A PRELIMINARY STUDY OF OPERATIONAL ADVANTAGES OF PICTORIAL NAVIGATION DISPLAYS

By

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Navigational Aids Evaluation Division

Technical Development Report No 241

Prepared for
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Under
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CIVIL AERONAUTICS ADMINISTRATION
TECHNICAL DEVELOPMENT AND
EVALUATION CENTER
INDIANAPOLIS, INDIANA

June 1954

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FOREWORD

The Air Navigation Development Board (ANDB) was established by the Departments of Defense and Commerce in 1948 to carry out a unified development program aimed at meeting the stated operational requirements of the common military/civil air navigation and traffic control system. This project, sponsored and financed by the ANDB, is a part of that program The ANDB is located within the administrative framework of the Civil Aeronautics Administration for housekeeping purposes only. Persons desiring to communicate with ANDB should address the Executive Secretary, Air Navigation Development Board, Civil Aeronautics Administration, W-9, Washington 25, D C

SUMMARY

In the preparation of an evaluation program for the Types III, IV, and V pictorial computers, a study of possible applications of these navigation displays to operational problems was required This report is, as its title indicates, a preliminary study of operational advantages of pictorial navigation displays with particular emphasis on application to air-traffic-control problems.

When compared to conventional symbolic instrumentation for displaying navigation information, the pictorial displays appear to have three primary advantages

1. Continuous usable navigation information of all airspace within radio range of the ground facilities is supplied to the pilot. A pilot is not restricted to flying radial courses from ground radio aids as he is required to with present forms of instrumentation. Savings in flight time are possible where indirect courses have previously been required. The most effective air-traffic-control patterns may be developed with a more expeditious flow of traffic being realized in many areas through greater use of lateral separation.
2. The navigation workload on the flight crew is materially reduced In the pictorial computer, a position indicator continuously displays the position of the aircraft on the aeronautical chart. The complex mental calculations and the visualization of position required by conventional instrumentation are eliminated This simplification should contribute to improved safety of operations through elimination of human error. In emergencies, flight crews will be able to devote more of their time to other duties with a minimum navigation workload. "Lost-aircraft" incidents should be reduced to a minimum.
3. A reduction in the number of ground radio aids required should be possible if most aircraft are equipped with pictorial navigation displays. In present high-density traffic areas, many additional ground radio aids are required to provide radial courses for the parallel or near parallel airways. This duplication of facilities could be reduced if aircraft could fly offset courses, as is possible with pictorial navigation displays.

In this report, the effects of possible navigation errors in the use of pictorial navigation displays with very-high-frequency omnirange/distance-measuring equipment (VOR/DME) facilities are discussed and are compared with present methods of navigation. A formula to determine spacing between adjacent flight tracks in terms of distance from the VOR/DME facility is also developed.

INTRODUCTION

The Air Navigation Development Board initiated Project 6.2.5 with the Technical Development and Evaluation Center in order to evaluate three types of pictorial computers from the standpoints of equipment performance and operational use. Two of the objectives were

1 To determine the advantages of the pictorial computers when they are used by the pilot as an aid in the terminal area in carrying out the instructions of the controller under both visual-flight-rule (VFR) and instrument-flight-rule (IFR) conditions when the pilot is using (a) standard traffic-control procedures and operations and (b) improved traffic-control procedures and operations
2 To determine the advantages of the pictorial computers when they are used by the pilot as an aid to en route navigation under both VFR and IFR conditions when he is using (a) standard procedures and operating techniques and (b) improved procedures and operating techniques.

All three pictorial computers have a common basic principle in that they display omnibearing-distance information in the form of a pictorial display with the position of an aircraft plotted directly on an aeronautical chart by a position indicator. This method of display of navigational information differs fundamentally from previously used methods. The development of these computers, or displays, is covered in detail in previously published reports.[1,2,3] Although the original developments and studies on this type of airborne equipment used the term "pictorial computer" in the titles and to describe the equipment, the trend in Radio Technical Committee for Aeronautics (RTCA) Special Committee 54 and at this Center is to refer to them as "pictorial displays" because this phrase describes more accurately the function of the equipment.

In the preparation of an evaluation program for the Types III, IV, and V Pictorial Computers, there was required a study of the possible applications of these navigational displays to operational problems, with particular emphasis placed on the application to air-traffic-control problems. Part of this material is based on a paper presented to RTCA Special Committee 54 by Mr T. K Vickers of this Center, and part is based on two reports published by this committee.[4,5]

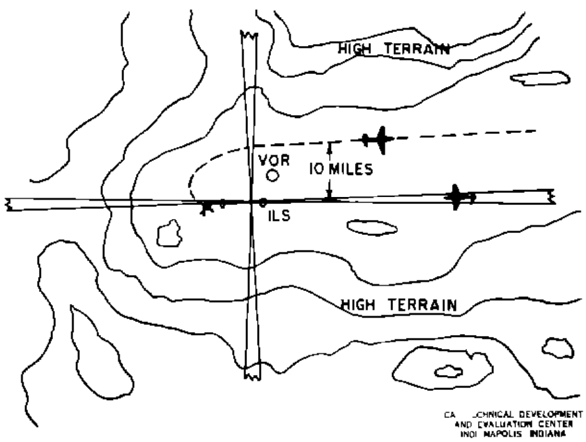

Fig. 1 Parallel Departure Track in Mountainous Terrain

[1]Logan E Setzer, "The Type III Portable Pictorial Computer, Part I, Development and Initial Tests," CAA Technical Development Report No 172, October, 1952.

[2]Logan E. Setzer, "The Type IV Rotatable-Panel Pictorial Computer, Part I, Development and Initial Tests," CAA Technical Development Report No 195, April 1954.

[3]Logan E. Setzer and Paul H. Leake, "The Type V Pictorial Computer with Automatic Chart Selection, Part I, Development and Initial Tests," CAA Technical Development Report No. 199, June 1954.

[4]RTCA Paper 216-52/SC54-6, dated November 13, 1952.

[5]RTCA Paper 217-52/SC54-7, dated October 8, 1952

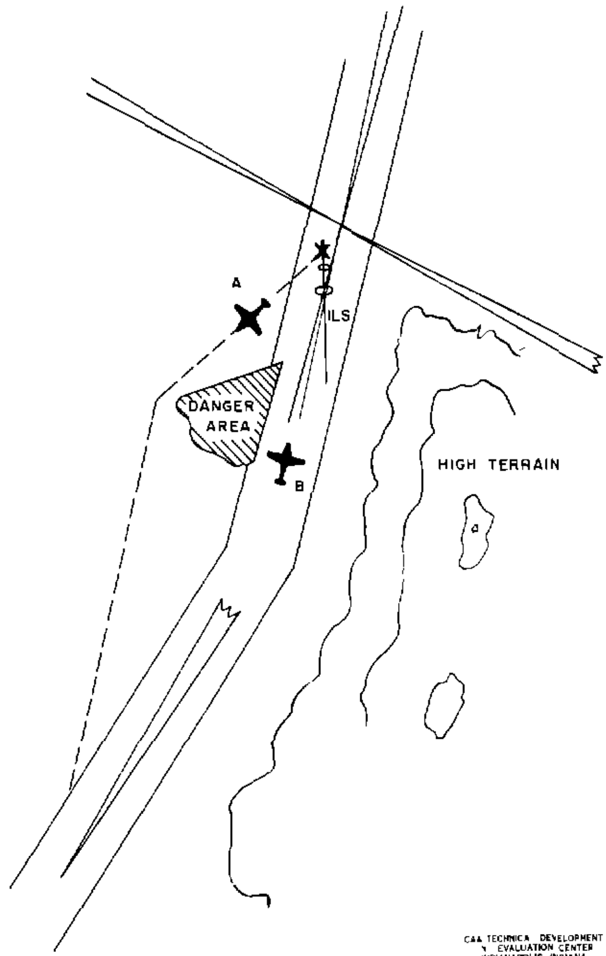

Fig. 2 Bypass Track Around an Airspace Restricted Area

GENERAL DISCUSSION

Perhaps the greatest advantage of pictorial displays is the continuous indication of position information in all airspace in a simple, direct form. When flying in terrain-problem areas or in congested-traffic areas where courses must be strictly adhered to for safety, the pilot needs rapid, accurate, and simple presentation of navigational data. Methods used by slower vehicles in surface transportation for determining position and course corrections required are normally too slow for use in high-speed aircraft In all of the commonly used aircraft radio-navigation systems and methods of instrumentation such as the low-frequency (LF) range, automatic direction finder (ADF), and VOR, a pilot is restricted to flying direct (radial) courses to or from ground radio stations. This restriction is a natural result of the limited navigation information continuously available. Only on radial courses does the pilot have immediate indications of course deviation to right or to left.

The pictorial display permits the flying of any course desired It is as simple to fly a desired track by-passing a ground radio station ten miles to the right as it is to fly a track directly to or away from that station. This ability can have an appreciable effect on air-traffic-control procedures. Greater use of lateral separation can be made in many areas with a reduction in delays to aircraft operators.

Another operational advantage gained by the use of pictorial displays is the ability of the pilot to navigate to any airport within range of a VOR/DME station. At the present time, only the major airports and airways are adequately served with radio aids With the pictorial display, a pilot may easily navigate to many more airports. This should be particularly advantageous for corporation-aircraft operations, for some military flights, and for the private pilot.

The pictorial-display presentation of navigational information is simpler than that of any other system developed to date. The location of the aircraft over the ground is presented directly on a chart by a position indicator No mental interpretation of instrument data or of aural signals is required. In previous systems, the pilot was required to mentally translate aural-range signals and visual indications of heading and of bearing in order to locate his position on a chart. The pictorial display accomplishes this job automatically The mental workload of the pilot should be materially reduced, particularly when numerous changes of course are required as in terminal-area flying.

Most of the navigation information needed by the pilot can be provided in one instrument when the pictorial display is used. Direction from a station, distance to the station, distance to the airport, and position with respect to the desired track over the ground are all presented to the pilot. Heading information is also included on some pictorial equipment. Fewer mechanical manipulations are required of the pilot. It is necessary only to select and to insert the proper chart in the pictorial display. It is not necessary to select desired radials and to adjust omnibearing selectors as courses change

Use of the pictorial display should almost eliminate "lost-aircraft" incidents. When these incidents occur during heavy-traffic conditions, other flights are delayed and hazardous traffic situations develop because of lack of position information from the lost aircraft. Similarly, many accidents in mountainous areas have resulted from pilot errors in interpreting navigation information It is believed that the pictorial display will reduce the number of such incidents by virtue of its simple presentation of position information directly on a chart. Similarly, in emergency situations such as occur with malfunctioning power plants or in severe icing conditions, the pilot will be free to devote most of his attention to the aircraft with a minimum of time required for navigation.

Use of pictorial displays will reduce the number of ground radio aids required, with a resultant savings to the Government If aircraft are equipped with pictorial equipments, VOR/DME stations can be installed in the most advantageous locations to provide maximum radio line-of-sight coverage Present sitings are made with respect to airports and existing airways and frequently do not provide the desired coverage in terrain-problem areas

Equipment savings in the aircraft are also possible. Omnibearing-selector (OBS), omnibearing-indicator (OBI), DME, and ADF instrumentation and LF and fan-marker receivers can be eliminated when adequate fail-safe operation of pictorial-display equipment is assured

The following sections of the report suggest some possible improvements which could be made in air-traffic-control (ATC) procedures if aircraft were equipped with pictorial displays and if the VOR/DME system were fully implemented. As wider knowledge and more experience is gained with this equipment, other uses will suggest themselves. A section is also devoted to a discussion of errors in the use of the omnibearing-distance (OBD) system with pictorial display.

It must be recognized that many of the traffic-control procedures outlined herein are more applicable in some areas than in others. For example, in some of the high-density-traffic areas today, a multiplicity of ground radio aids permits use of practically all of the available airspace. Even though OBD facilities were available and some aircraft were equipped with pictorial displays, these aircraft would probably have to conform to routes in use by the majority of flights in order to permit reasonable control of traffic. However, as more and more aircraft became equipped with pictorial displays, some of the ground facilities could be turned off and routes based on use of the OBD facilities with pictorial displays could be established. It should also be recognized that in many areas of the country ground navigational aids are limited in number and that new, improved procedures could be implemented immediately to reduce ATC delays and to provide better on-time performance for the entire system. Large economic savings in aircraft flight time could also be realized.

TERMINAL AREA

Departure Patterns.

Additional departure tracks will be usable with navigational guidance available in all airspace. Flights no longer need be restricted to the following of radial courses from ground radio aids such as LF radio-range legs, VOR radials, or ADF tracks to and from homing (H) markers With pictorial displays, there are no restrictions on the direction of tracks Courses

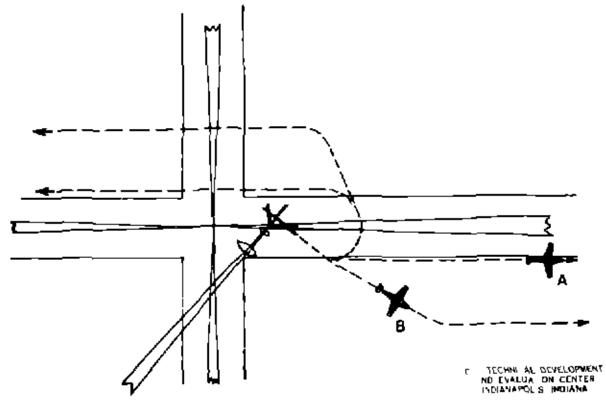

Fig 3 Parallel Departure Tracks for Lateral Separation

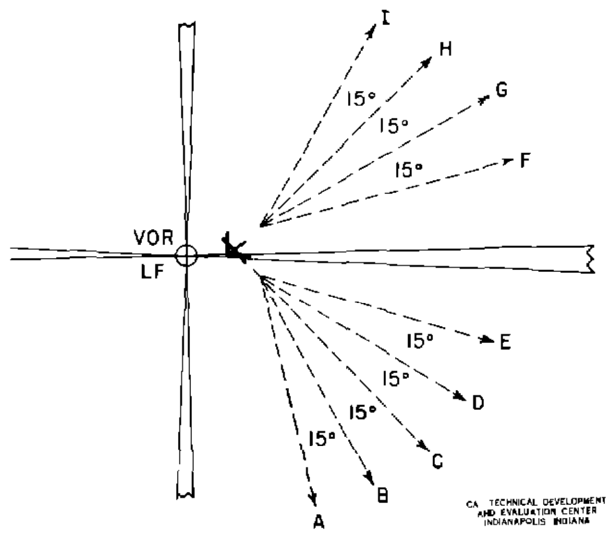

Fig 4 Angular Departure Tracks

may be in the most suitable direction without respect to the location of the ground radio aid Additional departure tracks making use of airspace unused at the present time can be set up at many airports to avoid inbound traffic and en route airway traffic

Pictorial displays will permit more efficient use of available airspace where terrain features or airspace restrictions are important considerations. In many areas, particularly in the western part of the country, airports are located in valleys with high terrain on one or both sides. Most of these locations are served by only one radio-range station, and IFR flight must be conducted along one course defined by the radio-range leg. As a result, many ATC delays occur even under light-traffic conditions. If an inbound aircraft is using the one course, a departing aircraft must wait on the ground until the inbound aircraft has completed the IFR letdown. Use of VOR will improve this situation by providing additional well-defined tracks at angles to the main course. However, where angularly divergent courses cannot be used effectively because of terrain, the pictorial display will in many cases permit use of a track parallel to the main course in order to permit two-way operation. Fig. 1 shows such an application

In other parts of the country, danger areas, caution areas, or prohibited areas require aircraft to fly circuitous routes to avoid this restricted airspace. With the limited navigational aids available, many single-lane airways exist, again causing delays to departing traffic.

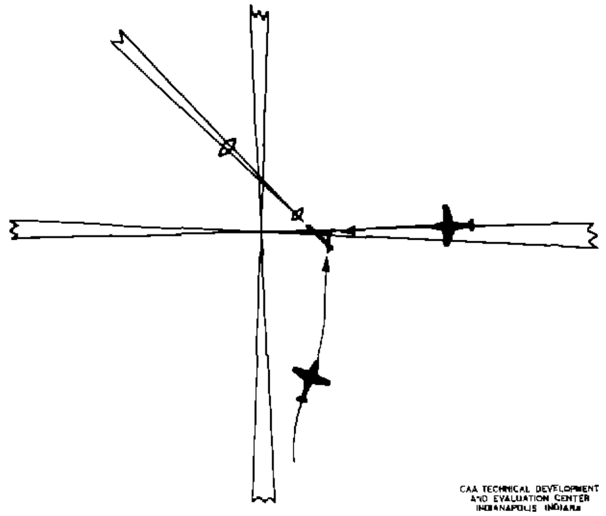

Fig. 5a Straight-In Approaches From Any Direction

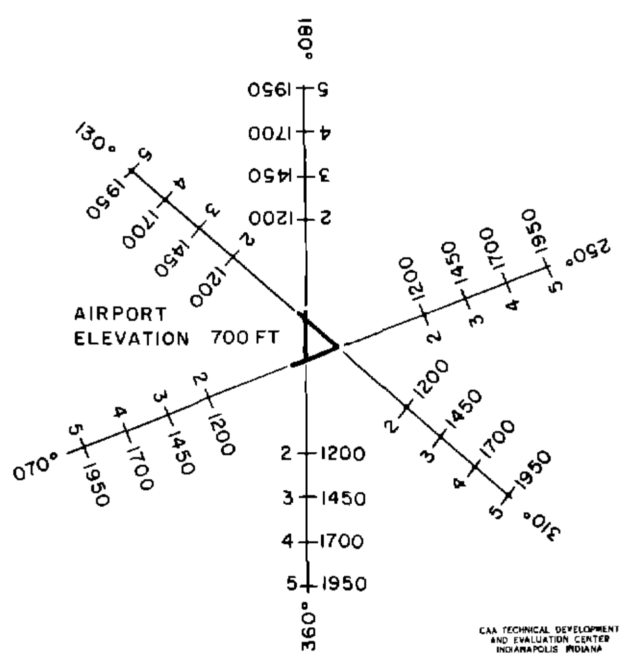

Fig. 5b Pictorial-Computer Approach Chart

In many places the pictorial display will permit more than one track to be used around a restricted area. Lateral separation can then be used between opposite-direction traffic during climbs and descents and will result in large reduction in delays Such an application is illustrated in Fig. 2.

Pictorial displays will also permit safe IFR navigation from many more airports. Present radio navigational aids generally serve major airports only The pictorial display will permit navigation from any airport within reception range of the OBD facility. The most desirable departure tracks for all airports in a given area may be set up to eliminate conflictions in traffic-flow patterns. This simplification will result in a more expeditious movement of traffic in many cases. Fewer ground radio aids will be required.

Any desirable configuration of departure tracks may be used when aircraft are equipped with pictorial displays. Parallel tracks are one possibility Parallel departure tracks will permit aircraft going in the same direction to climb to cruising altitude with lateral separation and with a minimum of delay. Today, aircraft are frequently delayed by waiting for longitudinal or vertical separation or by assignment of a climb-out on some course in a different direction than desired These advantages of parallel climb-out tracks are shown in Fig. 3.

Pilots using pictorial displays may fly angularly divergent tracks from any point and in the most suitable direction At present, angularly divergent tracks must be flown as radial courses from ground radio aids These aids frequently are not in the best location to provide the most suitable tracks over the ground No such limitation exists with the pictorial display For example, diverging departure tracks could be set up from a point one or two miles off the end of each runway to permit the establishment of lateral separation immediately after take-off, as shown in Fig 4

Present LF-range and ADF procedures require at least 45° divergence between courses for lateral separation. VOR and pictorial displays should permit the use of 15° course divergence for lateral separation, thereby permitting a much higher density of aircraft movements in a given airspace.

Approach Procedures.

For airports close to the VOR/DME facility, pictorial displays should permit, within certain weather limitations, instrument letdowns to any runway. Present aids generally permit an instrument approach to one runway only and necessitate the circling of aircraft underneath the overcast for landings on other runways. Although the pictorial display will not permit low approaches with the accuracy of the instrument landing system (ILS), letdowns to circling weather minima can likely be made from any direction of arrival. Aircraft would no longer be

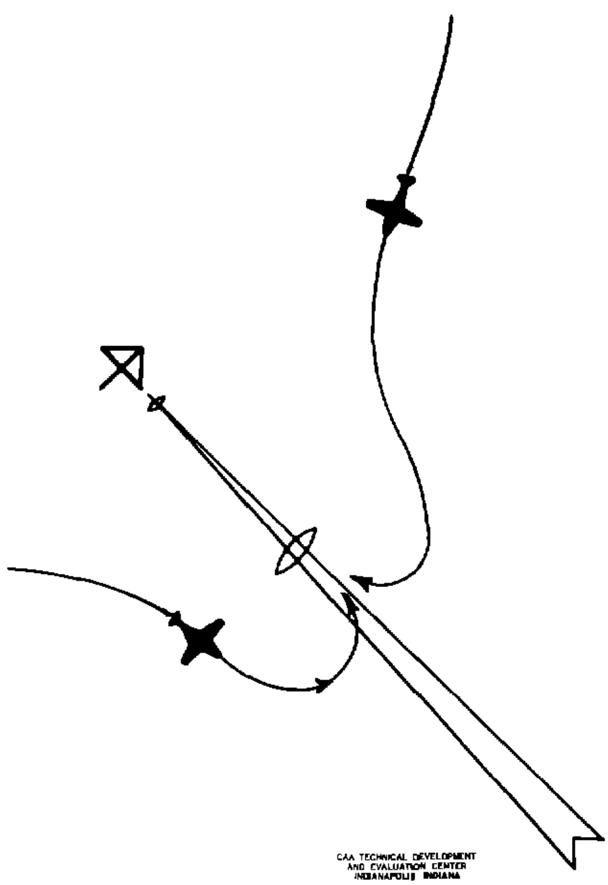

Fig. 6 Direct Transition Paths with Pictorial Computer

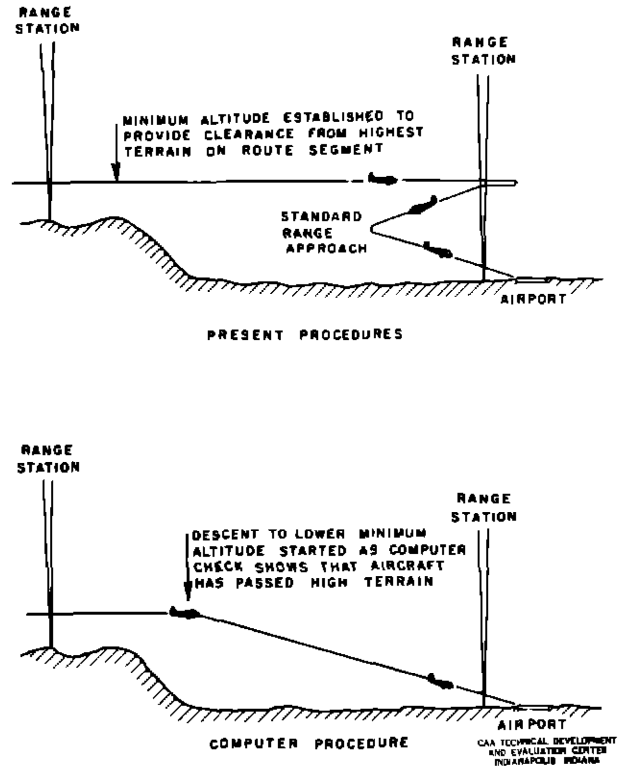

Fig. 7 Utilization of Lower Minimum Altitudes

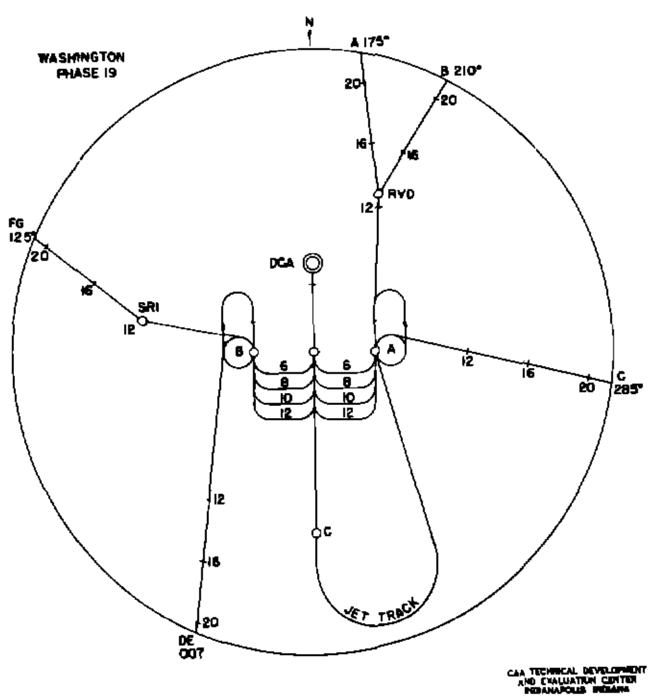

Fig. 8 Multitrack Approach System

required to proceed to a radio-range station or to an ILS before starting instrument approaches Instead, they could let down straight to the airport from any direction with a consequent earlier arrival time and speed-up of traffic See Figs 5a and 5b

When minimum weather conditions exist and the ILS must be used for approaches, pictorial displays will permit the most direct transition procedures from all en route airways to the ILS course Pilots will be able to line up inbound on the ILS course without the necessity of first checking over the outer marker, then proceeding out away from the airport, and finally making a procedure turn before starting inbound on approach This simplification in transition procedures, as shown in Fig. 6, should save many minutes of flying time and should speed the arrival of subsequent flights

The use of pictorial displays should permit lower initial-approach altitudes in many cases and should reduce the number of terrain-clearance fan markers required Under many weather conditions, lower initial-approach altitudes will permit aircraft to establish visual flight rules earlier and will expedite the arrival of subsequent flights, as illustrated in Fig. 7.

With the use of pictorial displays, it should be possible to define approach paths for jet aircraft away from other aircraft traffic patterns in order to permit accurate control of these flights with a minimum of confliction with conventional-aircraft traffic flow When present facilities are used, jet letdowns frequently must be made through the same airspace used by all other aircraft This leads to disruption of normal traffic flow as well as to delays of both jet and conventional traffic.

Pictorial displays will also permit use of multitrack approach systems wherein the pilot is assigned a specific track to follow from the holding fix to the final-approach course In this system, tracks are selected to provide separation from other aircraft on approach and to permit the maximum traffic flow This system, which has been tried by ATC simulation, promises improved over-all efficiency of approach timing, a decreased workload on ATC controllers, and a large reduction in air/ground communications As a result, safer and better control is provided with more consistent intervals between approaches over a long period of time. Fig. 8 illustrates the multitrack approach system with a path for letdowns of jet aircraft

One of the problems in air traffic control by radar is proper identification of aircraft Pictorial displays will permit more rapid identification of flights by giving the pilot continuous fix information The pilot, in turn, can advise the controller of his position at any time instead of waiting until he is over a ground radio aid

In radar-control procedures, flights are vectored by the controller from known fixes to the ILS course in order to provide the desired separation from other traffic. To obtain the flexibility necessary for proper spacing on final approach, pilots cannot stay on normal navigation courses during this transition procedure. Pictorial displays will provide continuous position information to the pilot during such maneuvers. This would be very desirable in the event of radio failure.

Holding Patterns.

Pictorial displays will permit better utilization of airspace for holding patterns. With present navigation aids, holding patterns are flown on a time basis, as shown in Fig 9. Transition procedures for entering the pattern and the possible effects of wind require large areas of buffer airspace for safety. With pictorial displays, holding patterns may be defined in miles rather than in time, and the desired pattern may be drawn on the pictorial-computer charts. This procedure is illustrated in Fig. 10. It will be simple for pilots to fly along the desired track shown on the chart. A reduction in buffer-airspace requirements should be possible for patterns close to OBD facilities.

In timed-approach procedures, pictorial displays should permit pilots to leave holding points at the desired time with better accuracy. Pictorial displays will also permit the holding of aircraft at any geographic point and in any desired pattern. Present LF-range and ADF equipment permits the holding of aircraft only at radio fixes defined by ground radio aids. The use of VOR and DME with conventional instrumentation is more flexible and permits holding between specified radial courses and mileage readings. The pictorial display will permit complete flexibility for holding at any desired point and in the most suitable pattern without necessitating the flying of radial courses from ground radio aids.

Holding of aircraft in adjacent patterns at the same altitude will also be possible. This will be particularly advantageous in bad weather conditions, such as during thunderstorm activity, or in icing conditions. Multiple holding at the same altitude will free other altitude levels for use by departing and en route airway traffic Possible patterns are illustrated in Fig. 11

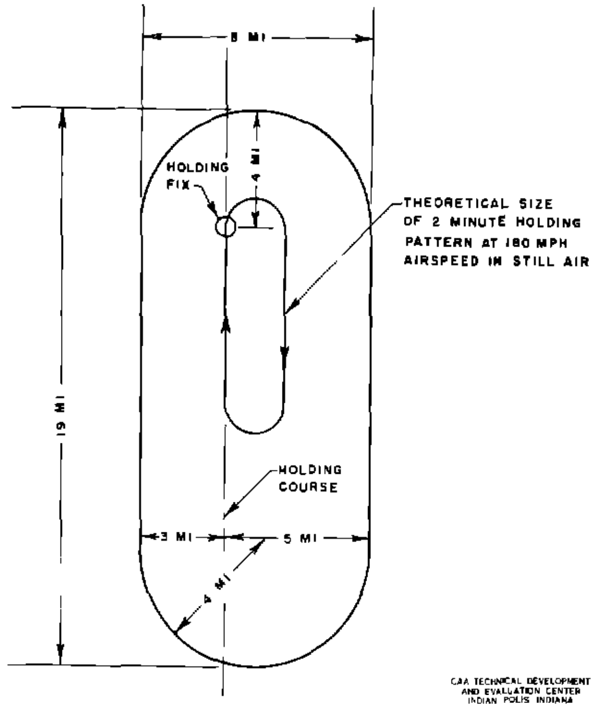

Fig 9 Dimensions of Holding-Airspace Reservation (Area 133 Sq Mi) for LF Navigation System

EN ROUTE AREA

General

In the en route traffic-control area, there are three basic types of air traffic-control problems These are

1. Overtake problems, that is, those problems associated with aircraft going in the same direction on the same route. These problems develop (a) when higher-speed aircraft are following slower aircraft at the same altitude and (b) when aircraft are climbing or descending through altitude levels occupied by other aircraft going in the same direction
2. Opposite-direction problems, that is, those problems associated with aircraft going in opposite directions on the same route. Normally, opposite-direction traffic is assigned alternate altitude levels for cruising Problems develop when aircraft desire to climb or to descend through altitude levels occupied by other aircraft going in the opposite direction
3. Crossing-course problems, that is, those problems associated with aircraft on different routes that are crossing or converging. Problems exist when aircraft are at the same cruising altitude or when either or both aircraft are changing altitude levels.

In en route air-traffic control, most control problems occur when aircraft desire to change altitude. Modern pressurized high-altitude aircraft frequently traverse more than 75 miles in climbing out to cruising altitude. Similarly, descent from cruising altitude may be started more than 100 miles from destination. These distances will be extended even further when jet aircraft enter the commercial air-carrier field. Present information indicates that jet transport aircraft may traverse more than 200 miles during climbs and descents. Changes of cruising altitude en route also are necessary at times because of adverse weather conditions terrain features, or operating considerations for best fuel economy.

When many aircraft are operating from a number of airports on numerous crisscross routes with each aircraft requiring up to 100 miles or more for climb to or descent from cruising altitude, a highly complex traffic-control problem results. If aircraft were equipped

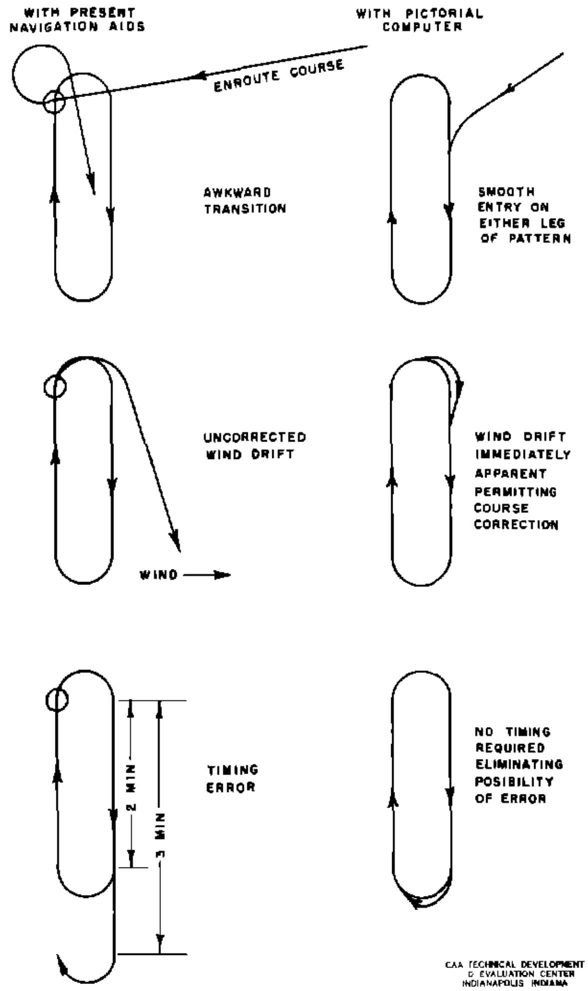

Fig. 10 Reasons for Large Dimensions of Holding-Airspace Reservations with Present Navigational Aids and Showing Improvements Possible with Pictorial Displays

with pictorial displays, these basic en route traffic-control problems could be materially simplified In many cases, lateral separation could be used to a greater extent. Solutions to problems would be simpler and more positive for the controller.

Overtake Problems.

On present LF-radio-range airways, aircraft climbing to cruising altitude or descending from altitude normally are provided altitude separation from other aircraft going in the same direction if adequate time separation (five minutes in some cases, ten minutes in others) does not exist. A procedure known as "laddering ' is widely used. A flight reports upon leaving each 1,000-foot level, and a subsequent flight climbs or descends to the vacated altitude. The greatest disadvantage with this procedure, aside from the heavy radio-communications load, is the necessity for all aircraft to limit their rate of climb or descent to that of the lowest-performance aircraft in a given series. In addition, if succeeding aircraft are going to higher cruising altitudes than preceding aircraft during a climb-out procedure, time separation must be used to provide at least five minutes time separation when altitude levels are crossed. This situation frequently occurs and results in lengthy delays to departing aircraft while they wait for time separation from preceding flights. Delays are particularly bad when a high-speed aircraft going to a high altitude wishes to depart following a slower-speed aircraft cruising at a lower altitude. A similar situation occurs for aircraft approaching the terminal area. In

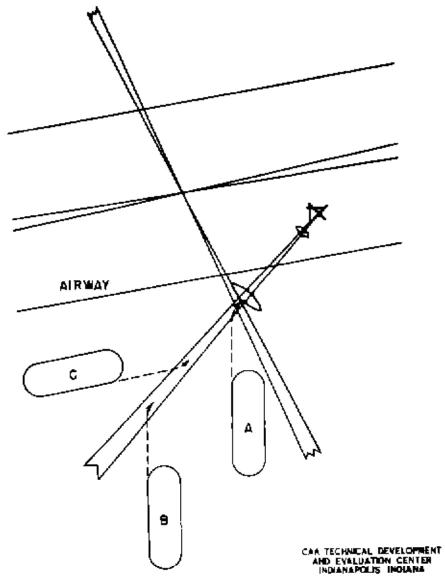

Fig. 11 Multiple Holding Patterns

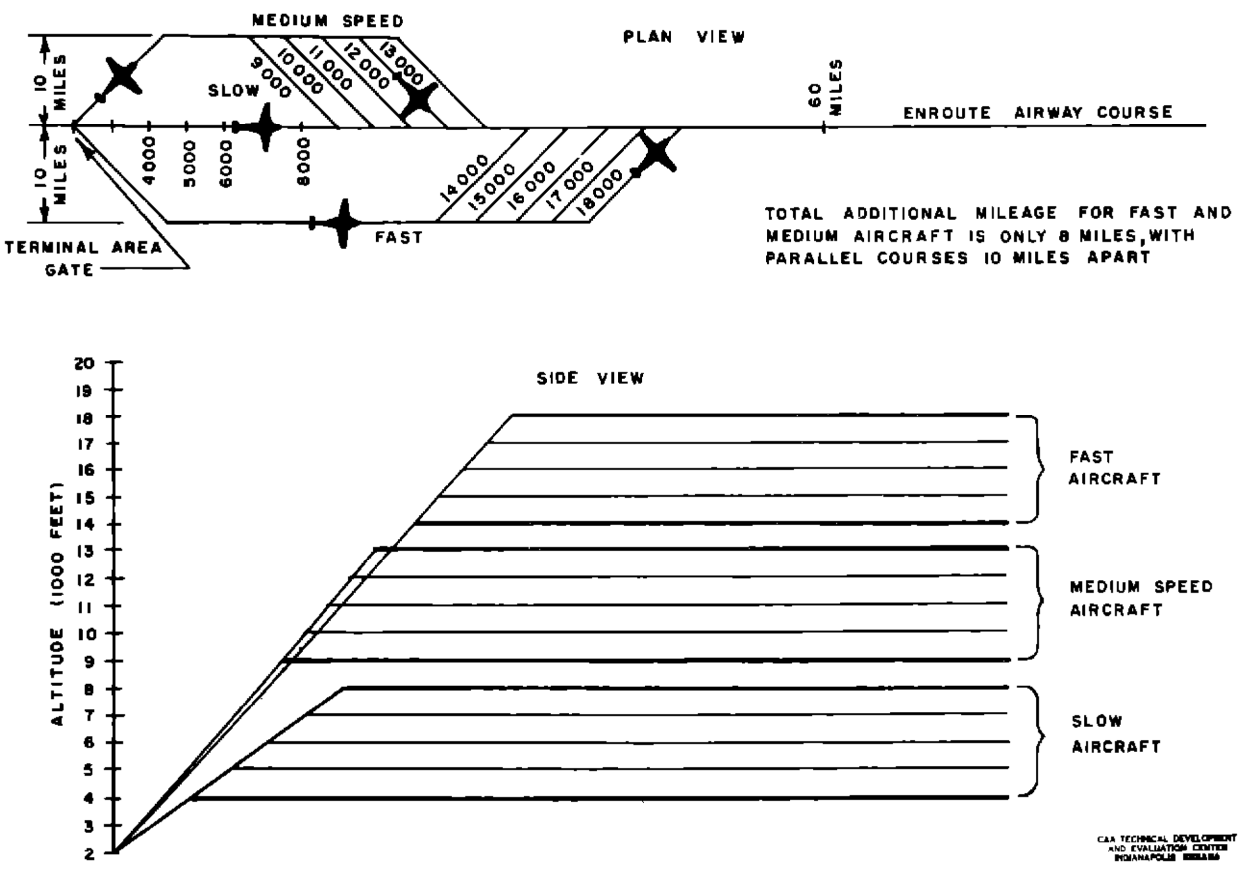

Fig. 12 Multiple Tracks for Different-Speed Aircraft Climbing to Cruising Altitude

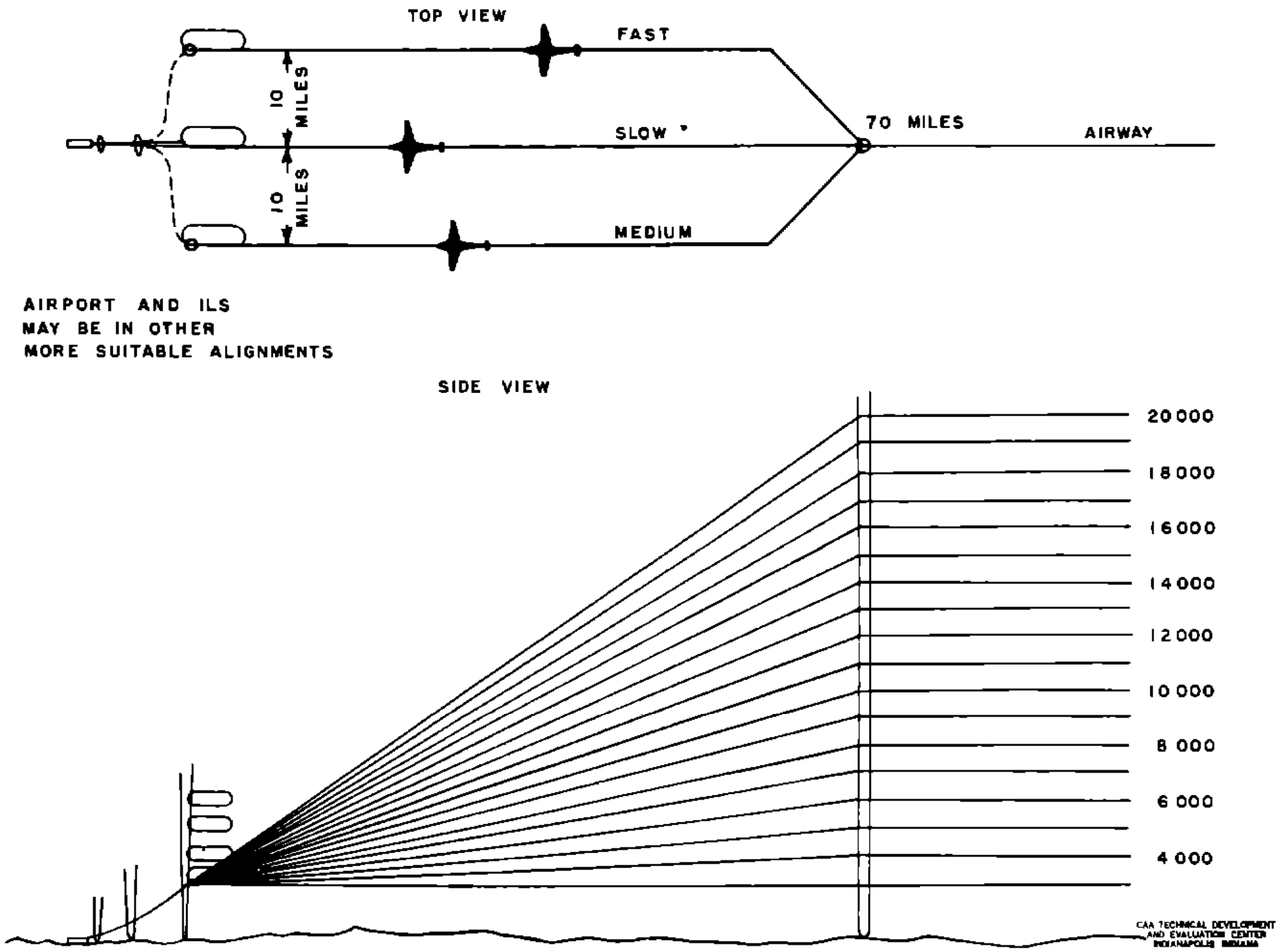

Fig 13 Multiple Descent Channels for Different-Speed Aircraft

many cases, an aircraft at a higher altitude does not have sufficient time separation to descend through the altitude of an aircraft following, with the result that the first aircraft is held at the higher altitude and is brought in after succeeding aircraft. If several aircraft are arriving in this situation, the top aircraft may be delayed 15 to 20 minutes, while aircraft which actually arrived later are cleared in first Frequently, it is the high-altitude, high-performance aircraft which is held up at the top of a series of inbound aircraft of lower performance With pictorial displays, it would be possible to delay the lower aircraft en route for a few minutes to permit a preceding aircraft to descend through the altitude level with standard time or longitudinal separation. A smoother, more equitable flow of traffic would result.

The pictorial display should permit the use of multilane climb and descent tracks to reduce the overtake type of problem. Figure 12 illustrates a possible multilane system for climbing aircraft of different speeds and rate-of-climb characteristics on separate tracks. After reaching cruising altitude, all aircraft can proceed on a common course with normal altitude or time separation. This system would prevent delays encountered by fast aircraft following slow aircraft. A similar arrangement of multiple lanes could be used to expedite the descent of aircraft of differing characteristics from cruising altitude to the terminal area. See Fig. 13 High-altitude, high-performance aircraft would no longer be penalized by slower aircraft operating at the lower altitudes. Similarly, when aircraft are en route at cruising altitude, pictorial displays would permit use of multiple lanes for change of altitudes or for a passing course around another aircraft at the same altitude.

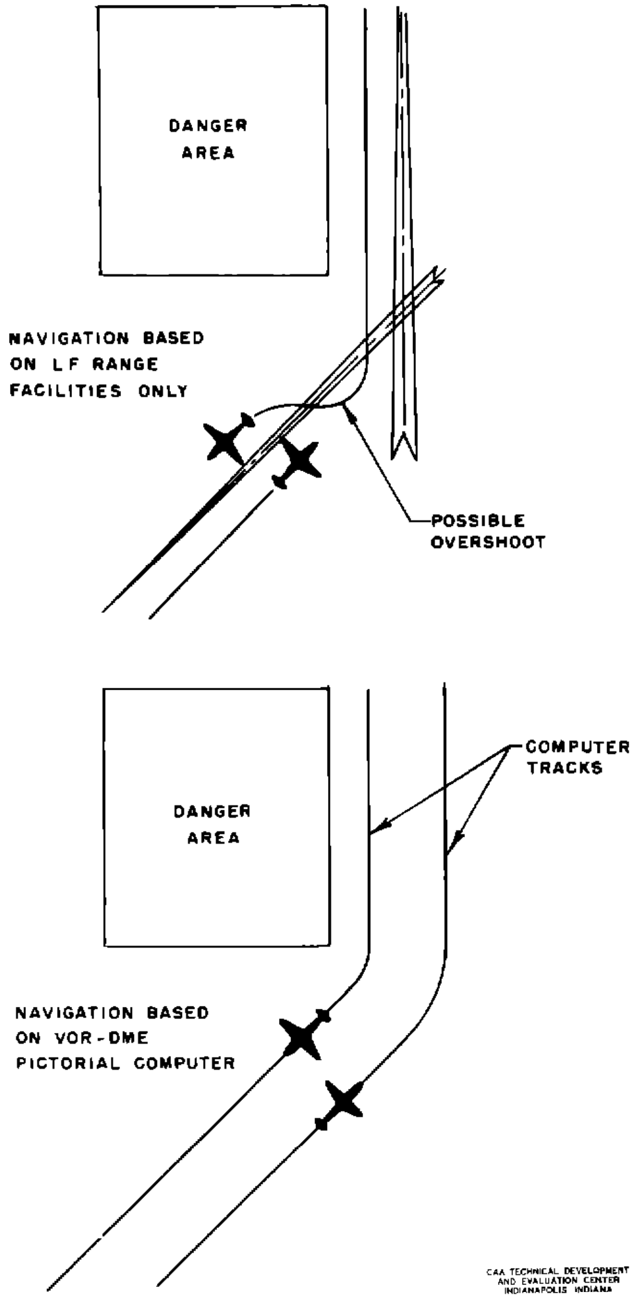

Fig. 14 Use of Right-Side Separation on Indirect Airways

Pictorial displays will also permit use of a specific longitudinal-distance separation between aircraft en route in the same direction. Aircraft could be instructed to maintain distance separation rather than time separation, as is done at present. It is believed that present separation standards between aircraft traveling in the same direction at the same altitude could be greatly reduced For example, a separation of 20 miles between aircraft en route may be feasible The preceding aircraft could report position to a succeeding aircraft every 40 to 50 miles to permit the second aircraft to check that the separation is being maintained This mileage separation could be used between aircraft traveling at a constant cruising altitude or between aircraft changing altitude.

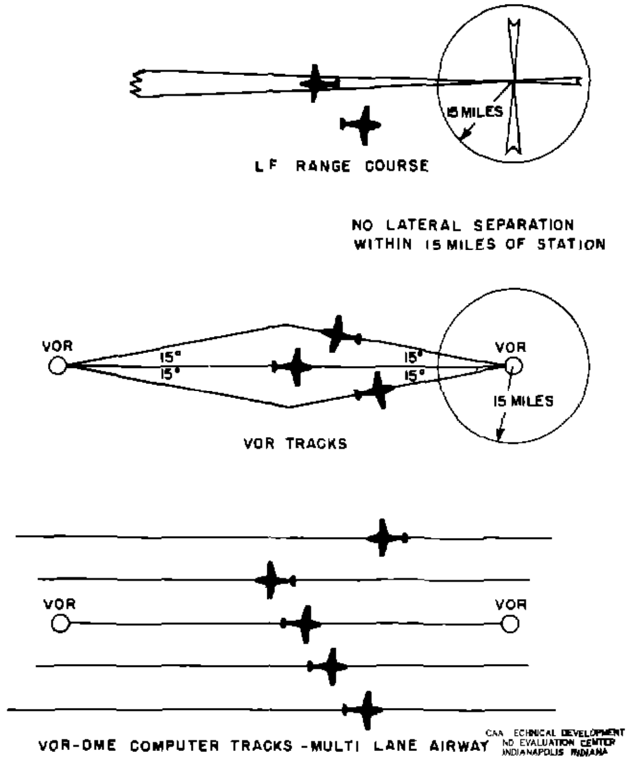

Fig. 15 Comparison of Facilities
For Use of Right-Side Separation

Opposite-Direction Problems

With the present airway system, aircraft frequently change altitude through levels occupied by opposite-direction traffic In some parts of the country, right-side lateral separation is used on LF airways to provide the necessary separation. The aircraft changing altitude is instructed to climb or descend well to the right of the on-course signal, with the other aircraft expected to be on-course or to the right of the course However, in many areas this procedure cannot be used because of poor course structure of the radio ranges, because of adjacent airways, or because of dog-leg airway courses See Fig. 14 In all areas, this right-side separation cannot be used within 15 miles of the range station because of narrow course width. A similar restriction exists with the 15° off-course alternate airway in the Victor airway system. These cannot be used for lateral separation within 15 miles of a station. Thus there are 30-mile gaps at stations on en route VOR or LF airways where lateral separation may not be used. See Fig. 15

To provide adequate time separation between opposite-direction traffic when right-side lateral separation cannot be used, the aircraft which is changing altitude must reach 1,000 feet above or below the other aircraft at least ten minutes prior to the time of passing. This amounts to 100 miles or more separation for two 300-mph aircraft approaching each other Similarly, unless both aircraft have reported passing the same fix, altitude separation must be maintained for ten minutes after the estimated time of passing before the altitude change can take place

With any density of opposite-direction traffic, it is virtually impossible to permit aircraft to climb or to descend on the same course. As a result, flights frequently are shuttled out on courses in other directions until they have reached cruising altitude or an altitude above the opposite-direction traffic before they may proceed on course. This is a time-consuming process and results in many delays To alleviate this problem in heavy-traffic areas, it has been necessary to install many additional ground radio aids to provide one-way airways. This is expensive from the standpoint of the additional ground equipment required, and in many areas it is extremely difficult to obtain radio-frequency assignments for the new facilities If aircraft were equipped with pictorial displays, it would be possible to have one-way airways on practically all routes without duplication of ground radio aids This would eliminate the opposite-direction type of problem from the control standpoint. It would also reduce many air-traffic delays occurring in the present system

Crossing-Course Problems

Solution of the third type of problem involving aircraft on crossing or converging courses should be materially simplified when aircraft are equipped with pictorial displays If aircraft on crossing courses are at the same altitude level with inadequate time separation and if another adjacent altitude level is not available for assignment, the second aircraft can be held at a specified minimum distance short of the intersecting courses until the first aircraft has reported passing the intersection of the courses This procedure is usable today only when there happens to be a radio fix available The pictorial equipment would permit holding at any place en route

Solution of crossing-course problems where aircraft are changing altitude would also be simplified Pilots could be assigned to reach a specific altitude prior to the point of course intersection with definite assurance that the flight would cross the intersection at the assigned altitude With present navigational aids and instrumentation, continuous fix information is not available, and as a result of wind or other factors, a pilot may reach the intersection earlier than anticipated with inadequate altitude separation from another aircraft. To guard against such possibilities, controllers must add additional restrictions on air-traffic clearances This, in turn, complicates the job of air-traffic control.

Miscellaneous Advantages.

In some areas, pictorial displays would permit use of lower minimum en route IFR altitudes This condition would be particularly advantageous in high-terrain areas where radio fixes are limited. Dependent on radio coverage, the equipment would also permit pilots to fly over the lowest terrain and to follow valleys in mountainous areas.

Pictorial displays should permit airways to be set up to by-pass congested areas of cities This is in line with recent recommendations for increased safety and reduction of noise nuisance

Pictorial displays should also permit the holding en route of aircraft at any location to establish separation from other aircraft. At present, any holding en route must normally be accomplished at radio fixes. Because of the long distances between fixes in certain areas, it is not always possible to delay or to hold aircraft to improve traffic flow. It is frequently desirable to delay an aircraft en route for a few minutes in order to establish adequate longitudinal separation from another aircraft at the same altitude and on the same course, on a crossing course, or on a converging course. When such an instance occurs at present, the controller must assign one of the aircraft a different altitude if no radio fix is available for holding one of the aircraft. Adjacent altitude levels may be occupied by other traffic with a resultant complication of control problems With the pictorial display permitting holding at any place, it would be possible for the controller to hold one of the aircraft a few minutes until adequate separation is established

More accurate navigation on direct courses between any desired points would be available with pictorial displays. This would also permit operation to and from many off-airway airports which are not served by adequate navigational aids at this time. This feature should be of particular importance to feeder-line operations, corporation-aircraft operations, and some military applications Pilots on cross-country direct-route flights would know their position with respect to controlled, heavily traveled airways and would be able to cross or to join those airways at the assigned altitude and place with greater accuracy and safety. Pilots would be able to estimate their time of arrival over fixes or other points with greater accuracy than heretofore.

The pictorial display permits determination of ground speed on any track. With normal DME instrumentation, ground speed can be determined for flight on radial courses to or from the station but cannot be determined readily for flight on non-radial courses.

Pictorial displays should permit several aircraft to use the same cruising altitude on parallel tracks en route when thunderstorms, icing, or other adverse weather conditions make it necessary.

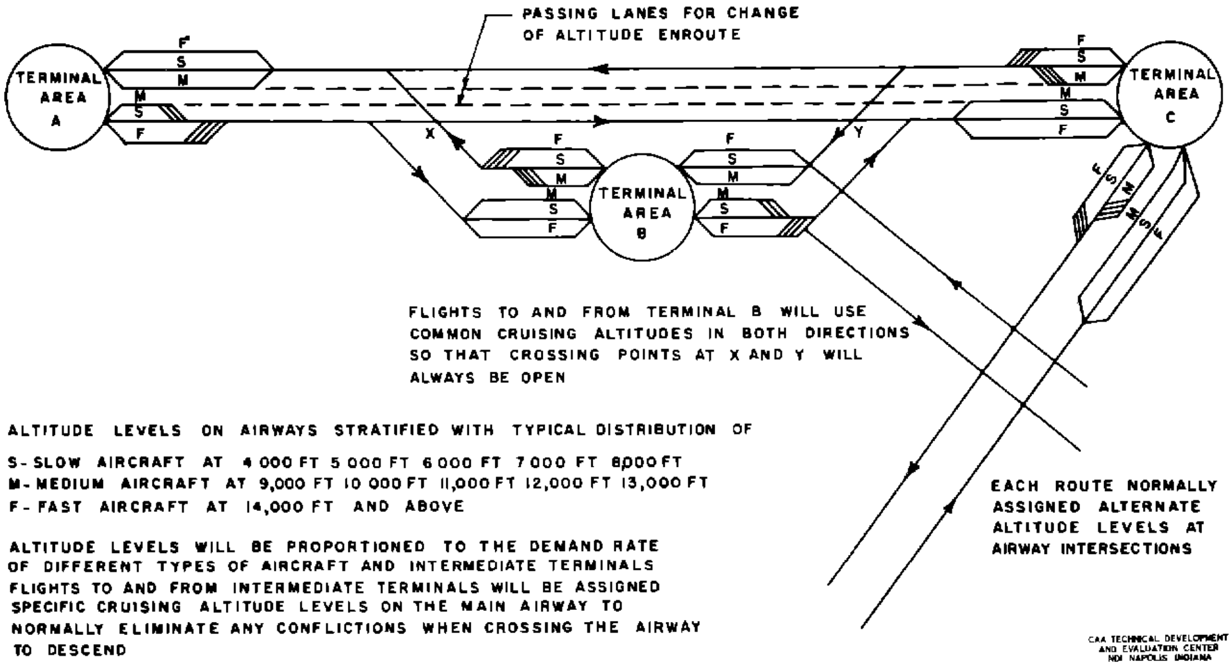

Fig 16 Future Airway for High-Density Traffic

Future Airway Planning.

A typical airway of the future might be envisioned as shown in Fig. 16. Terminal-area radar would vector aircraft to the appropriate departure gate or to appropriate departure tracks based on the use of pictorial-display navigation. The flight would then climb on a track assigned for aircraft of those speed and rate-of-climb characteristics until reaching cruising altitude. Upon reaching cruising altitude, the aircraft would proceed on the main course Altitude levels en route would be stratified with slow-speed aircraft at the low levels, medium-speed aircraft at the intermediate levels, and high-speed aircraft at the high-altitude levels There would be separate one-way airways for each direction to eliminate the opposite-direction problem. Normally, there would be no overtake problems at cruising altitude, because all aircraft at that level would have similar speed characteristics A passing lane parallel to the main course would be available if needed, however

Specific altitude levels could be assigned for aircraft on crossing airways. With continuous fix information available from pictorial displays, however, it is not believed that this would be necessary except where both crossing airways carried heavy traffic Altitude levels would be assigned for feeding aircraft off the main routes to the major intermediate terminals, as illustrated. Aircraft en route to the intermediate terminals would usually be assigned a proper cruising altitude for that terminal to minimize changes of altitude in feeding from the main-trunk airway.

Approaching the destination, a flight would be assigned the appropriate descent channel for that type aircraft The aircraft would be laddered down to a holding path at the terminal-control gate where radar vector-control procedures would take over. In lieu of radar, appropriate tracks based on use of the pictorial display could be assigned.

Ground navigational aids for such an airway could be located on hilltops or other suitable locations to provide maximum radio coverage. A minimum number of ground aids would be required Aircraft would require pictorial displays or course-line computers in conjunction with the normal VOR and DME receivers in order to fly the parallel tracks desired. Such an airway system would simplify the en route control problem and would permit a higher density of traffic flow with less delays than are experienced now.

ERROR FACTORS

A study of the operational advantages of pictorial displays would not be complete without a review of error factors Inherent in the use of all navigation systems are possible errors resulting from equipment inaccuracies and from human factors. From an air-traffic-control standpoint, these errors are important in establishing adjacent routes, or tracks, with adequate lateral separation to permit simultaneous movement of aircraft The number of discrete routes which can be provided in any given airspace is a direct function of the accuracy with which desired tracks may be followed Obviously, in a given channel of airspace, if navigation equipment and methods permit a course accuracy of ± 5 miles in one system as compared to ± 20 miles in a less accurate system, approximately four times as many aircraft can be accommodated with the more accurate system

LF Range

In the four-course low-frequency-radio-range system, the accuracy with which a desired track can be flown is dependent upon the width of the range courses and upon the ability of the pilot to aurally differentiate tone signals The courses generated by the ground equipment in this system are nominally 3° wide. However, in mountainous terrain the effective width of these courses at some distance from the station may be 8° to 10° due to multiple-course structure In a few cases, multiple courses 22° wide have been observed. Thus, the theoretical 3-mile (in this report all mileage figures are statute miles) width of the 3° course at a distance of 57 miles from the station may increase to an effective course width of 8 to 10 miles with multiples. In addition, static and other interference at the low and medium frequencies frequently make these signals unreadable for varying periods of time

A pilot flying along LF-range courses is expected to fly to the right of the centerline of the airway by aural monitoring Airways are designated as ten miles wide Theoretically, then, the allowable navigation error is one half the width of the airway or ± 2 1/2 miles at any distance from a station Radar observations indicate that aircraft are frequently outside this relatively narrow tolerance.

In many areas, right-side separation is used to effect a change of altitude wherein the pilot of one aircraft (normally outbound from a range station) is instructed to remain well to the right of the course to provide lateral separation from traffic flying on the airway in the opposite direction Since an aircraft inbound to the station is permitted to fly on-course (to the right of the centerline of the airway) under these procedures, the outbound pilot will normally proceed well off-course to insure that he is well to the right of the on-course signal Under such conditions, aircraft frequently are more than five miles from the centerline of the airway This is an important consideration in determining the spacing required between adjacent airways

ADF

Most of the aircraft flying IFR today are also equipped with automatic direction finders which permit the pilot to obtain relative bearings and to home on ground radio stations Although this equipment was originally installed as supplemental navigation equipment, it is used quite generally today as a primary source of navigation information. The pilot tunes in the L/MF station ahead, identifies the station aurally, and switches to ADF After a few minutes of flight to determine wind drift, the aircraft is tracked into the station. In many cases, however, the ADF needle will swing several degrees Nearby electrical disturbances may cause wide deviation of the needle, and distant stations on the same frequency may cause erratic readings. The resultant flight path may or may not be within the five-mile space between the centerline and the right-hand edge of an airway In many cases, large deviations from the airway are possible

To our knowledge, no adequate survey has ever been made of the actual navigation errors in the present L/MF radio range and ADF procedures so widely used today Such a survey should include not only potential equipment inaccuracies but also the amount of deviation in actual day-to-day use of these aids

VOR/DME.

A number of tests of the accuracy of the VHF omnirange have been conducted In 1948, RTCA Special Committee 45 recommended that 15° separation be used between adjacent courses for lateral separation when aircraft were more than 15 miles from the VOR This recommendation was based on the assumption that VOR courses could be flown with an accuracy of ± 5° with an additional buffer space of 2 1/2° being provided.

Under sponsorship of the Air Navigation Development Board, the Airborne Instruments Laboratory conducted a survey of VOR errors at three locations Patuxent River, Maryland, Phillipsburg, Pennsylvania, and Ogden, Utah, between May 1949 and September 1950 Results of these comprehensive error measurements are included in AIL Report No 540-1 of October, 1950

Recently, at the request of RTCA Special Committee 62, the Air Transport Association has sponsored a program of in-flight checks of VOR by air-carrier pilots. When over known fixes, pilots check VOR receivers against published radials. Results of over 5500 checks of this type indicate that observed errors follow a standard deviation curve with 99 7 per cent of the errors being within ± 5 63° of the published bearing and 95 per cent of the errors within ± 3.75° of the published bearing

Limited tests of the DME-system accuracies have been made AIL Report No 540-1 includes results of some measurements of the DME system

It is believed that in the near future accuracy tolerances of ± 5° for VOR and ± 5 per cent or 1 1/2 miles, whichever is greater, for DME will include over 99 per cent of the possible errors.

In actual practice, it is believed that the VOR/DME system will provide much more precise navigation information than is possible with the older types of navigation aids such as LF range or ADF. The absence of atmospheric static on very-high-frequency (VHF) and ultra-high-frequency (UHF) channels and the gain in readability of signals alone will contribute greatly to improved navigation accuracy in day-to-day operations

Error Formula.

As indicated earlier in this report, if aircraft were equipped with pictorial navigation displays or with course-line computers, it would be possible to use parallel airways or other configurations of flight tracks which are not radial tracks from an OBD facility. For ATC planning purposes it is necessary to know the minimum spacing required to insure lateral separation between adjacent tracks

Where navigation is based on the use of radial tracks from VOR stations, present practice requires a minimum of 15° between adjacent VOR radials for lateral separation. Adequate lateral separation is assumed to exist between aircraft on courses separated by 15° if the aircraft are more than 15 miles from the station For aircraft less than 15 miles from the station, vertical or horizontal (time) separation standards must be applied. Figure 17 illustrates the locus of possible errors and the buffer-space requirements for this condition.

With the introduction of DME as a primary navigational aid in conjunction with VOR, the locus of possible errors for any position becomes a sector of an annulus Figure 18 illustrates the area of possible error for an aircraft at an assumed position P The two radial sides of this sector are determined by the possible VOR errors The other two sides, which are arcs of circles centered at the OBD site, are determined by the possible DME errors Figure 19 illustrates how this area of possible error varies for a flight track across a pictorial-display chart.

In addition to the possible errors contributed by equipment such as transmitters, receivers, and indicators in the cockpit, a reading error must be considered. Experience to date with present pictorial navigation displays indicates that pilots can fly a course within 1/8 inch of a track drawn on the chart without excessive attention to the display. With optimum design of position indicators, it is believed that the reading error will not exceed 1/10 inch This 1/10-inch possible reading error is equivalent to a deviation from the desired course of 0.4 mile when using a 1 250,000 chart scale or of 1 6 mile when using a chart scale of 1 1,000,000.

In establishing adjacent tracks for lateral separation of aircraft, it is also necessary to provide a buffer space between areas of possible error. The actual amount of buffer airspace required is a matter for administrative decision It appears that one to three miles should be adequate for terminal-area chart scales of 1 250,000, with perhaps an increase to three to five miles for en route charts at a scale of 1 1,000,000 A compromise figure of three miles may be entirely adequate for all purposes One standard value would facilitate designation of suitable common tracks for both en route and terminal-area charts. For example, overflights may be using en route charts and aircraft landing or departing may be using terminal-area charts in the same airspace area.

Since we are interested in safe lateral separation between two aircraft, each of which will have a possible VOR/DME error plus a reading error, the total errors that must be considered are

2 (VOR/DME equipment errors) + 2 (reading errors) + buffer space = minimum spacing required between adjacent tracks (1)

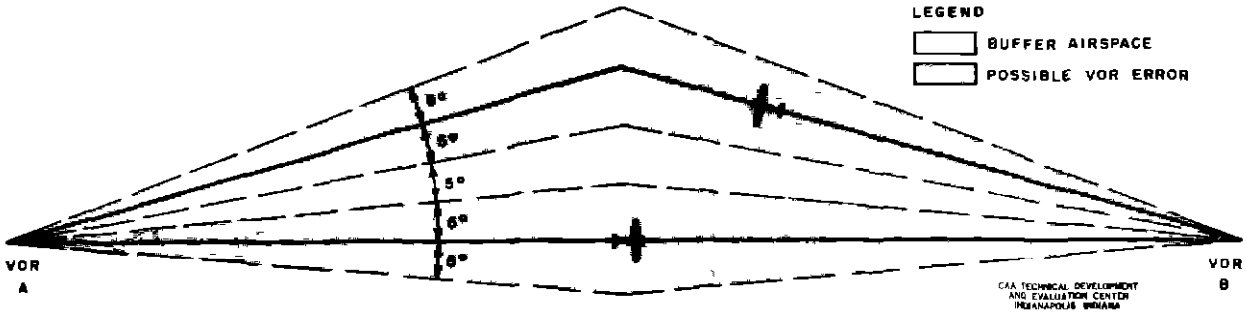

Fig 17 Locus of Possible Errors, VOR Only

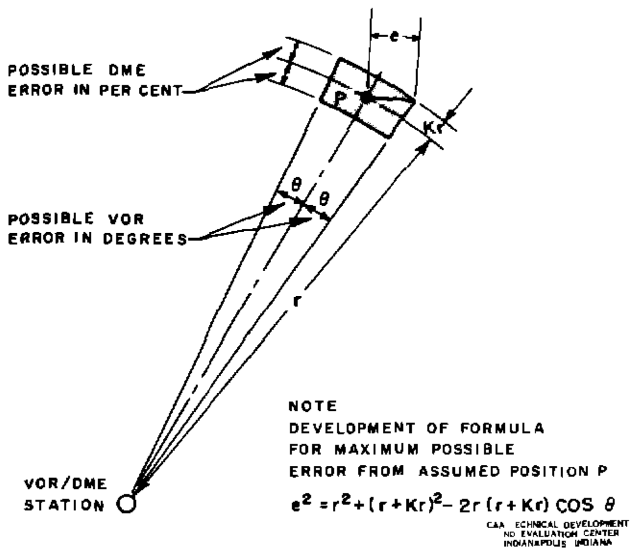

Fig 18 Locus of Possible Errors, VOR/DME Fix Development of Formula for Maximum Possible Error From Assumed Position P

As illustrated in Fig 19, the possible VOR/DME equipment errors increase as the distance from the OBD station increases It is possible to develop a formula to indicate the minimum spacing required between tracks in terms of the distance from the facility In reference to Fig 20, the length e from the assumed position P to either outside corner of the error area determines the maximum possible deviation of position resulting from VOR/DME equipment errors The length e may be determined from the general trigonometric formula for triangles

$$e^2 = r^2 + (r + Kr)^2 - 2r\,(r + Kr)\cos\theta \qquad (2)$$

where

e = side of the trangle opposite the error angle,

r = distance of the assumed position P from the OBD station,

K = possible DME error, in per cent,

θ = possible VOR error, in degrees

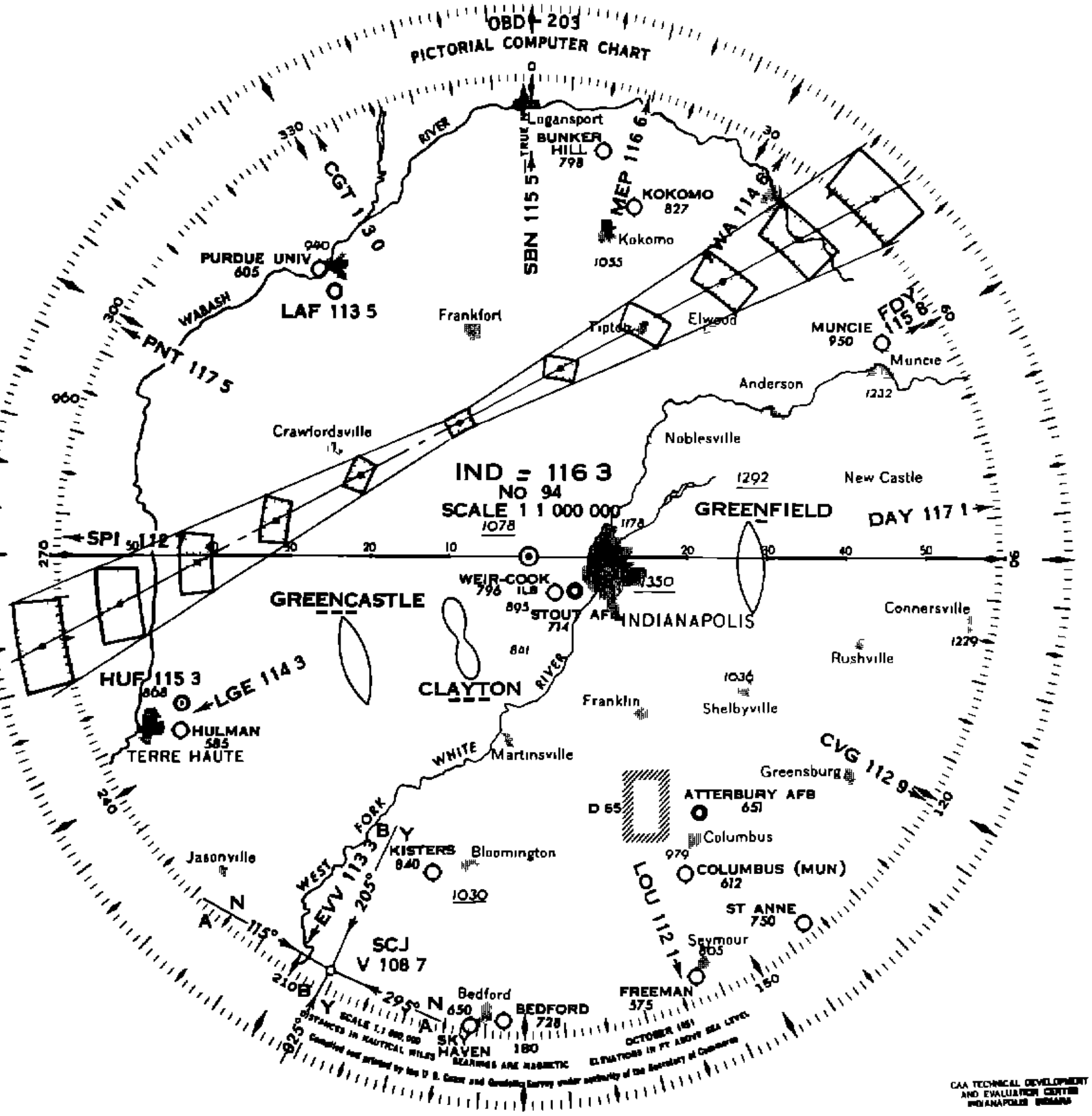

Fig 19 Variation in Area of Possible Error for One Flight Track

If the maximum possible VOR errors are ± 5° and if the maximum possible DME errors are ± 5 per cent, substitution of these values in Equation (2) results in a value of e = 0 1025r For practical purposes, this is a value of e = 0 1r For a given pictorial-display chart, the value of e at the edge of the chart will be a maximum To determine the spacing required between two tracks at the edge of the chart, this value of e may be substituted for the possible VOR/DME equipment errors in Equation (1) Thus,

$$2\,(0\ 1r) + 2\,(\text{reading error}) + \text{buffer} = \text{spacing between tracks} \tag{3}$$

An application of this formula to a specific case follows A typical ten-inch-diameter pictorial-display chart at 1 1,000,000 scale provides a usable radius of approximately 70 statute miles If there are also assumed a reading error of 1/10 inch or 1 6 miles and a buffer space of three miles and if the values are substituted in Equation (3), the spacing required between adjacent tracks at the edge of the chart is

$$2\,(0\ 1 \times 70) + 2\,(1\ 6) + 3 = 20\ 2 \text{ miles} \tag{4}$$

Any two parallel tracks drawn across this chart and spaced by 20 2 miles will provide at least a 3-mile buffer space between aircraft This is true regardless of the orientation of the tracks with respect to the OBD facility at the center of the chart. See Fig. 21

If it is desired that the tracks converge toward a terminal instead of remaining parallel, the spacing required at any distance from the OBD station may be obtained by substituting for r in Equation (3). In the foregoing example, the spacing required at 30 miles for the same chart is

$$2\,(0\ 1 \times 30) + 2\,(1\ 6) + 3 = 12.2 \text{ miles} \tag{5}$$

For distances less than 30 miles from the OBD facility, the possible DME error of ± 1 1/2 miles is greater than 5 per cent of the distance The basic Equation (2) to determine the value of e then results in a quadratic. By examination, the value of e varies from a minimum of 1 5 miles at the OBD station to a maximum of 3 miles at points 30 miles from the station. Table I indicates the value of e at various distances from an OBD facility between 0 and 30 miles

TABLE I

MAXIMUM POSSIBLE ERROR IN POSITION FROM VOR/DME EQUIPMENT ERRORS

Distance from OBD Station (miles)	Errors (miles)
0	1 5
1	1 5
2	1 5
3	1 5
4	1.6
5	1 6
10	1 8
15	2 0
20	2 3
25	2 7
30	3 0

Figure 22 illustrates, on a 1 1,000,000-scale chart, the minimum spacing required between tracks that are not parallel Conditions assumed are

Total possible VOR errors = ± 5°

Total possible DME errors = ± 5 per cent or 1 1/2 miles, whichever is greater

Reading error, 1/10 inch = 1.6 miles

Buffer space = 3 miles

Table II gives the minimum spacing between tracks at various distances from an OBD station for chart scales of 1 250,000, 1 1,000,000 and 1 2,000,000.

To make best use of the available airspace for lateral separation, there is an obvious advantage in using the largest-scale charts possible since the reading error of 1/10 inch results in the smallest error. On the other hand, a pilot flying en route would prefer to cover the largest possible area on one chart and to change charts only as it becomes necessary to switch to a new station for reception

When compared with the use of a VOR system using symbolic instrumentation such as cross-pointer indicators and omnibearing selectors, the use of a VOR/DME system with pictorial displays will apparently require wider separation between adjacent tracks because of

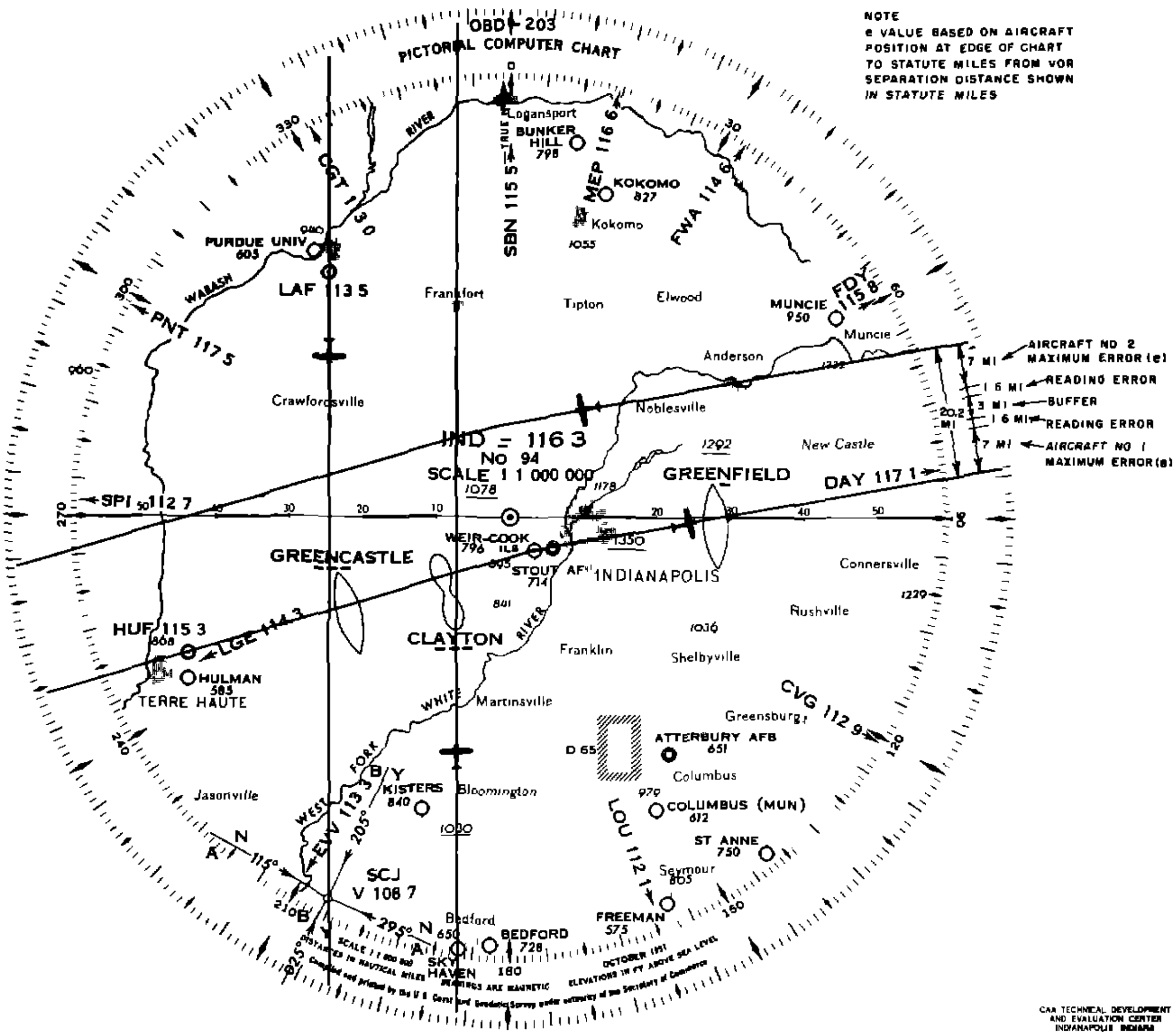

Fig 20 Minimum Spacing Between Parallel Tracks

the possibility of greater reading errors in the instrumentation. For example, with pictorial displays using two OBD stations spaced 100 miles apart, two or more parallel airways could be set up with a spacing, based on the previous error factors (Table II), of 16.2 miles between airway centerlines If conventional instrumentation (OBS and cross pointer) is used, aircraft are restricted to flying radial courses. The spacing required between airways centerlines could be reduced to 11.7 miles, based upon ± 5° VOR error with a three-mile buffer space at 50 miles from the station. The use of this spacing presupposes that the pilots change to the next VOR station midway between stations and assumes that there is no reading error with conventional instrumentation Two parallel airways would require twice as many VOR ground stations but no DME equipment.

For high-altitude operations en route with stations spaced 300 miles apart and with a buffer space of five miles, the use of OBD facilities with pictorial displays would require , spacing of 41.4 miles between parallel airways. When only VOR is used with conventional instrumentation, parallel airways could be spaced 31 2 miles apart, again if there were a

SPACING REQUIRED BETWEEN ADJACENT TRACKS FOR LATERAL SEPARATION*

Distance from OBD station (miles)	Spacing Required Between Tracks: 1 250,000 map scale (miles)	1 1,000,000 map scale (miles)	1 2,000,000 map scale (miles)
0	6 8	9.2	12 4
5	7.0	9 4	12 6
10	7 4	9 8	13 0
15	7 8	10 2	13 4
20	8 4	10 8	14 0
25		11 6	14 8
30		12 2	15 4
40		14 2	17 4
50		16 2	19.4
60		18 2	21 4
70		20 2	23 4
80			25 4
100			29 4
120			33 4
140			37 4

*Each aircraft may have possible errors of VOR, ± 5°, DME, ± 5 per cent or 1 1/2 miles, whichever is greater, reading error, 1/10 inch. A buffer space of 3 miles is included

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five-mile buffer at the midway point of frequency change and if there were no reading error with conventional instrumentation. To achieve this closer spacing, two parallel airways would require twice as many VOR ground stations, three parallel airways, three times as many VOR ground stations, and so on. Whether it is valid to assume no reading error with conventional instrumentation is also doubtful

It can thus be seen that many factors must be considered in the development of an ultimate system of airways and routes. Density of traffic, number of discrete routes required, airspace available, and economic factors must all be brought into proper balance with equipment requirements and with error factors Tables I and II indicate the desirability for continued work to reduce the possible system errors in the OBD system

CONCLUSIONS

Preliminary studies indicate that use of pictorial navigation displays with VOR/DME facilities would

1. Permit navigation in all available airspace with a minimum number of ground radio aids to navigation.
2. Reduce navigation workload (compared to that incurred in the use of conventional symbolic instrumentation) of flight crews in flying complex patterns
3. Contribute to greater safety by elimination of some possible sources of human error.
4. Reduce lost-aircraft incidents through continuous presentation of position information in a direct, simple form
5. Permit flight along any desired course without requiring normal flight paths to be along radial courses from ground radio aids
6. Permit savings in flight time by use of the most direct courses
7. Permit navigation, within certain error tolerances, to any airport within radio line-of-sight coverage of VOR/DME facilities.
8. Permit greater use of lateral separation with more expeditious movement of traffic in some air traffic control areas.

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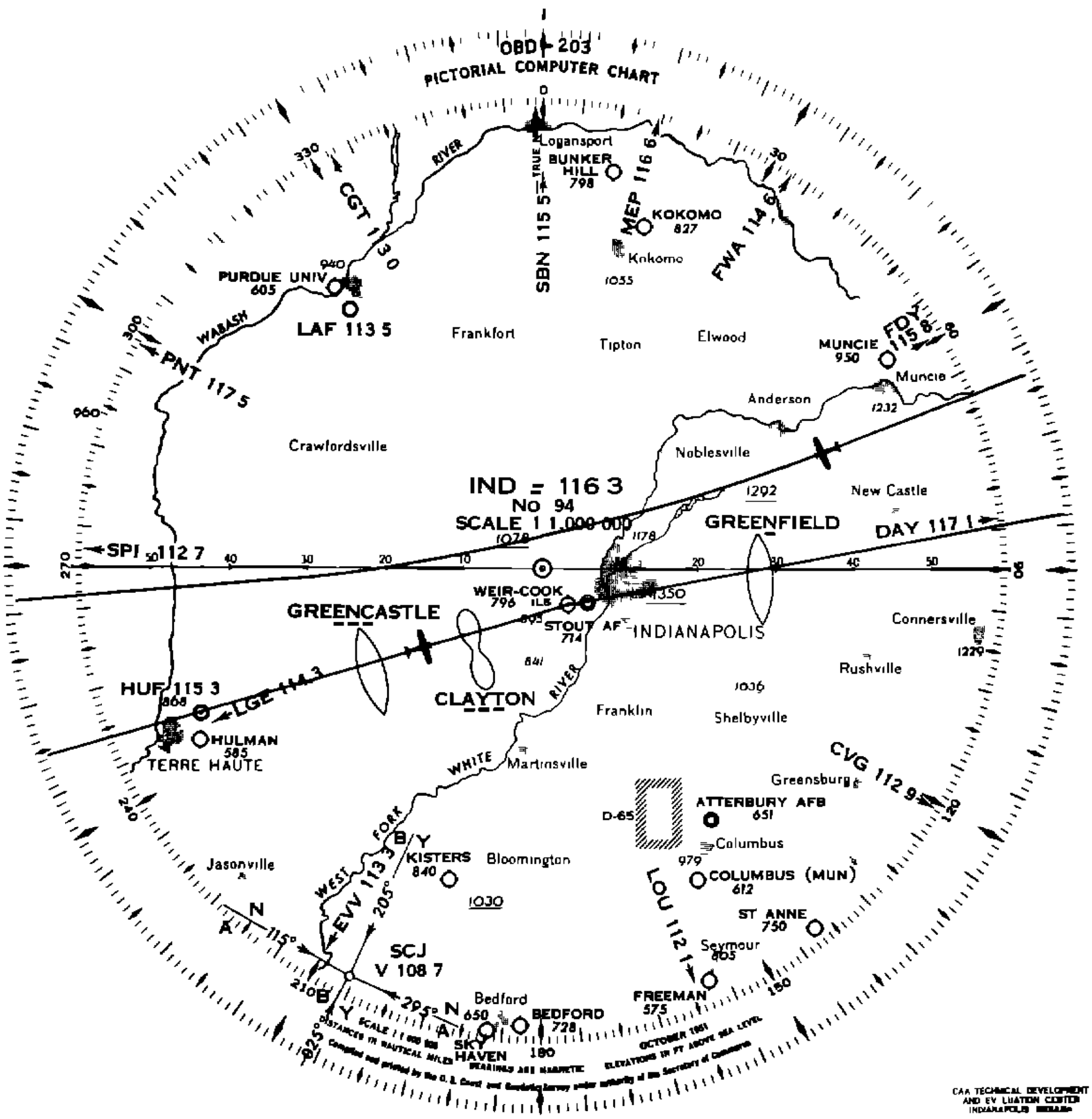

Fig 21 Minimum Spacing Between Nonparallel Tracks

Possible improvements to patterns and procedures could include the following

1 Departure Area.

A. Use of angular divergence tracks, parallel tracks, curved paths, or other desired patterns to provide lateral separation between flights

2. En Route Area

A. Multiple-track operation with lateral separation for aircraft climbing to cruising altitude

B Multiple-track airways at the same altitude level when traffic or weather conditions require.

C. Use of lower altitudes after clearing high terrain, thus eliminating need for terrain-clearance markers and permitting lower initial-approach altitudes

D. Continuous fix information available for air traffic control purposes, with more accurate estimates over fixes ahead

E. Holding at any point when traffic or emergency conditions require

3. Terminal-Arrival Area
   A. Better utilization of airspace by defining the physical size of holding patterns in spatial dimensions rather than in time, thus reducing the size of buffer airspace requirements.
   B. The holding of aircraft in the most appropriate geographical areas rather than holding at specific points served by ground radio aids.
   C. More accurate timing by pilots when leaving approach fixes in timed-approach procedures.
   D. Approach guidance, within certain weather limitations, to any runway for airports located close to OBD facilities.
   E. Shorter transition procedures to ILS courses with a reduction of delays inherent in present navigation systems where specific radio courses must be followed and where approach paths are thereby lengthened.
   F. Special approach tracks and corridors for jet aircraft to provide minimum confliction with conventional-aircraft patterns without requiring additional radio aids

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