to demonstrate the feasibility of the onboard avionics associated with the pilot-oriented ATC concept.

RESULTS AND OBSERVATIONS

This study was conducted to examine the automated terminal-area air traffic control system concept described in this report in which the primary man-machine interface is in the cockpit. A terminal-area sequencing and flow management concept was developed, and preliminary sizing of the required data interface was made. Certain aspects of the system operation, using error-free measurements, were simulated to mechanize this concept. A study of the pilot interface with the automated system was then performed.

In general, this initial simplified simulation study has shown the concept to offer the potential for a significant increase in ATC system capacity, safety, and flexibility when compared with a system in which the primary man-machine interface is on the ground. The following specific results detail this finding based on this initial simplified simulation:

1. Ground computer algorithms which output computer-desired positions and altitudes as functions of time according to simple standard rules appear easy to design and implement for the case studied in the simulation, namely random entry of three classes of arriving aircraft from known routes to an arbitrary but unchanging dual runway. Computer time and memory requirements for the case studied increase significantly when a ground-generated guidance function is added to the algorithms which compute the aircraft speed and heading on the basis of actual and computer-desired aircraft positions. The data base required of the ground computer in order to perform this function safely and efficiently for arbitrary aircraft increases prohibitively.

2. The relative position comparisons required for automatic monitoring of the flight paths of an aircraft are reduced from $n(n - 1)/2$ (19 900 for 200 aircraft) to n (200 for 200 aircraft) when computer-desired positions are compared with measured aircraft positions (the difference required to be within certain bounds), rather than comparing measured positions of all aircraft with each other.

3. The "natural order" spaced arrival sequence (i.e., the landing sequence that occurs if aircraft of different performance are allowed to fly approaches with no delay, assuming no requirement for separation) interrupted with departure insertion(s) (between any two arrivals whenever the earlier arrival is of higher speed) sufficiently increases final longitudinal spacing so that three classes of aircraft can use a common straight approach path. This assumes approach speeds varying from 85 to 140 knots and the altitude profiles shown in figure 6. Verification of these initial results requires a combined single- and multiple-aircraft simulation and flight program.

4. A requirement for a data link common to all aircraft was determined to be 10 000 bits per second for the simulated system on the basis of the following conditions: a sector 200 by 200 n. mi., a maximum of 200 aircraft, plan position resolution of 3 meters (10 ft), altitude resolution (6-km (20 000-ft) maximum) of 3 meters (10 ft), 200 video map features with the above resolutions, a 4-second repeat rate, and assuming a 10-percent information overhead.

In addition, the following observations were made during the simulation study:

1. Dispersion times for touchdown for the simulated jet transport with no stability augmentation and under no influence of winds were small (less than 1 second) for pilots with minimal training with the system when concentrating on the four-dimensional guidance aspect of the system. This negligible error in actual touchdown time compared with

computer-desired touchdown time allows a single runway capacity of 72 aircraft per hour assuming a runway occupancy of 35 seconds and a 15-second go-around decision time prior to touchdown (50-second total aircraft spacing).

2. Classification of participatory CTOL aircraft into three classes by speed performance appears to allow sufficient latitude for small dispersions in the time error at touchdown when the data for the simulated jet transport are extrapolated to cover all three classes.

3. Time-line errors as large as ±10 seconds at the outer marker could be nulled by the time touchdown occurs with the aircraft properly trimmed for landing, although a far more detailed pilot and copilot workload and task studies are required to refine these initial results.

4. Lateral deviations of several miles from the computer-desired flight path are within the capability of the piloted aircraft, including the last 40 km (25 miles) prior to touchdown, in order to avoid weather or intruder aircraft and yet safely enter the final-approach pattern and land on time. This flexibility of use of the system is possible only if the pilot generates the guidance and control commands in order to meet the situation constraints presented to him by onboard-generated displays based on ground-generated situation data.

5. The increased safety of this system is attributable to several factors. The pilot is aware of the local traffic. The number of people monitoring the operation of the system (all concerned pilots in addition to the ground controllers) is increased. The video map has safety-related aspects such as high elevation points. The workload of the ground controller is lower and thus he can concentrate on monitoring the system for unsafe developments rather than being concerned with the generation and transmission of aircraft guidance and control information. The pilot is aware of his situation when an emergency occurs or equipment fails.

6. In actual practice, traffic position information in the terminal area would probably be updated at intervals of up to 4 seconds (the present surveillance radar rate). This rate is believed to be adequate for the situation map display, provided that the reference aircraft heading is used to rotate the entire situation display more frequently. On this display runs were made with an update rate of one per second, which was deemed adequate by NASA research pilots.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., September 29, 1972.

APPENDIX A

SEQUENCING AND SEPARATION ALGORITHM

A complete flow diagram of the automated sequencing and separation algorithm simulated is shown in figure 23. It should first be noted that the landing slot assignments are coded by denoting the route and class of the assigned aircraft and stored as a list within the computer. Unassigned slots are denoted by zeros, and assigned slot values are given by two digits: the first indicates the aircraft route and the second, the aircraft class, for example,

Aircraft route — 92 — Aircraft class

When a new aircraft enters the terminal area and requests a landing slot assignment, its route number and class are used to calculate the time remaining to touchdown with no delay. This determines the earliest possible landing slot which the aircraft may use. All later landing slots are checked for aircraft with common route and class to avoid passing of delayed aircraft at the same altitude along a particular route. The resulting landing slot is then checked for availability, and the first available slot is tentatively assigned.

To avoid the situation where an aircraft immediately precedes a slower aircraft (figs. 7, 8, and 9), this combination is separated by one or more departures. The next two checks in the sequencing and separation algorithm provide this separation by checking ahead and behind the assigned landing slot for NSEP slots. The check ahead looks for faster aircraft, and if one is found, the assigned landing slot is moved back so that it is separated from the faster aircraft by NSEP landing slots. The check behind looks for slower aircraft and the landing slot is reassigned to immediately follow the slower aircraft. After any landing slot reassignment, the availability of that slot is checked and both speed class separation checks are repeated.

The final landing slot assigned to the aircraft is then used to determine the amount of time which the aircraft must be delayed and thus the type of delay (early deceleration or flight-path extension) which must be performed.

APPENDIX B

DERIVATION OF RECURSIVE EQUATIONS FOR RUNWAY SPACING DELAY

Aircraft are assumed to have possible landing times satisfying conditions which lead to the Poisson distribution (ref. 5):

$$P(n,T) = \frac{e^{-\lambda T}(\lambda T)^n}{n!} \qquad (n = 0, 1, 2, \ldots) \qquad \text{(B1)}$$

where n is the number of aircraft that could land in time interval T and λ is the expected rate of arrival.

If the time interval T is taken as the required time spacing at the runway and $m(k)$ is defined as the number of delaying aircraft after k possible landing slots have occurred, then

$$m(k+1) = m(k) + n(k) - 1 \qquad (k = 1, 2, \ldots) \qquad \text{(B2)}$$

describes the accumulation process.

The expected value of $m(k)$ can be found from the probability distribution of $m(k)$. The following table includes the initial recursive terms required to determine this distribution:

m	$L_m(k)$ for k equal to –		
	1	2	3
0	$P(0,T) + P(1,T)$	$L_0(1)\left[P(0,T) + P(1,T)\right] + L_1(1)P(0,T)$	. . . .
1	$P(2,T)$	$L_0(1)P(2,T) + L_1(1)P(1,T) + L_2(1)P(0,T)$	. . . .
2	$P(3,T)$	$L_0(1)P(3,T) + L_1(1)P(2,T) + L_2(1)P(1,T) + L_3(1)P(0,T)$	
3	. . . .	. . . .	. . . .

By defining $L_m(k)$ as the probability of m accumulated or delaying aircraft at iteration k, the following recursive equations can be written from inspection of the table:

$$\left.\begin{aligned} L_0(k+1) &= L_0(k)\left[P(0,T) + P(1,T)\right] + L_1(k)P(0,T) \\ L_m(k+1) &= \sum_{i=0}^{i=m+1} L_i(k)P(m+1-i,T) \qquad (m = 1, 2, 3, \ldots) \end{aligned}\right\} \tag{B3}$$

The expected value of $m(k)$ is

$$E\left\{m(k)\right\} = \sum_{m=0}^{M} m(k)L_m(k) \tag{B4}$$

where the series is truncated at M terms.

APPENDIX C

DERIVATION OF ARRIVAL-TO-DEPARTURE LIMIT AND RUNWAY ARRIVAL EFFICIENCY

It is defined that aircraft of different speed classes, designated in ascending speed order by the integer n, can land in a continuous spaced sequence and that one departure is to be inserted whenever a high-speed aircraft precedes a slower aircraft. Since only one departure is to be inserted, the probability of this event is

$$P(D) = P(A)P(D/A) \tag{C1}$$

where $P(A)$ is the probability that the preceding aircraft was an arrival and $P(D/A)$ is the conditional probability that a departure will be required given that the preceding aircraft was an arrival.

Since the sequence is defined as continuous, the only events that can occur are a departure or an arrival. Therefore,

$$P(A) = 1 - P(D) \tag{C2}$$

Combining equations (C1) and (C2) yields

$$P(A) = \frac{1}{1 + P(D/A)} \tag{C3}$$

The conditions for inserting a departure between two arrivals yield

$$\begin{aligned} P(D/A) = {} & P(N)\left[P(1) + P(2) + \ldots P(N-1)\right] + P(N-1)\left[P(1) + P(2)\right. \\ & \left. + \ldots P(N-2)\right] + \ldots + P(2)P(1) \end{aligned} \tag{C4}$$

where $P(n)$ is the probability that a given arrival is of speed class n of N total possible classes.

The arrival-to-departure limit is defined as

$$L = \frac{P(A)}{P(D)} = \frac{1}{P(D/A)} \tag{C5}$$

and is interpreted as the average number of arrivals before a departure is required for continuous use of the runway.

Runway arrival efficiency is defined as the average percentage of time that the runway could be devoted to arrivals and is expressed as

$$\eta_A = \frac{P(A)\ \Delta t_A}{P(A)\ \Delta t_A + P(D)\ \Delta t_D} = \frac{1}{1 + \frac{P(D/A)\ \Delta t_D}{\Delta t_A}} \tag{C6}$$

where Δt_A and Δt_D refer to arrival and departure spacing times, respectively.

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4. Gainer, Thomas G.; and Hoffman, Sherwood: Summary of Transformation Equations and Equations of Motion Used in Free-Flight and Wind-Tunnel Data Reduction and Analysis. NASA SP-3070, 1972.

5. Wadsworth, George P.; and Bryan, Joseph G.: Introduction to Probability and Random Variables. McGraw-Hill Book Co., Inc., 1960.

TABLE 1.- SEQUENCING ALGORITHM OUTPUT

Allowable runway sequence number	Natural-order sequence	Spaced sequence	Minimum departure introduction sequence
1	1	1	1
2	0	0	0
3	2	2	2
4	2	2	2
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	0	0	0
11	21	2	2
12	2	1	0
13	0	2	1
14	11	1	2
15	0	1	0
16	3	3	1
17	0	0	1
18	32	3	3
19	112	2	3
20	0	1	0
21	131	1	2
22	1	2	0
23	1	1	1
24	3	3	1
25	11	1	2
26	21	1	0
27	2	1	1
28	1	3	3
29	1	1	0
30	0	1	1
31	1	2	1
32	0	1	1
33	121	2	3
34	22	1	0
35	1	1	1
36	0	1	1
37	1	1	2
38	3	2	0
39	11	1	1
40	212	2	2
41	0	2	0
42	0	1	1
43	11	1	1
44	0	3	1
45	21	1	1
46	3	1	2
47	23	2	0
48	0	1	1
49	0	2	2
50	2	1	2
51	1	1	0
52	12111	2	1
53	0	1	1
54	31	3	3
55	0	2	0
56	0	3	1
57	0	2	1
58	31	1	2
59	0	1	0
60	1	2	1
61	0	1	2
62	1	1	0
63	2	1	1
64	0	3	1
65	23	1	2
66	0	3	0
67	0	1	1
68	1	1	3
69	0	1	0
70	1	2	2
71	131	2	3
72	23	3	0
73		1	2
74		1	0
75		1	1
76		3	1
77		1	2
78		2	0
79		3	1
80			1
81			1
82			3
83			0
84			1
85			3
86			0
87			1
88			1
89			1
90			2
91			2
92			3
93			0
94			1
95			1
96			1
97			3
98			0
99			1
100			2
101			3

TABLE 2.- SPEED-PROFILE SUMMARY

Aircraft class	Speed, knots				
	Entry	Prior to outer marker	After outer marker	At glide-slope change	Approach
1	150	123.5	118.5	115	85
2	250	153.5	143.5	135	110
3	350	195	175	160	140

TABLE 3.- ASSUMED COORDINATES OF NAVIGATIONAL AIDS

Map symbol	Navigation stations	Coordinates from O'Hare, n. mi.	
		x	y
ORD	Chicago (O'Hare)	0	0
MKE	Milwaukee	-19.5	66.5
RFD	Rockford	-58.7	13.0
PLL	Polo	-71.8	-3.3
BDF	Bradford	-74.0	-51.3
PNT	Pontiac	-35.4	-70.8
EON	Peotone	6.5	-42.3
JOT	Joliet	-17.7	-27.0
API	Naperville	-9.0	-13.0
CGT	Chicago Heights	18.2	-28.0
OXI	Knox	57.0	-18.0
GSH	Goshen	84.8	-24.0
SBN	South Bend	71.0	-10.5
ELX	Keeler	78.2	12.1
PMM	Pullman	78.2	31.8
MKG	Muskegon	78.8	74.0
FWA	Fort Wayne	125.0	-55.0
PIA	Peoria	-83.0	-80.0
LAF	Lafayette	41.3	-83.0
OBK	Northbrook	-2.1	11.8
CVA	Cordova	-114.3	-19.0
MXT	Midway	10.0	-14.2
JVL	Janesville	-54.0	32.5

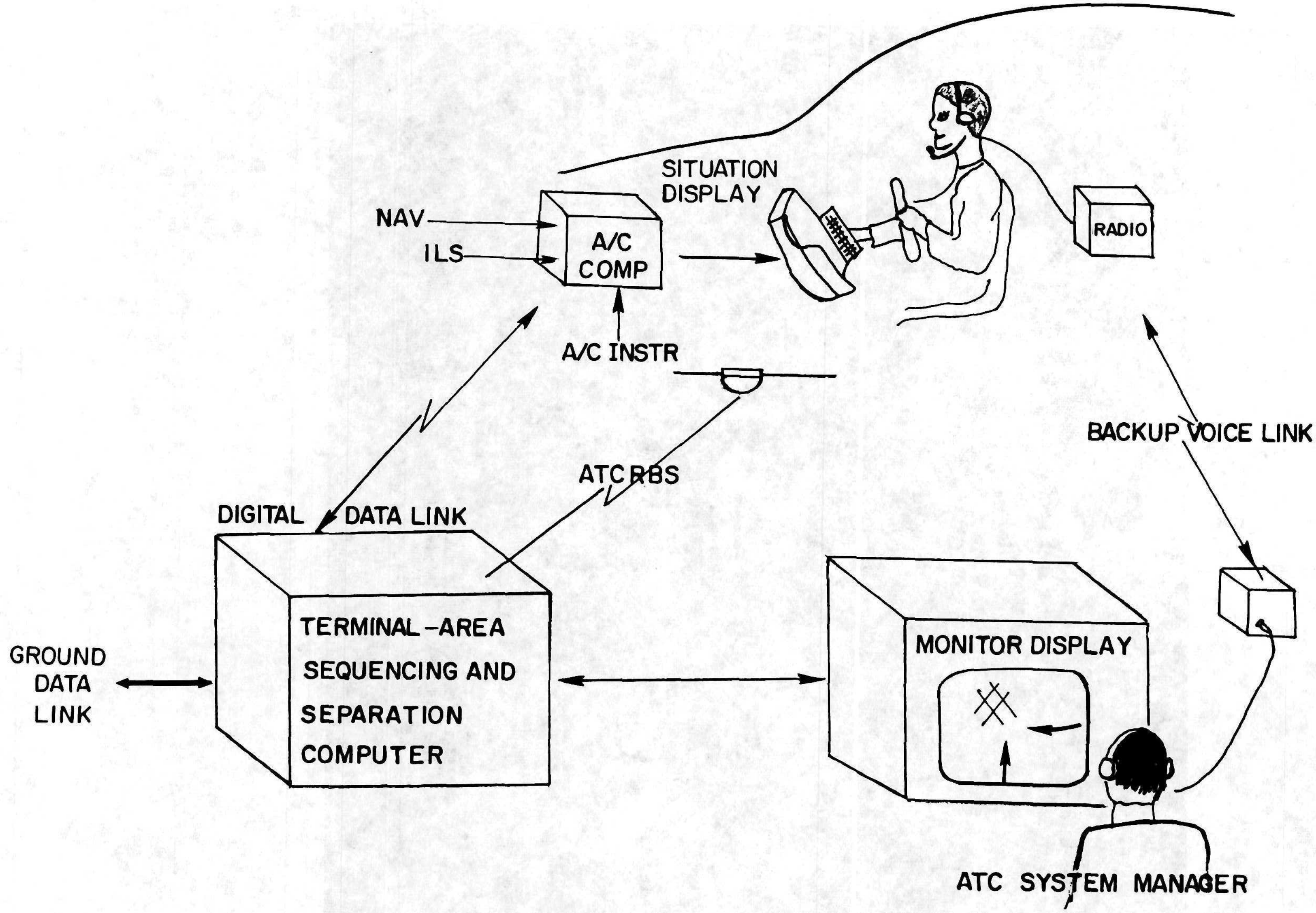

Figure 1.- Pilot-oriented ATC concept.

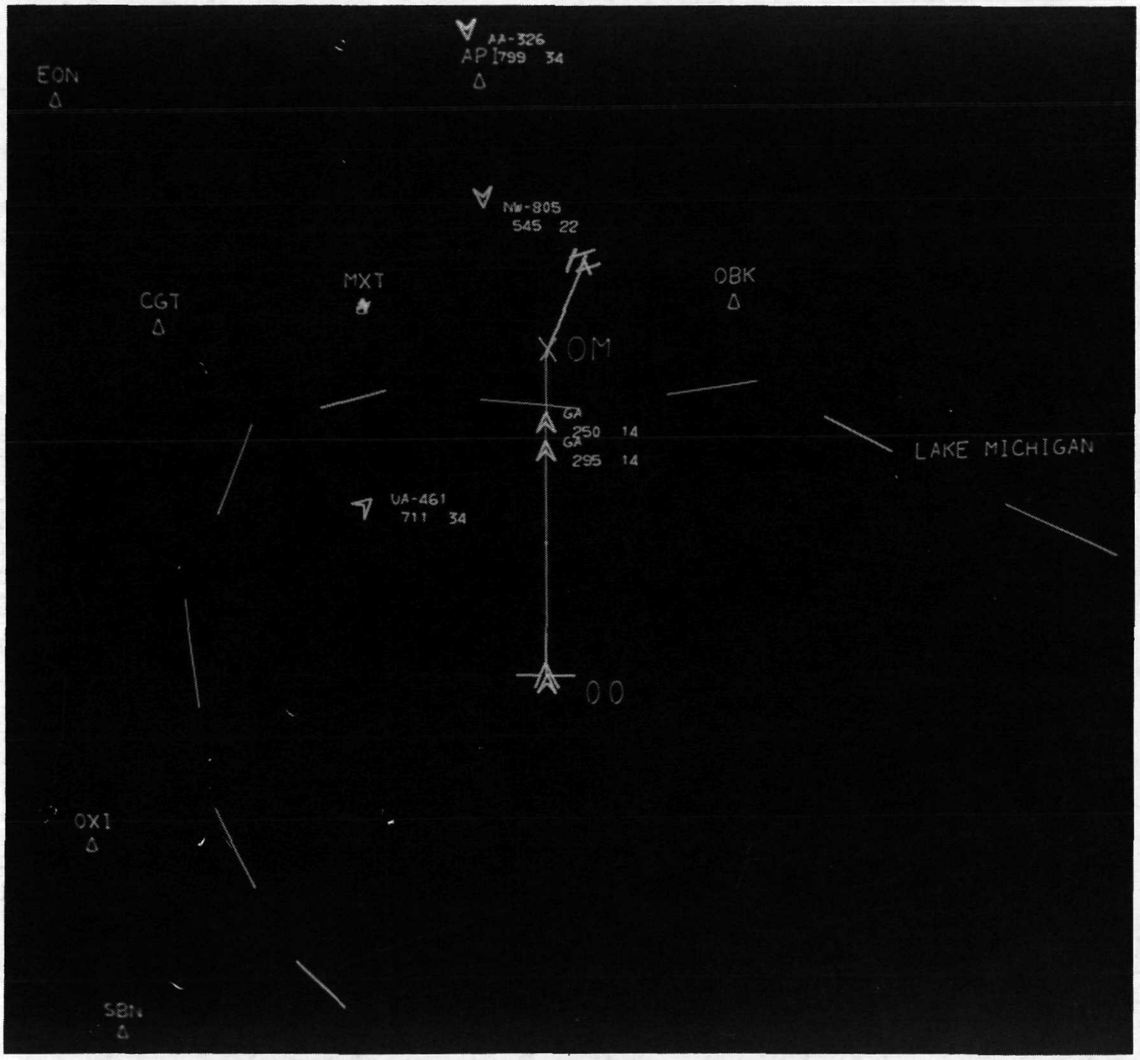

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Figure 2.- Pilot's situation display.

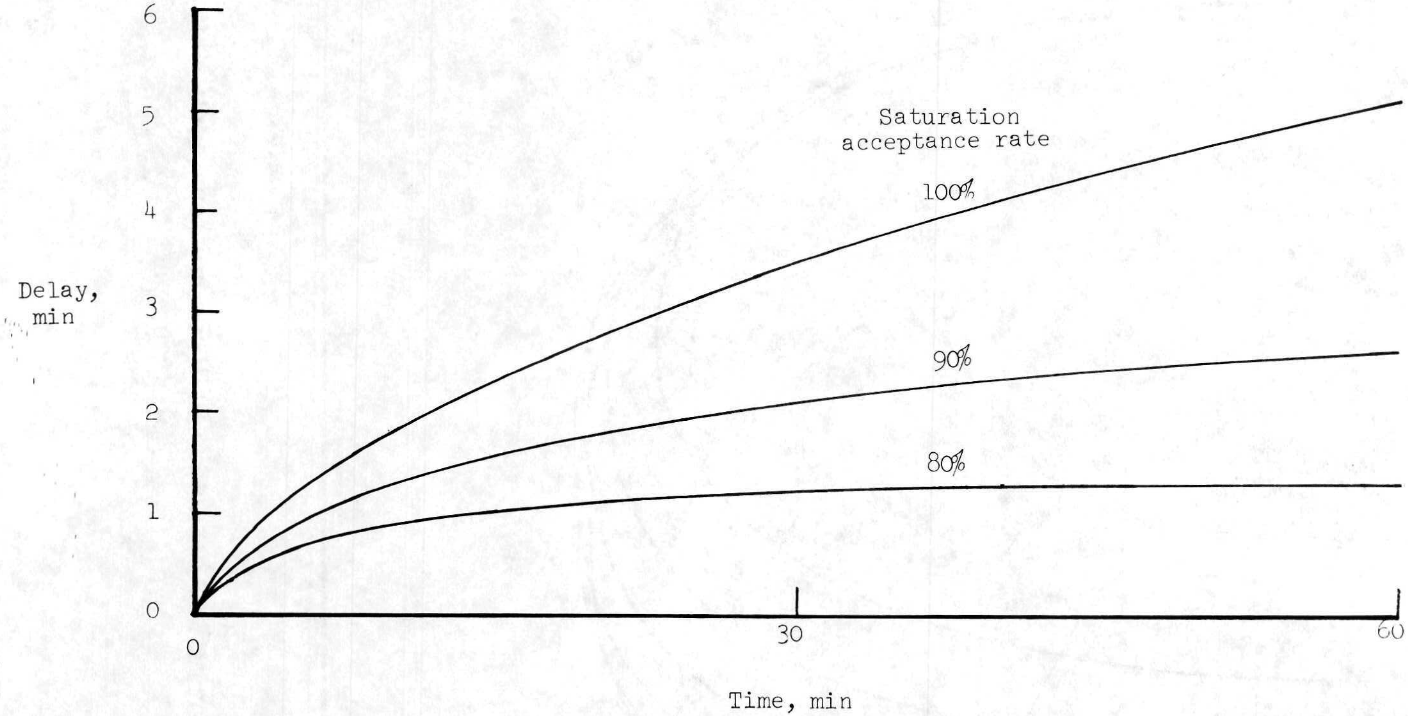


Figure 3.- Expected value of runway spacing delay.

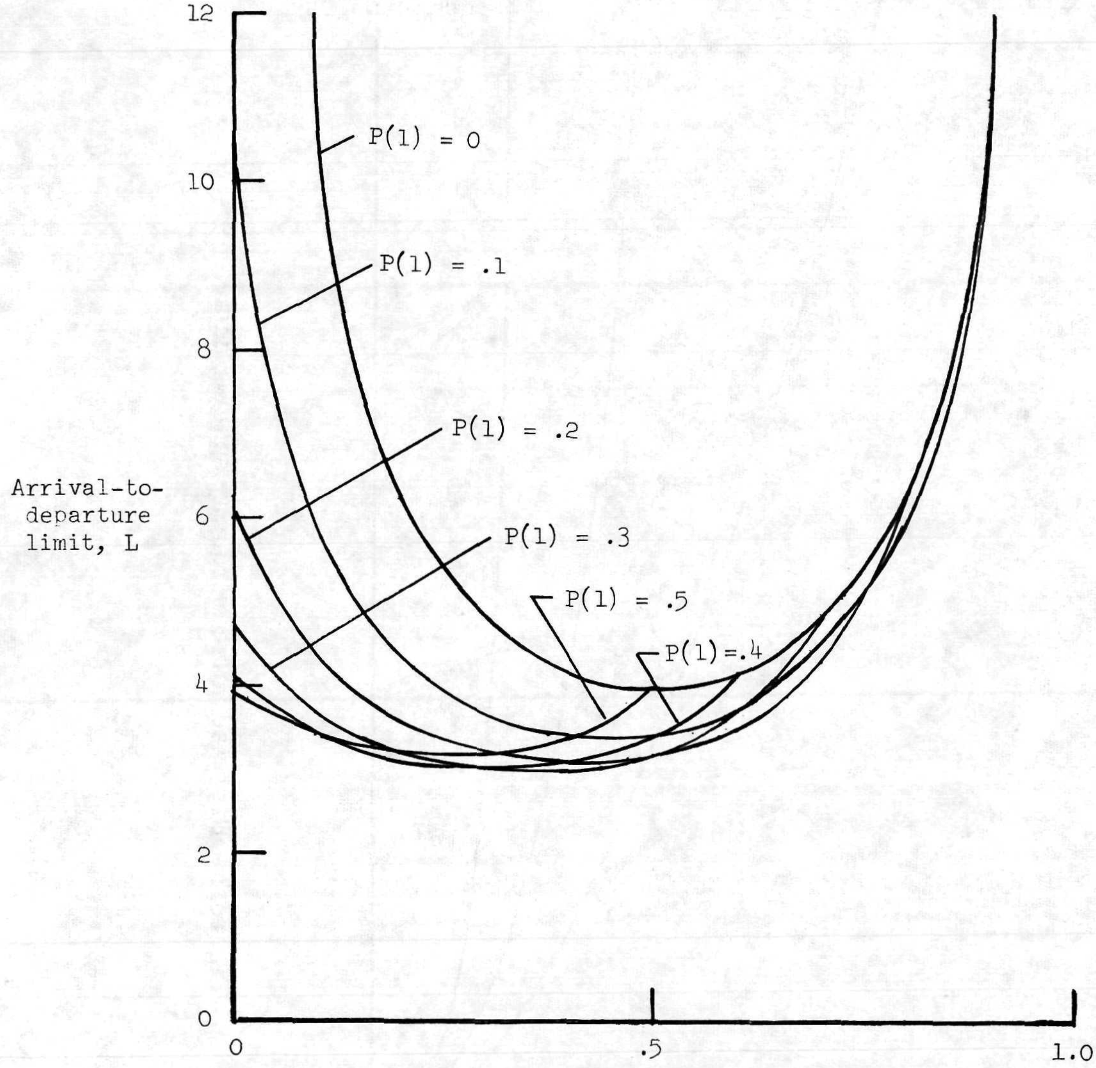


Figure 4.- Arrival-to-departure limit for full runway utilization. $P(2) = 1 - P(1) - P(3)$.

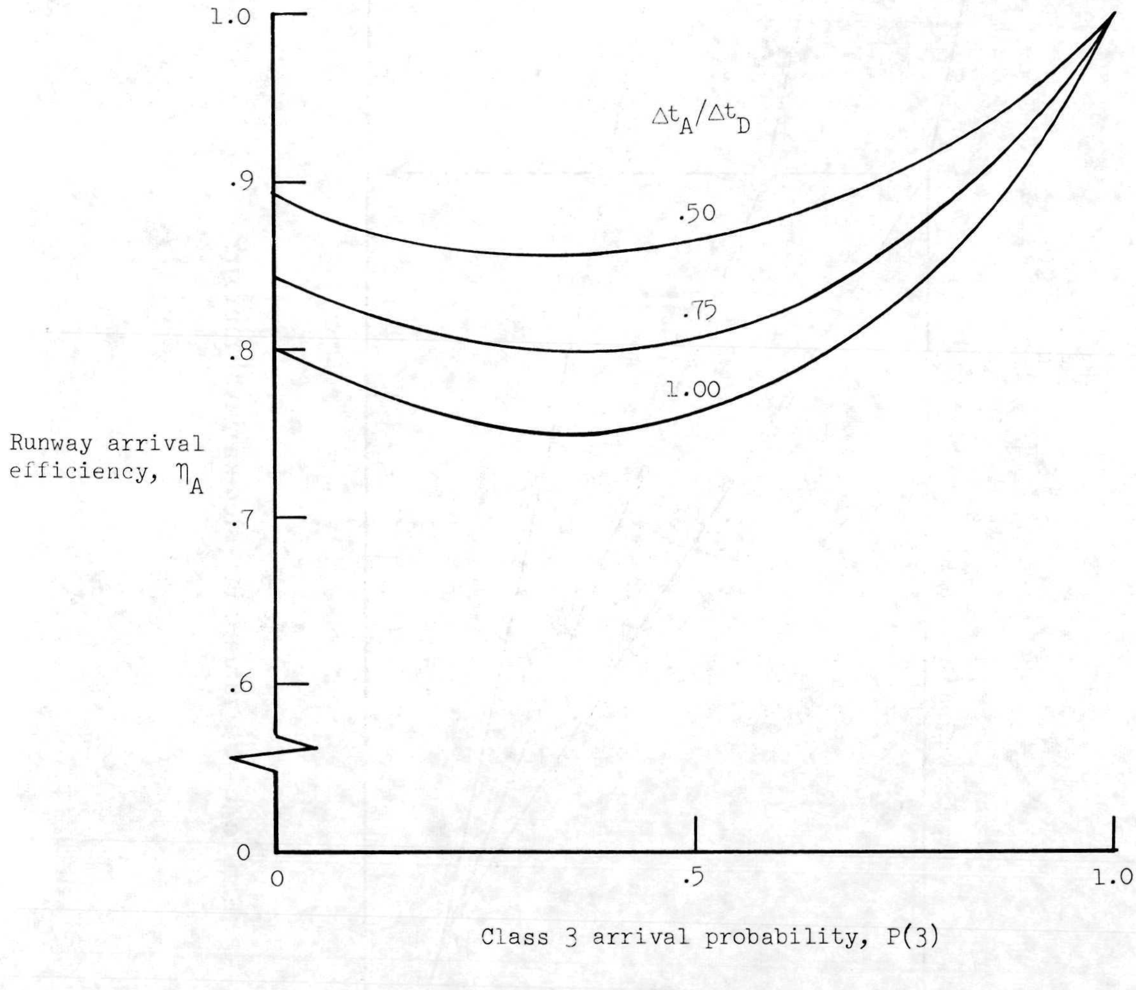


Figure 5.- Runway arrival efficiency. P(1) = P(2).

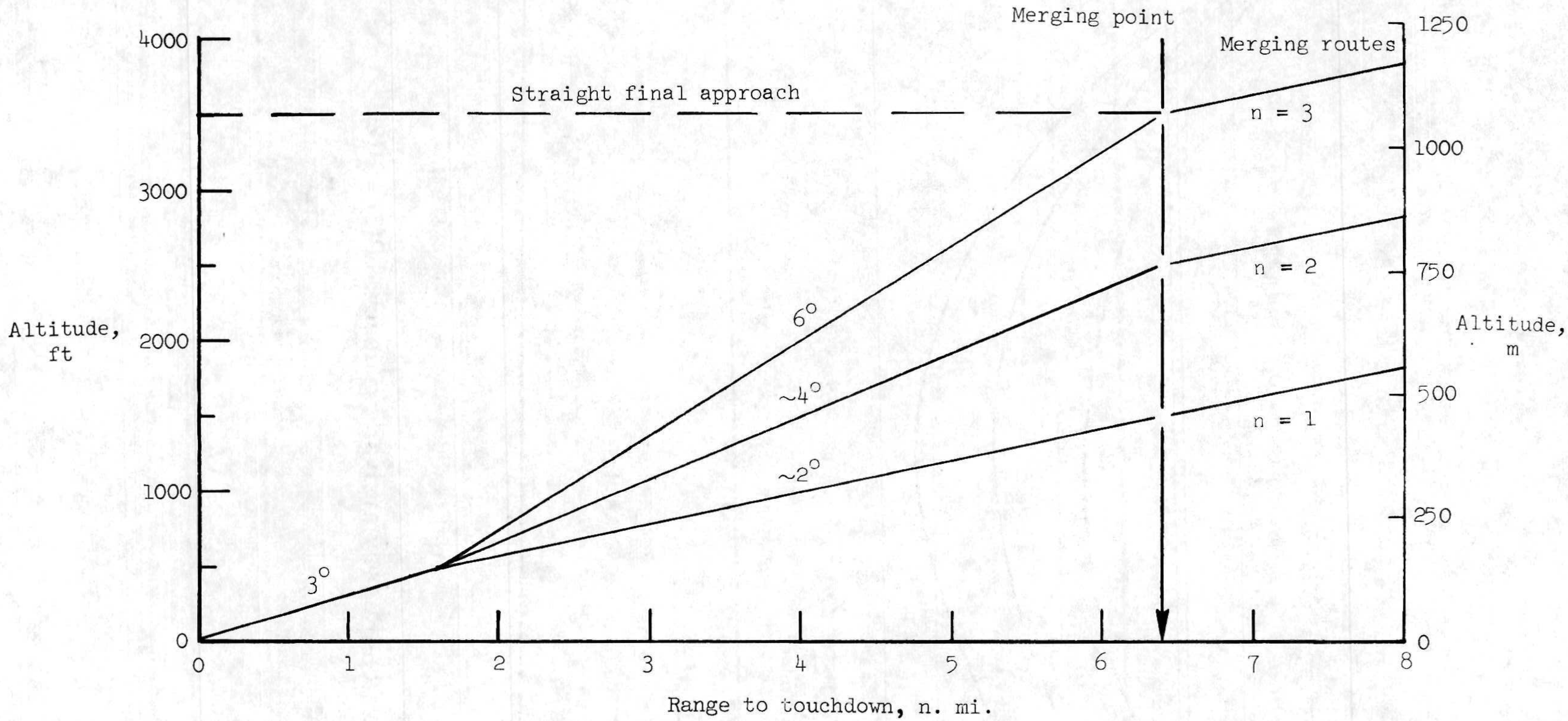


Figure 6.- Variable glide-slope arrival merging.

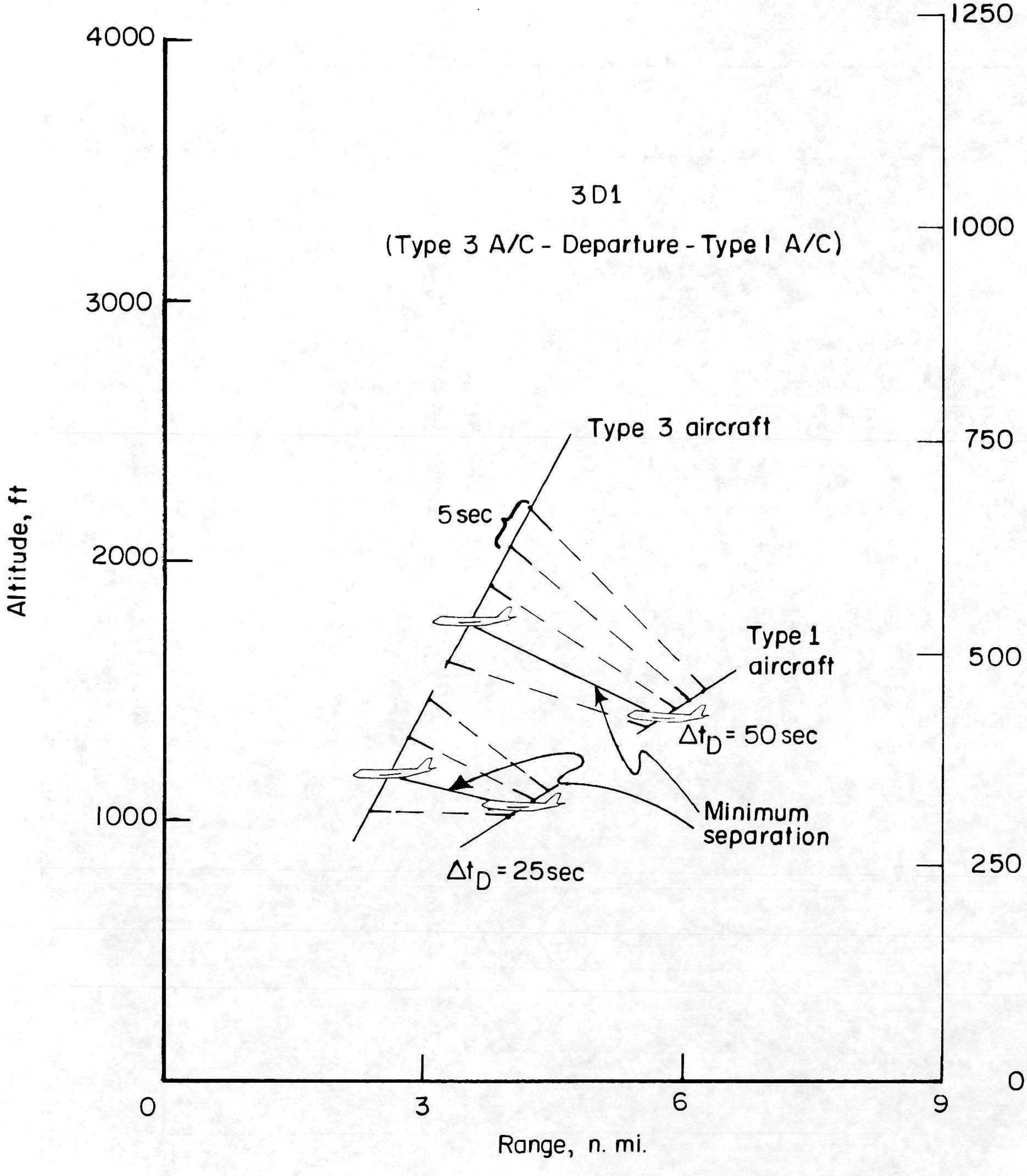


Figure 7.- Approach time sequence showing worst case separation for 3D1 landing sequence.

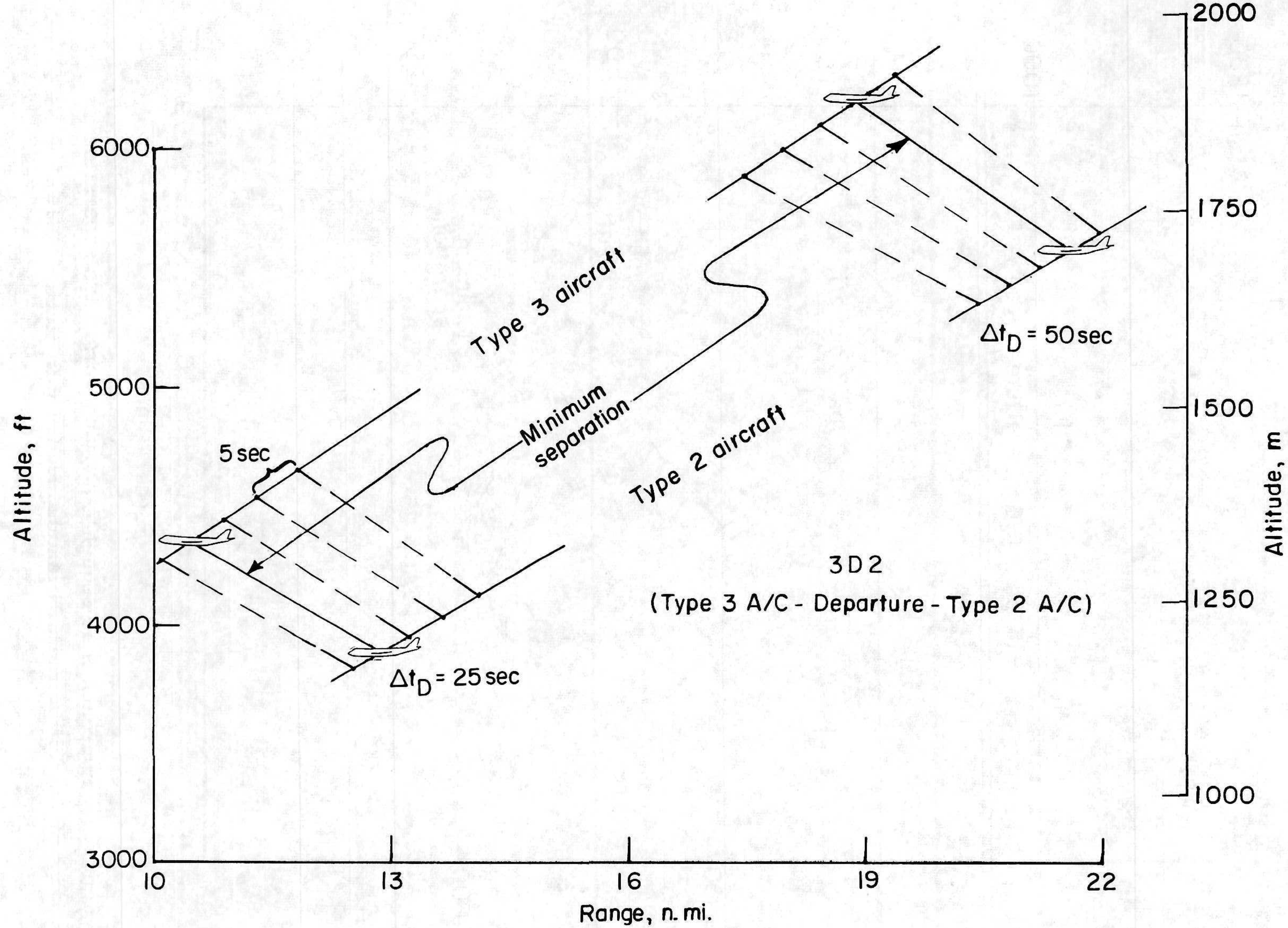


Figure 8.- Approach time sequence showing worst case separation for 3D2 landing sequence.

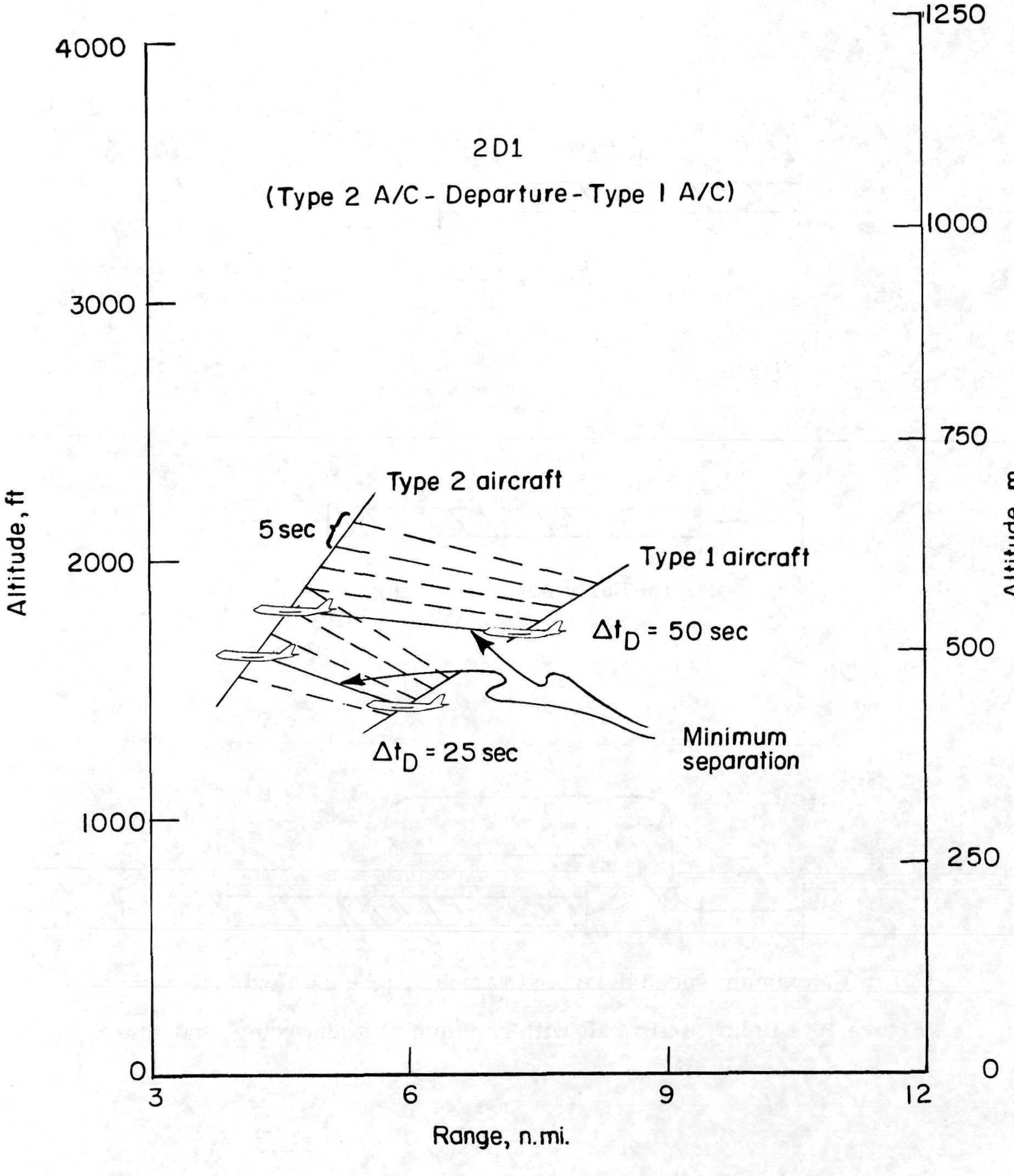
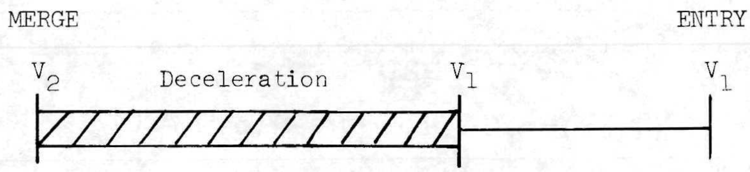
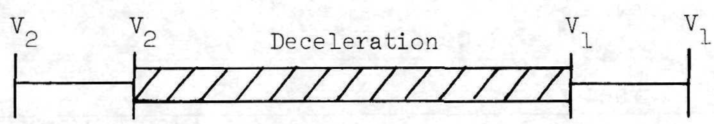


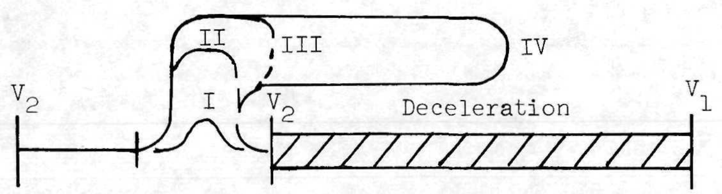
Figure 9.- Approach time sequence showing worst case separation for 2D1 landing sequence.



(a) No delay.

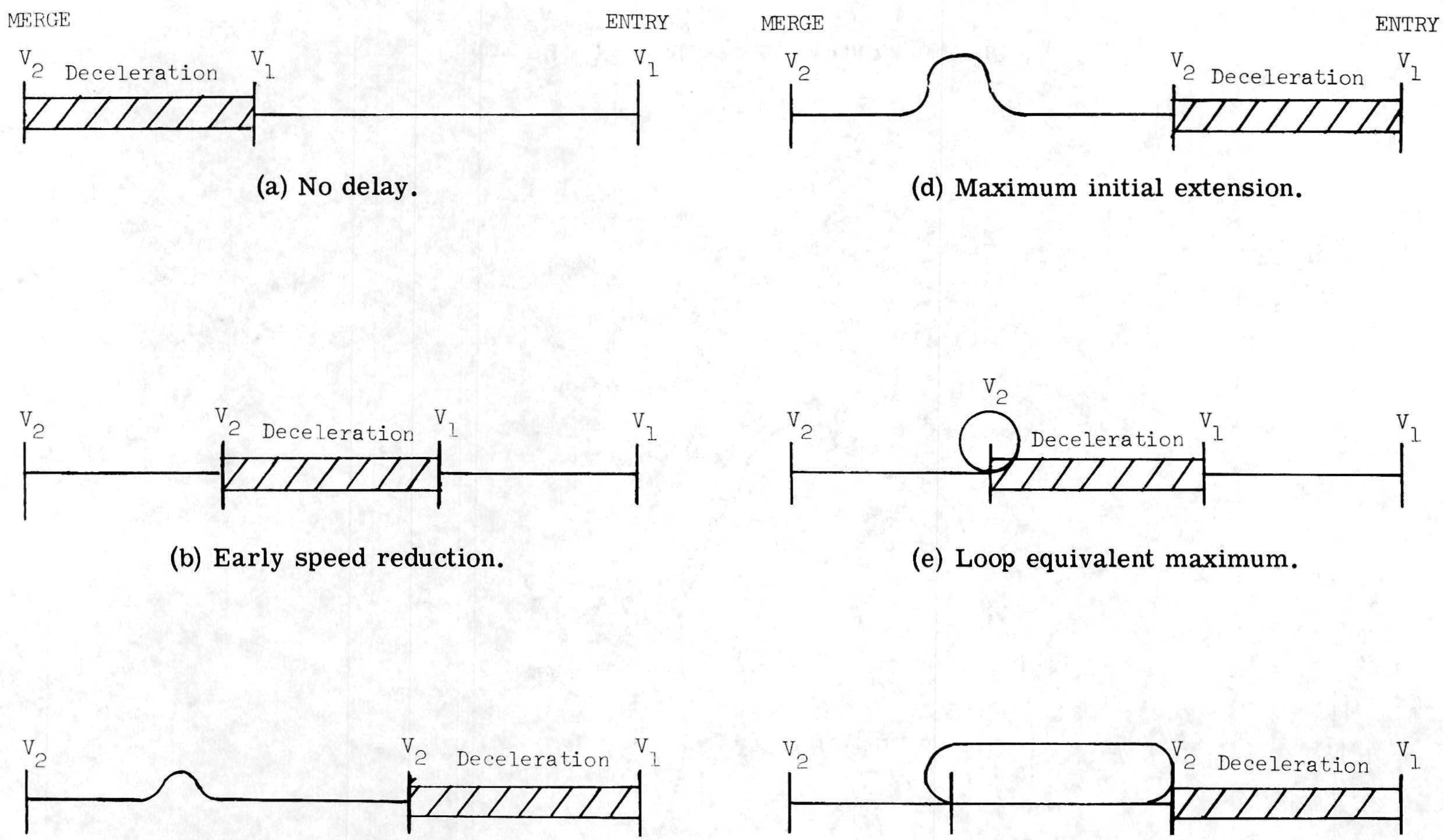


(b) Early speed reduction.



(c) Maximum speed delay and various flight-path extensions.

Figure 10.- Delay of aircraft with common altitude, route, and speed.



(a) No delay.

(d) Maximum initial extension.

(b) Early speed reduction.

(e) Loop equivalent maximum.

(c) Initial flight-path extension.

(f) Large delay extension.

Figure 11.- Delay with minimum lateral displacement.

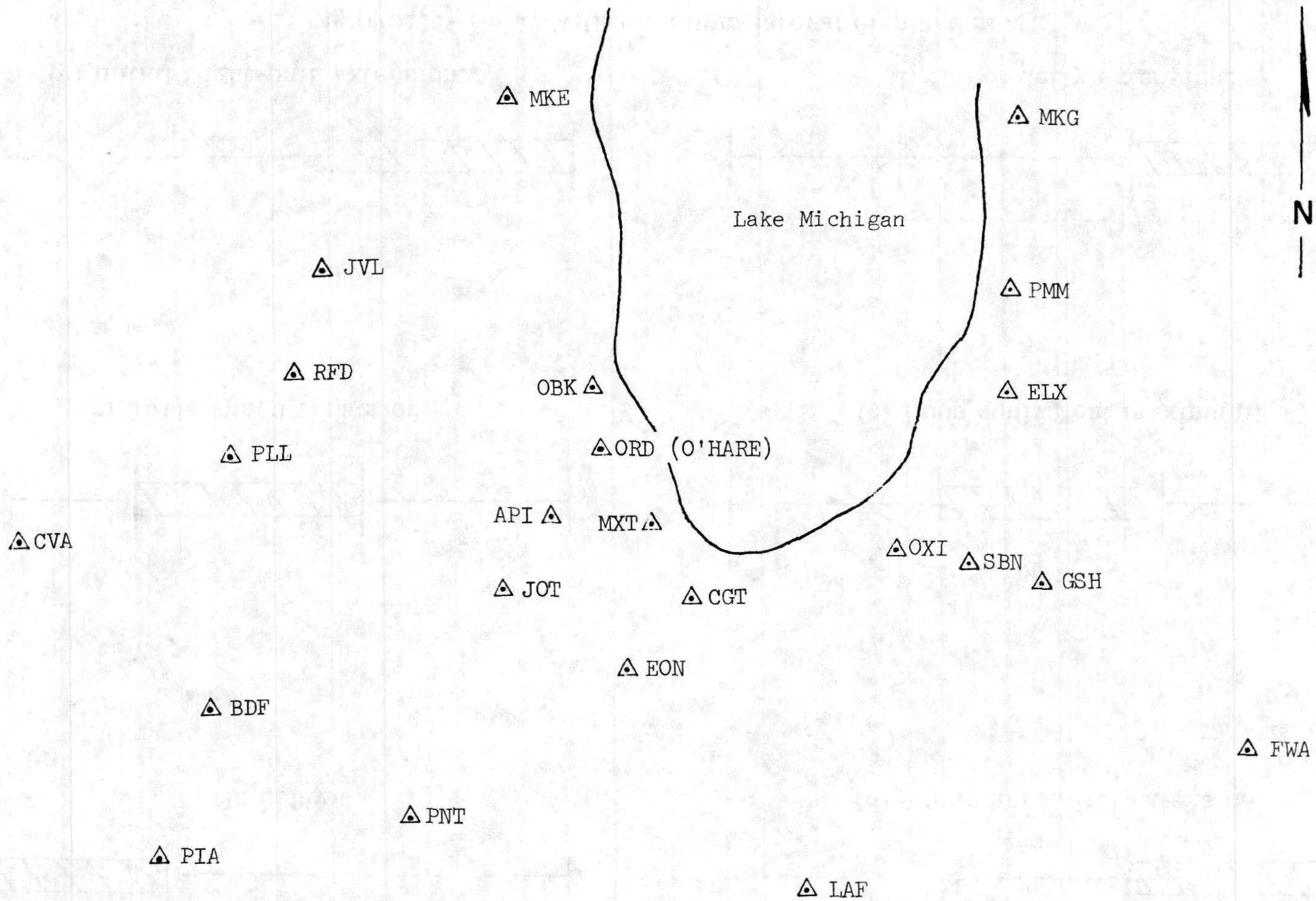
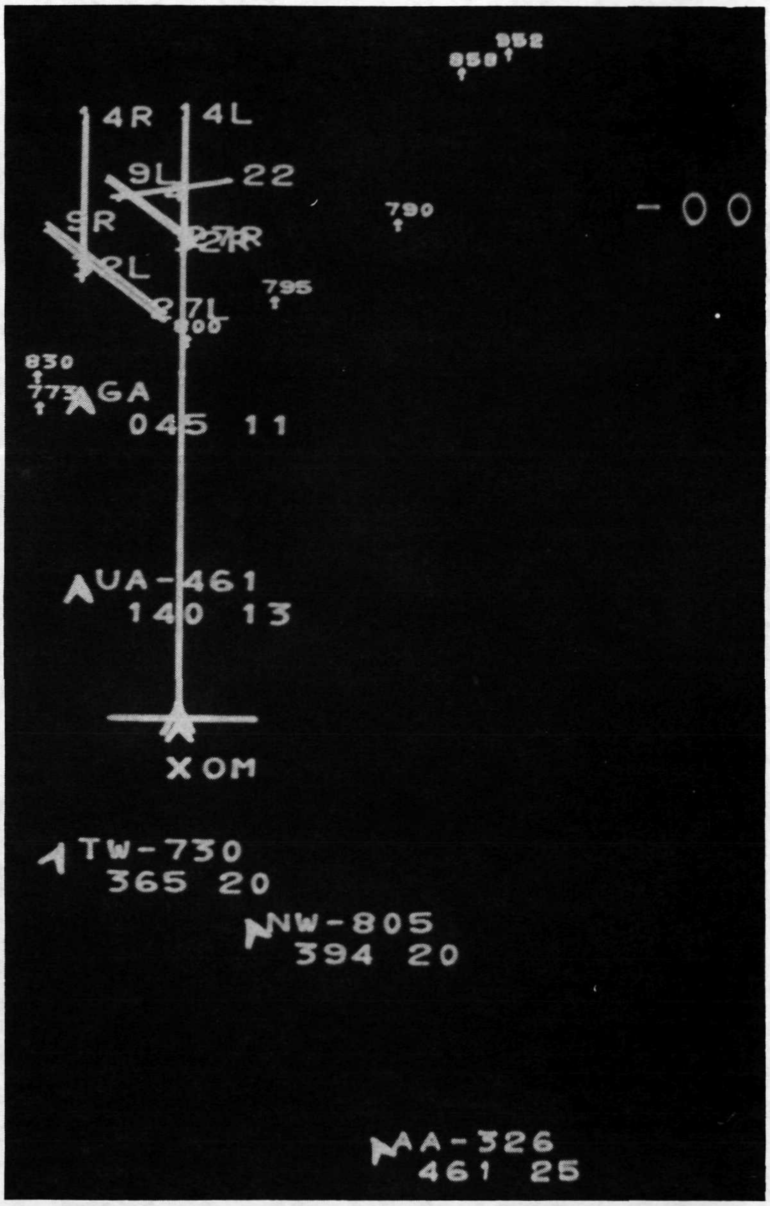


Figure 12.- Navigation map of Chicago area.



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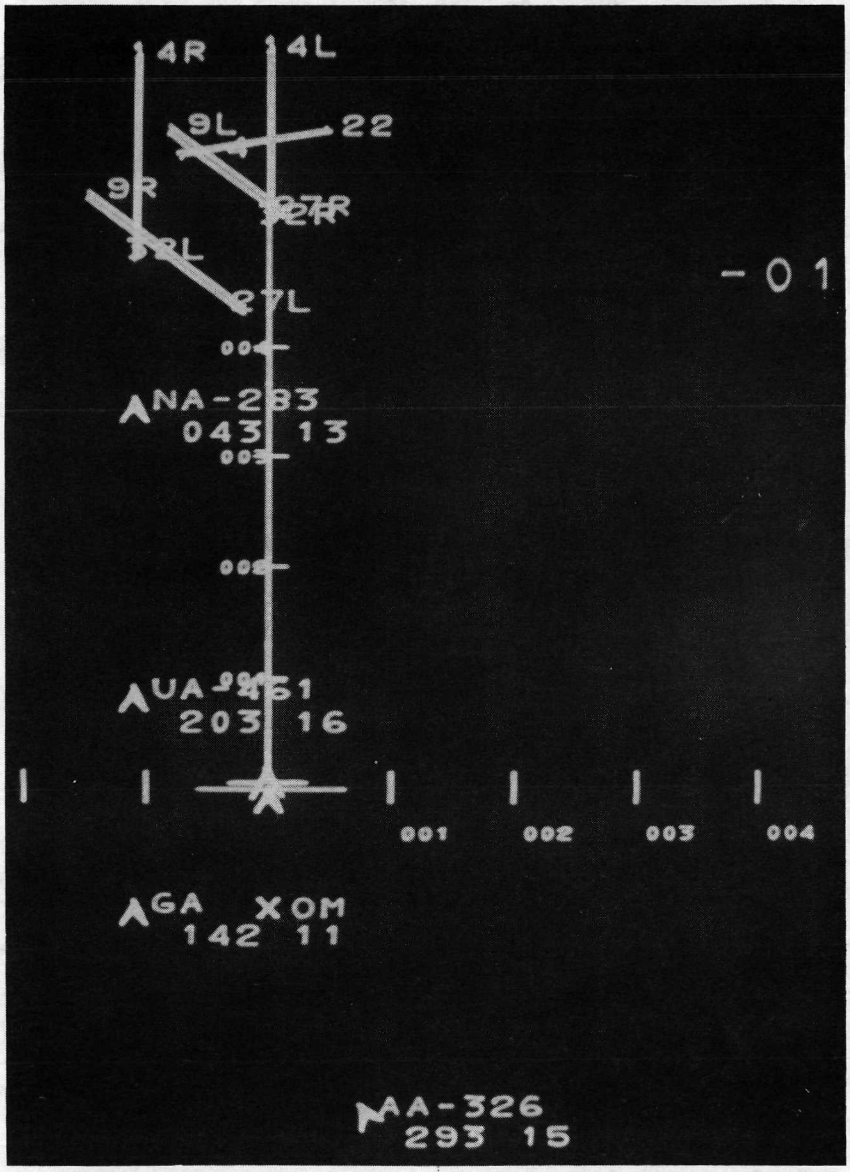
(a) With high elevation points.

Figure 13.- Pilot's situation display.



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(b) With range marks.

Figure 13.- Concluded.

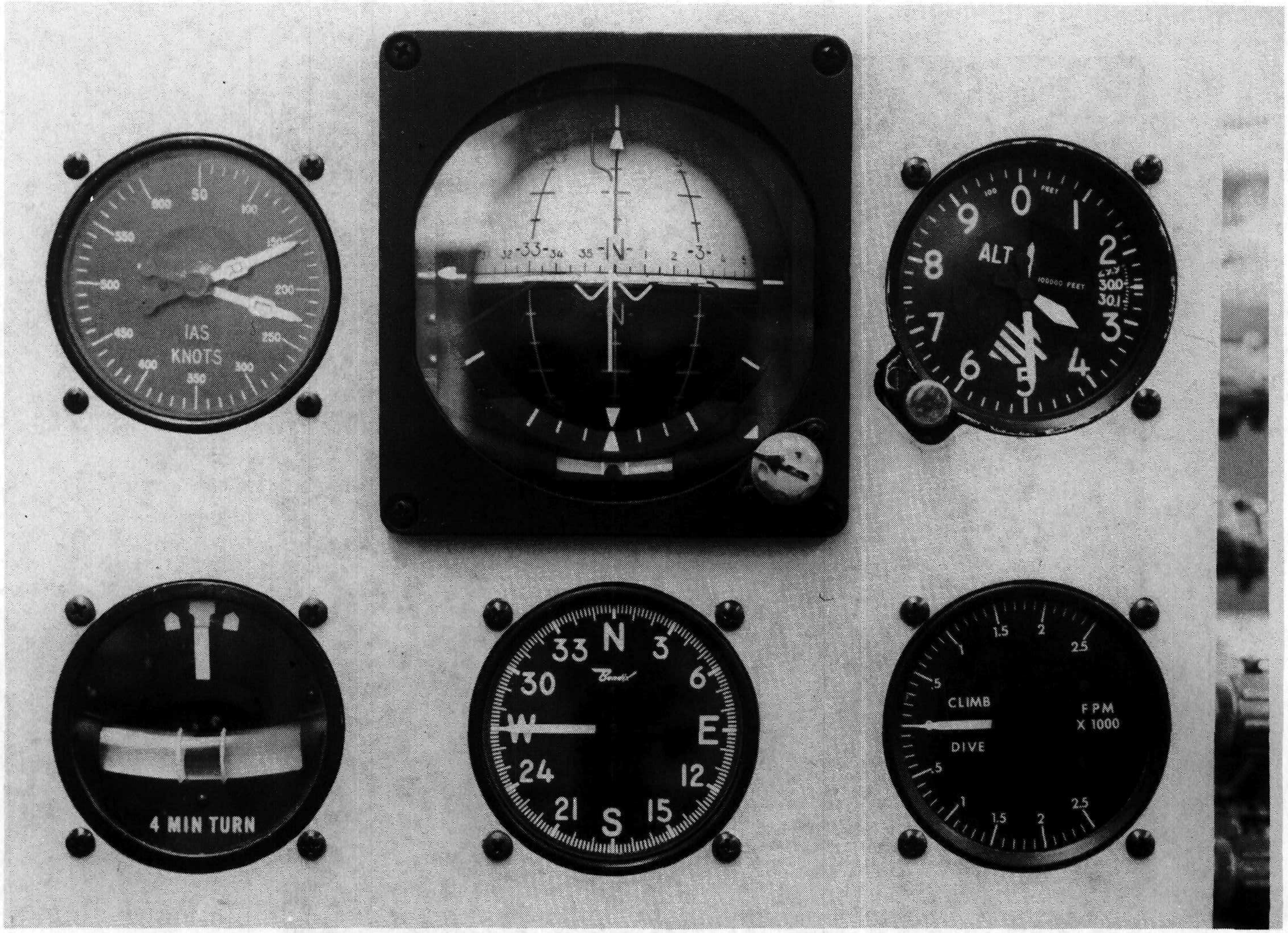

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Figure 14.- Simulated aircraft instrumentation.

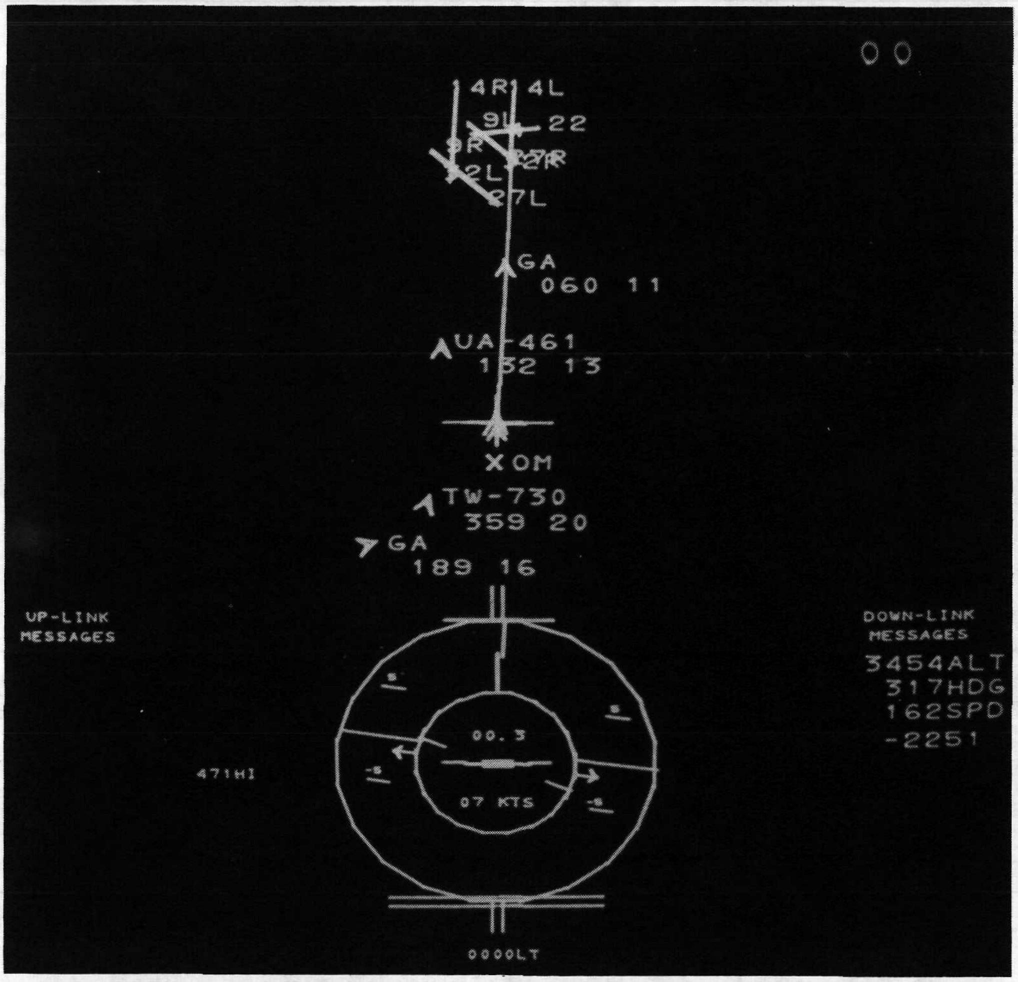

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Figure 15.- Pilot's display with integrated flight director.

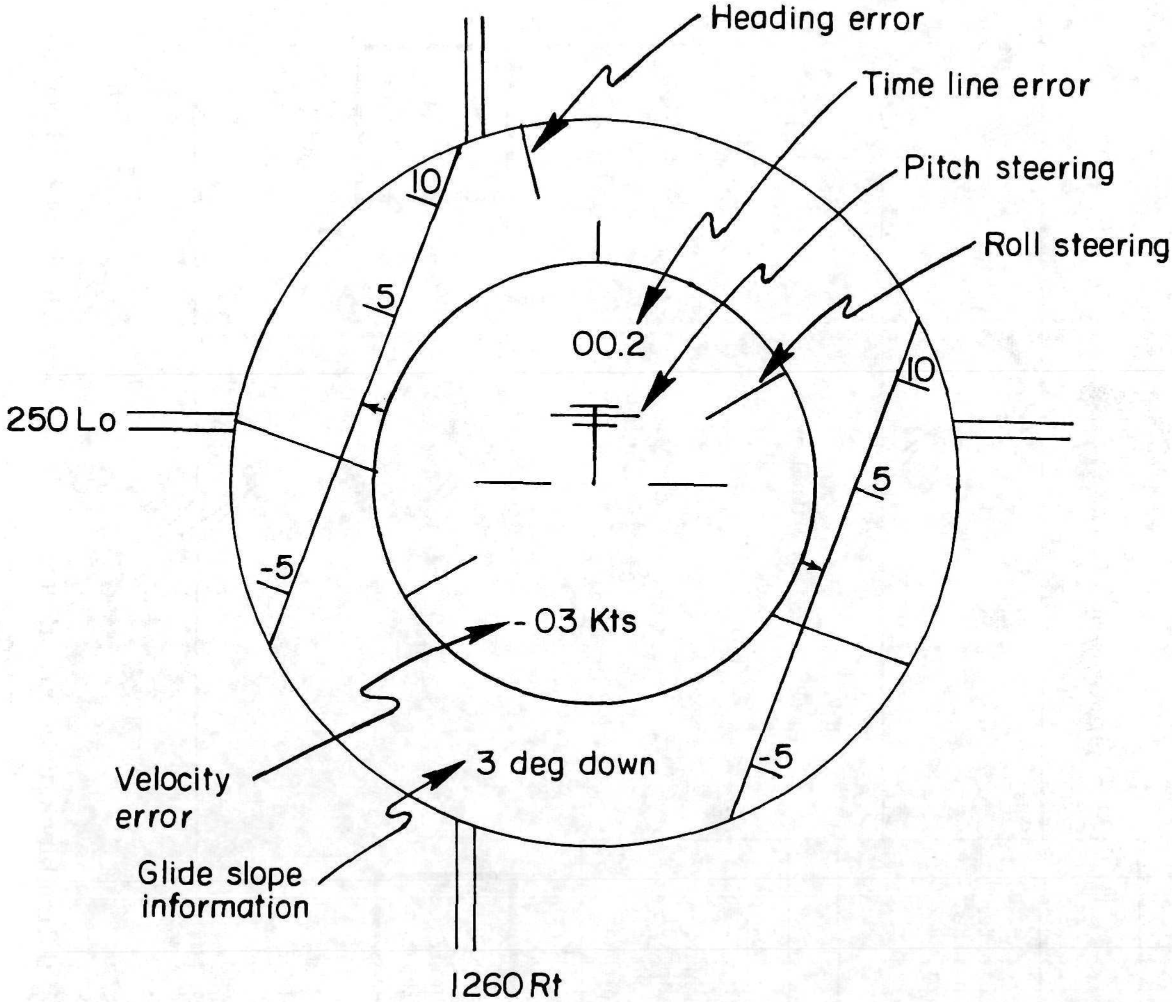

Figure 16.- Nomenclature for integrated flight director.

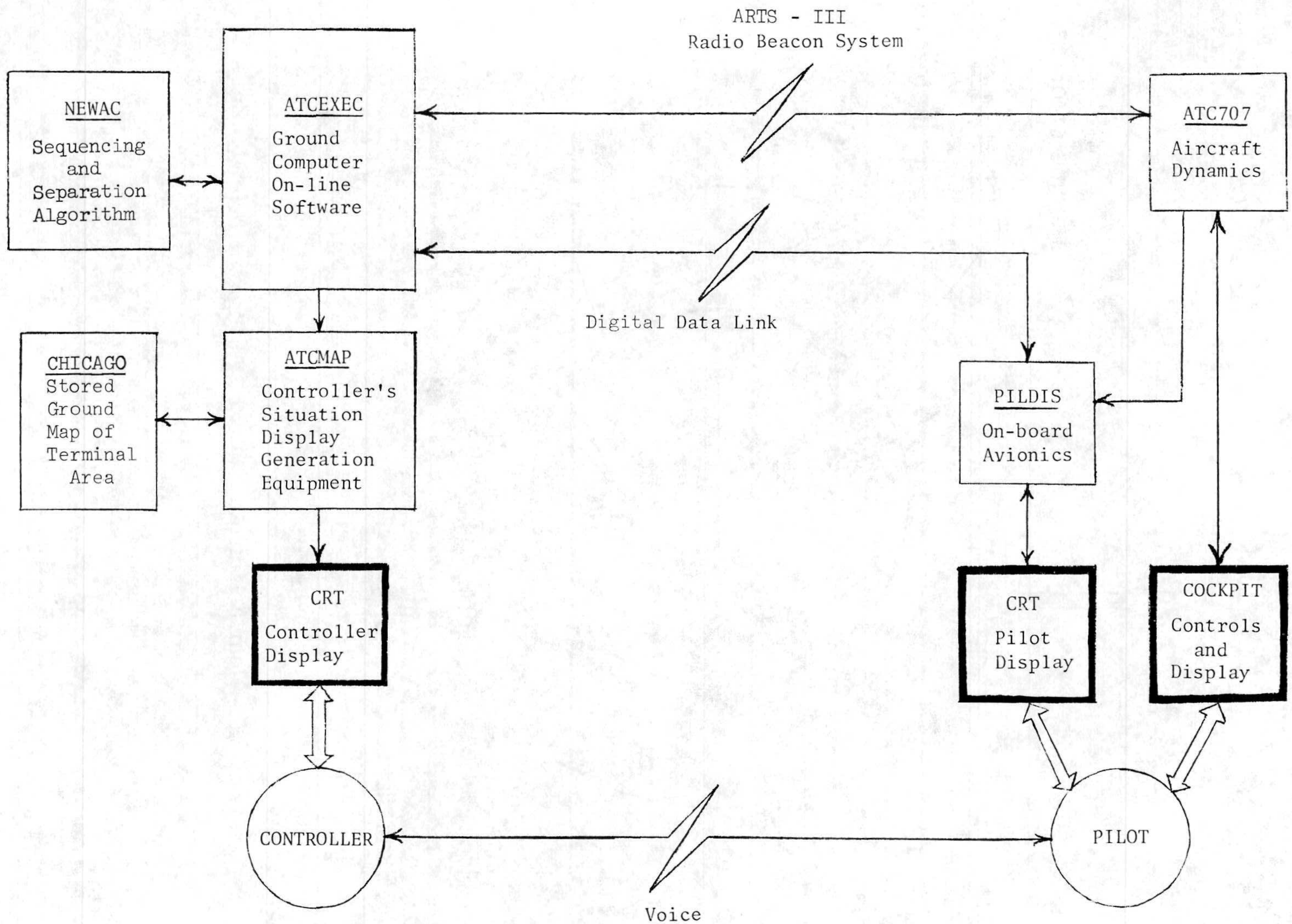

Figure 17.- Simulation block diagram. (Note: Underlined words denote subroutine names; heavy boxes denote hardware.)

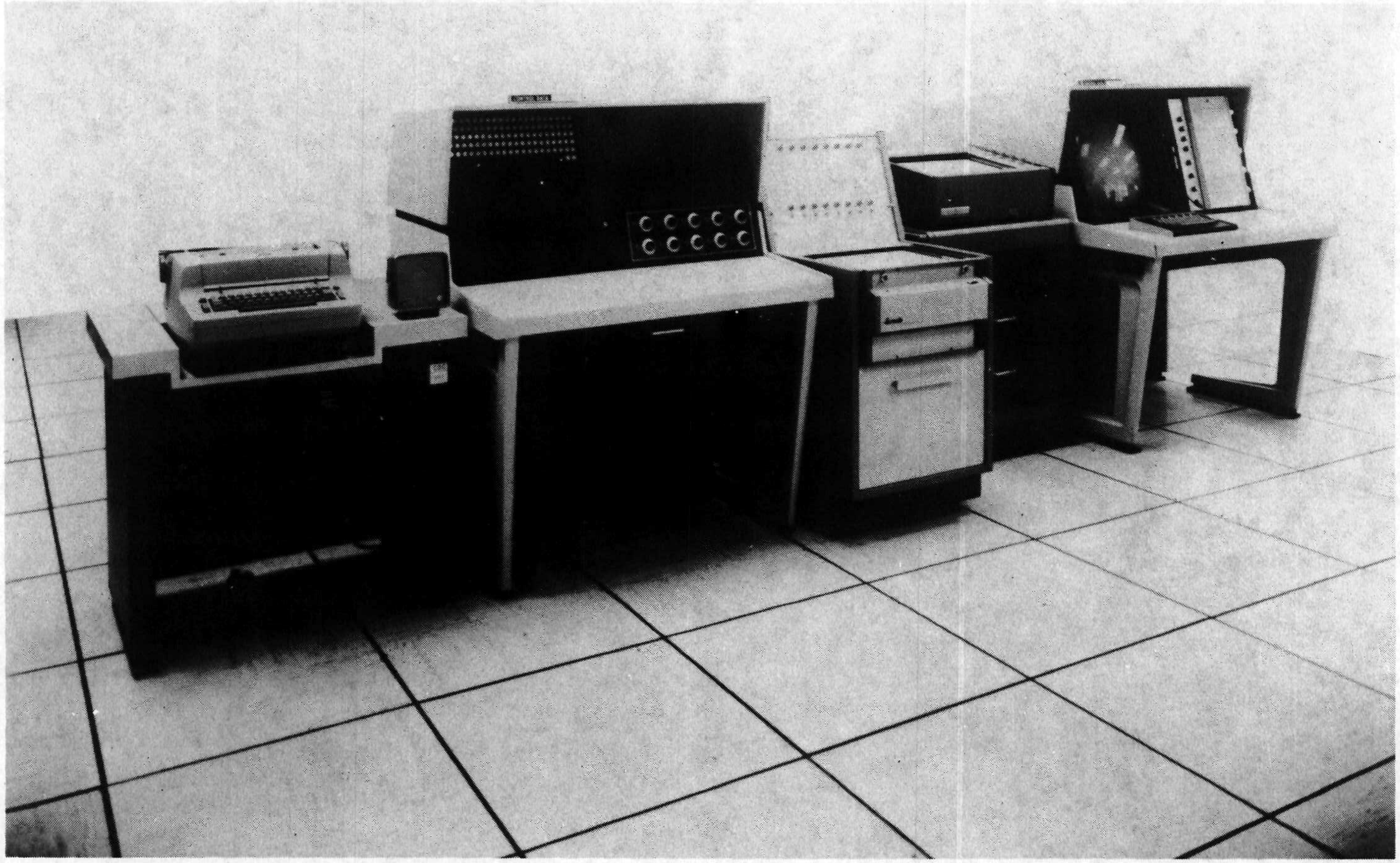

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Figure 18.- Simulation program control station.

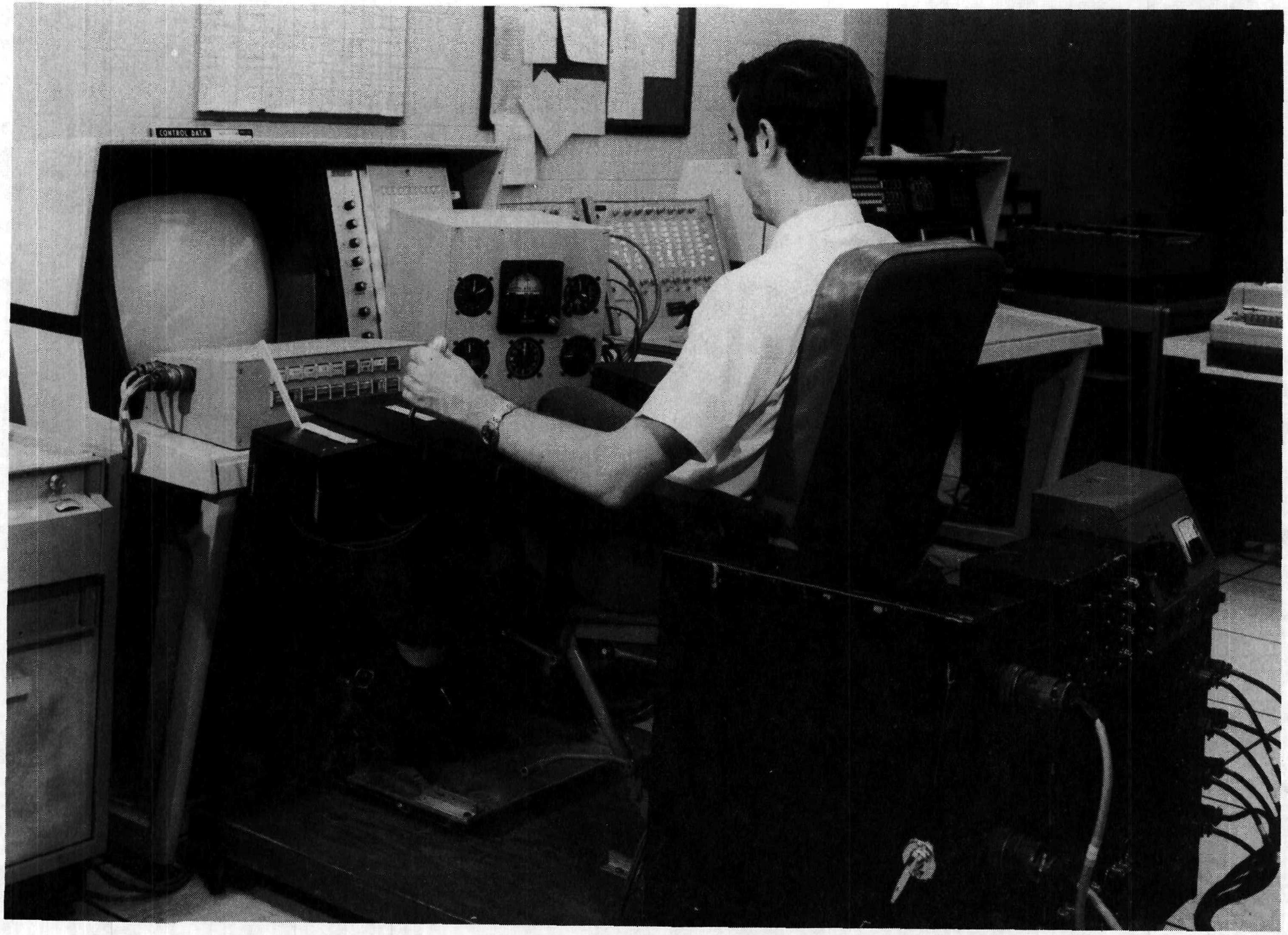

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Figure 19.- Rollup simulator cockpit and CRT display.

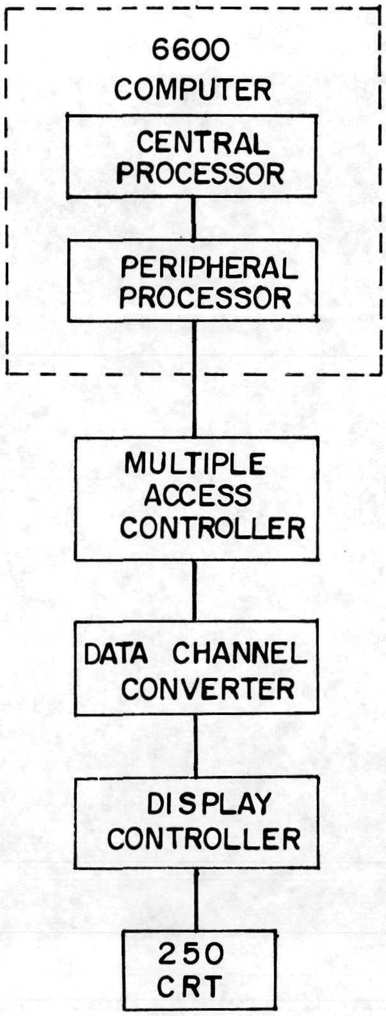

Figure 20.- CRT system schematic.

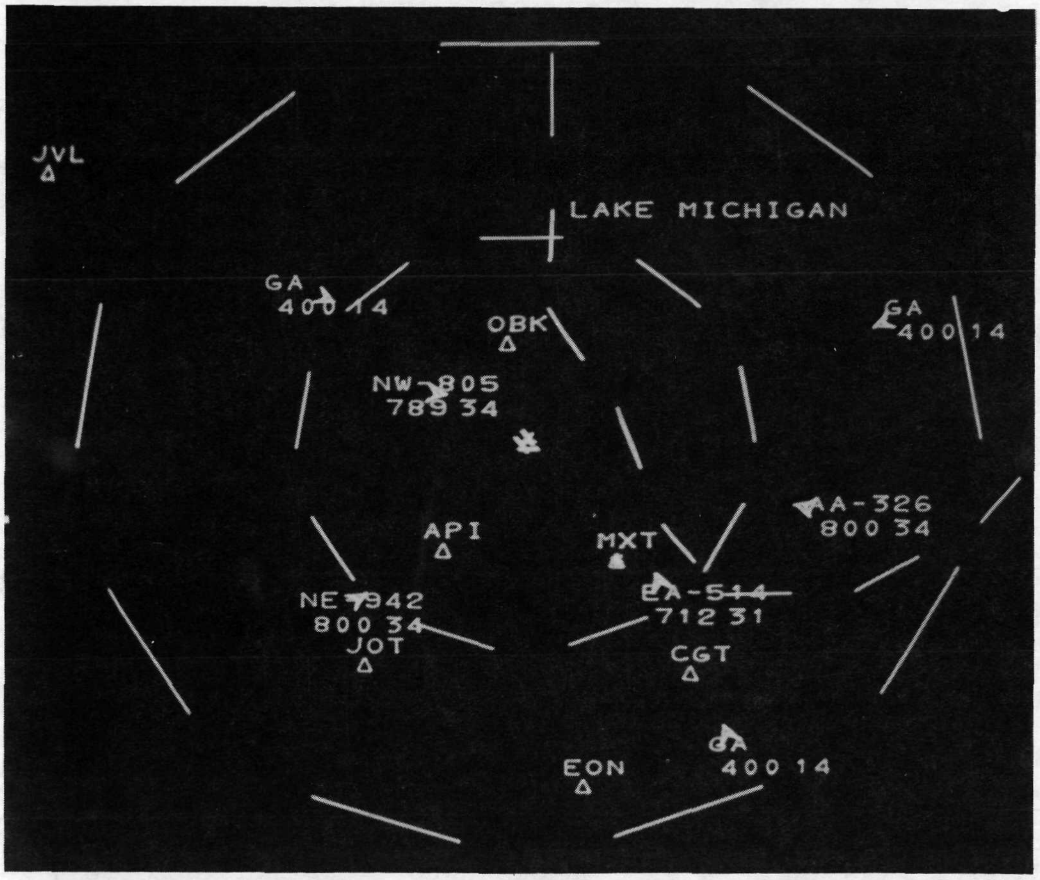

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Figure 21.- Controller's situation display.

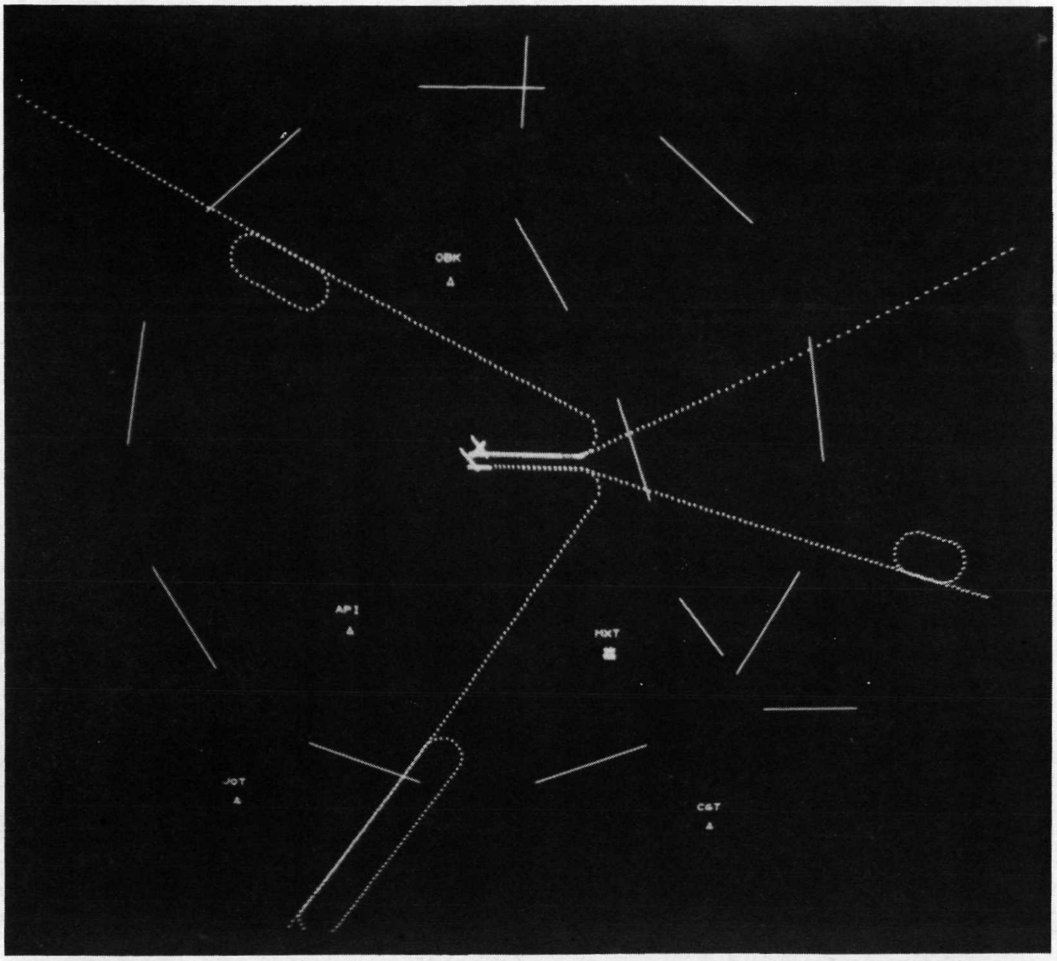

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Figure 22.- Plot of flight path against time.

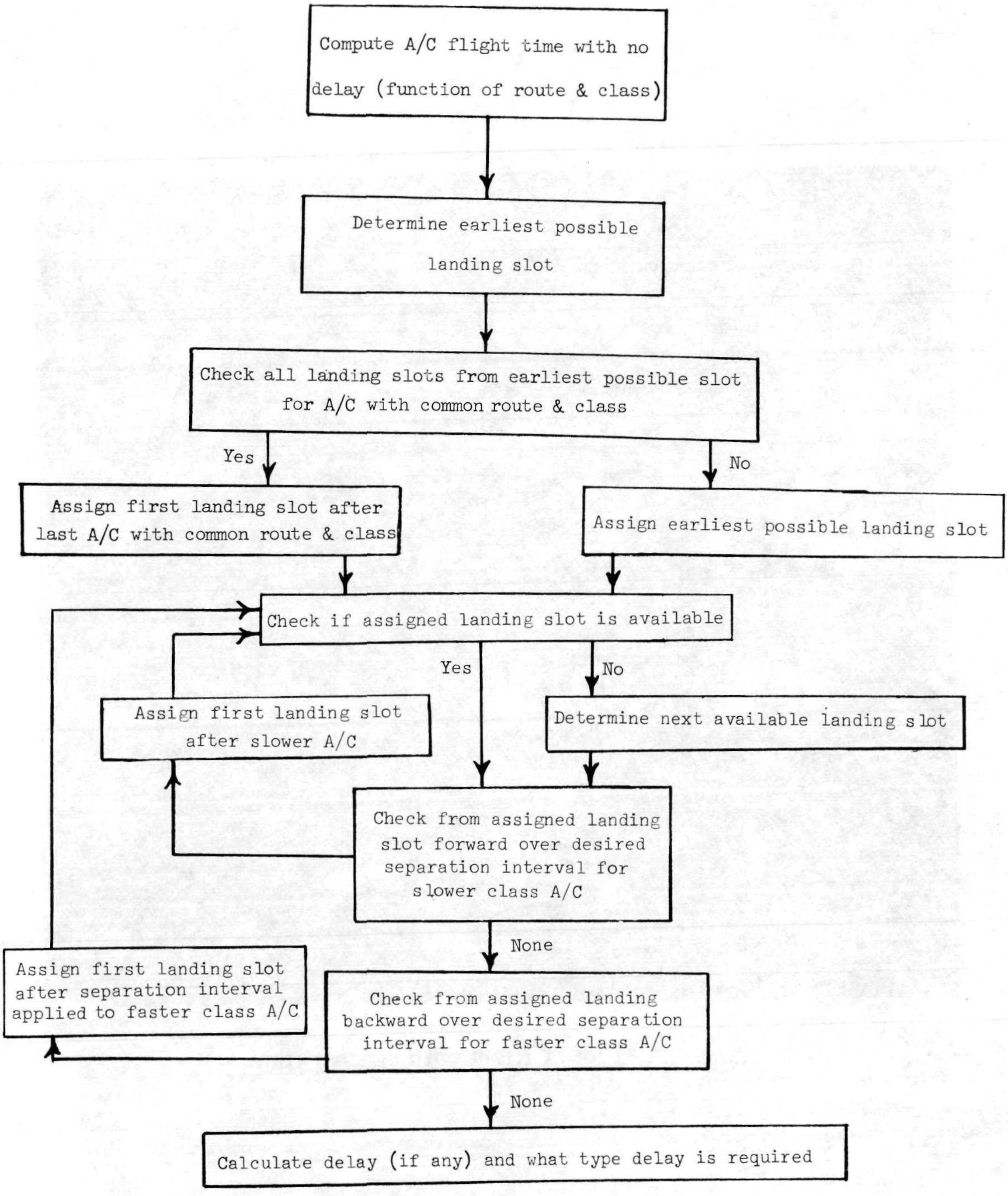

Figure 23.- Flow diagram of sequencing and separation algorithm.

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