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EVALUATION OF PROPOSED AIR TRAFFIC CONTROL PROCEDURES IN THE WASHINGTON TERMINAL AREA BY SIMULATION TECHNICS

FOR LIMITED DISTRIBUTION

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SUMMARY

This report describes the evaluation of a number of proposed traffic control procedures for the Washington National Airport terminal area by making comparative operational tests on each proposal, using traffic simulation methods. The equipment used was modified from the original Navascreen pictorial display, and the human element, both in the air and in the control tower, was simulated to a considerable degree.

Seven proposed systems were tested under simulated high-density traffic conditions through the use of a standard air traffic control problem comprising 36 inbound aircraft. The distribution of aircraft types, speeds, routes and entry times was set up to produce as realistic a situation as possible. The programming or scheduling of each aircraft on each run was carefully controlled to supply precisely the same traffic input to each problem. All the proposed systems comprised various methods of implementing radar vectoring procedures, in the control of air traffic, in accordance with the published recommendations of Special Working Group 5 of the Air Co-ordinating Committee. The various systems differed in the layout of radio facilities, clearance limits, routing and traffic control procedures employed.

In addition to the comparative evaluation of the various systems, some related work was done on an investigation of controller work-load capacity. These tests are described in Appendix I of this report.

No over-all recommendations are included in this report since certain considerations (such as economical aspects) were beyond the scope of this program.

INTRODUCTION

The introduction of surveillance radar equipment as a traffic control aid and the increase in traffic load in the Washington National Airport terminal area, have necessitated a change in the traffic control procedures to take advantage of the radar equipment and to increase the traffic-handling capacity of the airport The need for new procedures, particularly, has been apparent during instrument weather conditions. A number of new traffic control procedures have been proposed. Evaluation of these proposed procedures normally would have necessitated trial operation of each one in order to obtain data on their relative merits; since a paper-study program would not reveal all of the information desired. Since an actual operational evaluation was impractical, the use of simulation technics offered an attractive means of collecting data which approaches that obtained during actual operations.

As a result of work completed on the evaluation of the Navascreen equipment, a pictorial display proposed for air traffic control use, it was apparent that the equipment could easily be modified into an air traffic control simulator Since air traffic controllers operate the equipment, and other individuals operate the computers and use voice communication channels for each aircraft being simulated, the human element is introduced into the system to a considerable degree It has been found that the human element, both in the air and on the ground, is a major factor in the control of aircraft, with presently available equipments and facilities.

From work completed using the equipment for simulating air traffic control problems, it was believed that the equipment and methods could be of aid to the Office of Federal Airways in obtaining data on the proposed traffic control procedures for the Washington terminal area. A program for this work was initiated by the Air Navigation Development Board as a result of a request from the Office of Federal Airways. Some of the advantages of using simulation methods, instead of actual flight tests, are apparent from the fact that approximately 2,500 simulated flights were flown through the various systems during the 70 runs required for this evaluation. Even if the necessary aircraft of the types simulated had been available, the costs of operating such aircraft would have been tremendous in a program of this size.

EVALUATION OBJECTIVES

The evaluation of the various air traffic control systems was conducted with regard to the following tentative requirements:

1. The system shall provide a high rate of flow for inbound and outbound traffic. If possible, in addition to landings on the ILS-PAR runway, the system shall permit straight-in approaches and landings on at least one other runway.
2. A change in the direction of landing shall not require a radical change in the jurisdiction between approach control sectors, or in ARTC clearance procedures.
3. The system shall entail a minimum of interference with Andrews Field traffic.
4. The system shall be adaptable to existing navigational facilities.
5. The system shall possess simplicity and flexibility of control procedures.
6. Air/ground communications procedures shall be as simple and short as possible.
7. The system shall require a minimum of inter-agency and inter-controller co-ordination.
8. The system shall be adaptable to the use of proposed future automatic data transfer equipment.

9. The system shall provide for low entry altitudes for ARTC use.

10 The system shall conform to existing separation standards.

11. The system shall be so arranged that all maneuvering necessary to bring arriving aircraft into the final approach path, with proper separation, can be accomplished well within the expected radar coverage of the terminal area.

12. The system shall be able to function efficiently, during periods when the radar is inoperative.

EQUIPMENT INSTALLATION

The installation of the modified Navascreen, control and recording equipment used for these tests is illustrated in Figs. 1, 2 and 3. Fig 1 is a floor layout of the various equipment components Fig. 2 is the simulated control tower, with the three controllers at the operating position. The large pictorial display on the projection screen shows the area under control. This is projected along with the six spots simulating aircraft. This display simulates the view normally seen on an indicator using radar information In Fig 3, the six operators seated at consoles, simulate aircraft movements and provide the communication contacts between the pilots and the ground controllers The consoles contain computers which in turn operate the six projectors shown at the right in Fig. 3. The operators, by turning the proper controls on the consoles, can set in the position, heading and speed of the aircraft involved; and the computers will automatically move the spots or target positions on the large screen until the controls are changed.

Targets were set up on the screen in accordance with a schedule based on the basic problem Maximum utility of each target was obtained by controlling it on final approach as far as the outer marker only, at which time it was removed and set up immediately as another aircraft. As a result, the six targets, used over and over again, provided a continuously saturated traffic flow

Time recordings of the communication channels were obtained on an Esterline-Angus recorder Photographs of the screen showing the positions of aircraft were obtained at set intervals by the use of a special 35 mm motion picture camera.

To conduct the control of a problem, two approach control sector positions were established Each controller was provided with a flight progress board and a duplex channel for communication with the console operators. Each console operator could select either communication channel as required. Full radio communications procedures, including the issuance of weather information to all pilots, were used

Simulation of the air route traffic control center functions was obtained by the provision of a co-ordinator position which had a direct interphone connection with a flight data position. The co-ordinator forwarded inbound flight plans to the flight data position and also assigned the individual flight plans to the console operators. The flight data position, which was located between the two sector controllers, received and posted flight plan information on special flight progress strips and then transferred each strip to the proper sector controller A simple multi-fix flight progress strip layout was used. The flight data position also kept the co-ordinator advised of altitude assignments in each sector.

Throughout the evaluation tests no attempt was made to idealize the traffic problem in any way. Instead, every effort was made to keep the situation as realistic as possible. For example, when using the timed approach procedures, pilots, who had been issued a fix departure time, did not necessarily leave the fix at the precise time specified. In order to simulate present-day operations, random times were issued by the co-ordinator to the pilots, through the use of a roulette wheel. These random times varied from 30 seconds early to 60 seconds late

During each phase of the evaluation, radar failure was simulated at unannounced times. This was accomplished by drawing a large curtain between the sector control positions and the screen This allowed the console operators to see their targets on the screen and to follow instructions received from the control positions, while the controllers were working "in the blind" with only the flight progress strips as a guide in determining aircraft positions. When the radar became inoperative, aircraft under control were cleared to various clearance limits consistent with the control method being employed and were assigned new altitudes as necessary When the situation required that aircraft return to Springfield at altitudes below 3,500 feet, immediate co-ordination with the departure controller was necessary, since these altitudes over Springfield normally were reserved for departing traffic. During all cases of non-radar operation, standard ANC approach control procedures were employed until such time as radar surveillance again was available.

Several communication failures also were simulated. Whenever this occurred, the unreported aircraft were handled in accordance with paragraphs 2 1700 and 2 1701 of the ANC Manual of Operations. It was assumed that missed approaches would be conducted in accordance with current Forms 511, applicable to the Washington terminal area

Radar altitude coverage was taken into consideration by using, as a guide, the chart on Page 9 of the Federal Airways Manual of Operations I-B-7. When a target was at an altitude or in a position where it normally would not be seen by radar, standard ANC procedures were effected for such aircraft until such time as a target was in a position to be seen on a radar scope.

EVALUATION METHOD

In order to obtain comparative measurements on the operation of each of the proposed procedures, it was necessary to develop a standard traffic problem for the simulation tests. In this problem, a realistic distribution of arrival intervals was obtained through use of the Poisson formula:

$$P_n(m) = m^n e^{-m}/n! \quad (1)$$

where

$P_n(m)$ is the probability that n aircraft will appear in a given interval
m is the average number of aircraft arriving during the interval
n is any interger between zero and infinity
Using data derived from this formula, Franklin Institute personnel prepared a number of probability curves, for various average hourly arrival rates. Their curve using an average arrival rate of 47 aircraft per hour was chosen as the basis for the standard traffic problem This decision was based on a desire to obtain a saturated traffic flow slightly greater than the maximum acceptance rate of a single landing runway under instrument conditions. This curve furnished the distribution of arrival intervals listed in Table 1.

TABLE I

Interval (Secs.)	Average Interval (Secs.)	Percentage of Aircraft Arrivals
0 to 20	10	23
20 40	30	17
40 60	50	13
60 80	70	11
80 100	90	8
100 120	110	7
120 140	130	5
140 160	150	4
160 180	170	3
180 200	190	2
200 220	210	2
220 240	230	1
240 260	250	1
260 280	270	1
280 300	290	1
300 320	310	1

To obtain a random sequence of outer-marker arrival times, 100 cards were marked in accordance with Table I, 23 cards were marked 10 (for 10 seconds), 17 were marked 30, 13 were marked 50, etc The 100 cards were shuffled thoroughly and drawn one at a time. From this recorded sequence, a block of 36 consecutive arrival intervals was selected as the basis for the standard traffic problem.

The 36 aircraft were divided into three speed groups as follows 11 were designated slow, 15 medium and 10 fast. Thirty-six cards were marked accordingly, shuffled thoroughly and drawn one at a time. The resulting sequence was recorded along with the sequence of approach intervals. A similar procedure was used to obtain a random distribution of inbound flight routes. Using data obtained from operations in the Washington Area, the 36 cards were marked as follows

TABLE II

No of Cards	Route	Designation
6	A	Lisbon to Riverdale
5	B	Beltsville to Riverdale
7	C	Dover to Andrews
9	E	Doncaster to Mt. Vernon
2	F	Elkins to Springfield (direct)
7	G	Arcola to Springfield

These cards were thoroughly shuffled and drawn one at a time. The resulting run was recorded with the previous interval and speed data. Each aircraft in the problem was given a flight identification, either commercial, military or civil. As a result, the basic problem then comprised the following data

TABLE III

Aircraft Identification	Speed	Route	Interval (Secs.)
E506	F	E	---
P908	F	G	70
FT196	M	A	10
AF6332	S	E	30
A331	M	G	30
V4529	S	B	50
U612	M	G	150
A414	M	C	50
E453	S	G	70
N314	M	F	30
E653	S	A	150
N803	M	G	50
A60	F	G	90

TABLE III (Continued)

Aircraft Identification	Speed	Route	Interval (Secs.)
T358	F	G	10
NAL4	M	C	10
A416	M	E	50
AF4211	M	B	10
V347	M	A	50
N13	S	B	10
X487	M	E	90
E511	F	A	50
X51	S	E	230
E456	S	E	130
SAM4998	F	E	10
NAL458	F	E	30
AF424	F	C	10
V647	S	C	70
V377	M	C	10
AF242	M	E	130
AF093	F	C	50
X498	S	F	30
P300	M	B	30
X808	S	A	10
AF777	F	C	50
A593	E	B	10
E371	S	A	50

These data were used to derive the basic S-t (space-time) curve for the problem In drawing this curve, three speed zones were designated in order to provide a fairly realistic but standard deceleration of each aircraft from cruising speed to approach speed. The cruising speed zone extended inbound to a line ten miles from the outer marker; the intermediate speed zone extended from this line to another line five miles from the outer marker, the approach speed zone extended from the latter line all the way to the touchdown point. The speeds of all aircraft in the problem were set up as follows:

TABLE IV

Speed Classification	Cruising mph	Zone Speeds Intermediate mph	Approach mph
Fast	290	220	150
Medium	240	190	140
Slow	180	150	120

Following the technique developed by the Franklin Institute in their air traffic control studies, three transparent templates were used for plotting the space-time relationships of all aircraft in the problem. This basic S-t curve, which is illustrated in Fig. 4, formed the input program of the traffic in the standard problem. Fundamentally, it showed the arrival times and approach intervals which could be expected if no traffic control were exercised, and if each aircraft took the shortest practical flight path to the outer marker. Normally, the shortest practicable flight path was considered to be a straight line from the holding fix to the outer marker; except that aircraft which had to turn more than 90 degrees to line up with the approach course were required to complete a right angle base leg of 2 1/2 miles, extending from the outer marker. Distances on all flight routes were calibrated in accordance with this base leg requirement For the convenience of the console operators, the outlines of the approach and intermediate speed zones also were printed on all terminal area maps used in this study.

Since the basic S-t curve did not take into account the delays which would be inevitable if standard separation were provided between aircraft, a second S-t curve was prepared. This curve, which was designated the "adjusted" curve and is shown in Fig. 5, indicated the optimum approach sequence and arrival times of all aircraft, assuming that perfect control is exercised and standard separation is used between all aircraft in the problem. These adjustments were made assuming that:

1. The separation between all aircraft entering a sector is 1,000 feet, and is maintained until the aircraft are on the final approach path.
2. Aircraft on the final approach path are separated by at least three miles at all times.
3 All aircraft descend at a rate not to exceed 500 feet per minute.

In the evaluation runs, the exact outer marker arrival time of each aircraft was recorded by means of a multi-channel Esterline-Angus recorder. This actual arrival time was compared with the theoretical arrival time of the same aircraft on the basic S-t curve, and also with the arrival time of the aircraft on the adjusted S-t curve of the theoretically perfect air traffic control system. These comparisons were used to obtain the following measurements.

1. The "absolute delay," which is the difference between the theoretical arrival time on the basic S-t curve and the actual arrival time of the aircraft concerned. This delay represents the excess of flying time required over that required via the shortest practical flight path with no traffic.
2. The "system delay," which is the difference between the arrival time on the adjusted S-t curve and the actual arrival time of the aircraft. This delay represents the excess flying time required beyond that theoretically necessary to bring in the aircraft with proper separation from other aircraft, and also constitutes an index of the efficiency of the traffic control system

being tested.

Actually, neither of these delays can be compared with the traffic delays being recorded in present air traffic control operations, inasmuch as present delay records cover only that portion of time during which the aircraft is being held at a holding fix. The two types of delays computed during this evaluation study include not only the holding time, but also the time lost during path stretching and velocity control. A graphic comparison between the various types of delays is shown in Fig 6.

Division of Control

The area covered in the simulation tests is a circle of 17 miles radius, centered on the Washington National Airport. This circle represents the proposed Washington terminal area, and coincides with the expected surveillance radar coverage at this location.

Normally, two controllers shared the work load of handling arriving traffic. In the early stages of this evaluation, an inner controller and an outer controller were used. This system was ultimately discarded because the shifting of the control of each aircraft from outer to inner controllers required considerable co-ordination at the point of change of jurisdiction. This changeover required re-identification of the various aircraft by the inner controller, as well as a frequency change by the pilot. The resulting operation produced intermittent overloading of the inner controller. The subsequent dual-sector system was developed in order to eliminate these disadvantages. It established two control sectors which operated independently of each other until such time as it was necessary to perform co-ordination to determine the sequence and spacing of arrivals on the final approach. With the exception of Phase I of this evaluation, standard altitude separation of 1,000 feet was used between all aircraft arriving in a sector, and was maintained until such aircraft were on the final approach course and separated by at least three miles. In all phases, no effort was made to provide altitude separation between aircraft arriving in one sector and those arriving in the other sector.

In order to provide fixed control boundaries for two sectors which could feed equally well the approach paths of Runways 36 and 15, the circular terminal control area was divided along the south course of the Washington ILS (approach path to Runway 36) and the 330-degree radial of the Washington TVOR (approach path to Runway 15). This division, illustrated in Fig. 7, was used in all phases of the study except Phase V. The east sector formed by this division was designated Sector A and the west sector was designated Sector B. Each sector was provided with a separate communications channel

Normally, inbound aircraft entering Sector A came under the jurisdiction of the Sector A controller, while inbound aircraft entering Sector B came under the jurisdiction of the Sector B controller. However, the standard traffic problem used in these tests included several surges of inbound traffic entering one sector. This type of situation was alleviated by a simple system of cross-feeding or transferring excess aircraft into the opposite sector. Normal cross-feeding routes are illustrated in Figs. 8, 9 and 10. It should be borne in mind that cross-feeding was employed not as a regular control procedure, but only as a means of relieving excessive work loads caused by surges of traffic into one sector, and served as a very useful aid in the smooth handling of traffic peaks Whenever cross-feeding was employed, 1,000-foot altitude separation was provided between the aircraft being transferred, and other aircraft in both sectors, until the transferred aircraft entered the sector to which it had been directed. During the transfer period, the necessary separation required the co-ordination of both controllers.

Instrument Approach Aids

Each proposal was tested for approach operations to Runway 36. In these tests, aircraft were guided to the outer marker, at which point it was assumed that the pilot would complete approach either by reference to the ILS or through use of the PAR system.

It was assumed that all military aircraft completed approach to Washington National Airport unless the weather permitted them to make straight in visual approaches to Bolling Field, in which case no basic changes were required in the control procedures prior to the time such aircraft reached the outer marker.

In making the simulation tests for southeast approaches on Runway 15, aircraft were lined up with the 150-degree radial of the Washington terminal omnirange and were guided to an imaginary radio fix 5.3 miles from touchdown. At this point it was assumed that the pilot would complete letdown to minimum altitude either by reference to the TVOR or by further guidance from the ASR system.

Provision for Departures

Because of a shortage of Navascreen targets, it was possible to run only inbound traffic through the evaluation tests. However, the importance of maintaining a high rate of departure flow was not overlooked. This factor was handled by providing, in all phases of the evaluation, definite departure channels which could function continuously without interference from inbound traffic, except for momentary take-off restrictions caused by landing aircraft. In addition, arrival routes and holding patterns were arranged to provide sufficient air space for departures to proceed on normal departure routes while radar contact was being established. Normal departure channels under the restrictions encountered are shown in Fig 11.

Variation between Runs

In each run recorded, every effort was made to keep the problem input the same. However, controllers were rotated from run to run in order to equalize some of the personnel variations. Each problem was handled as expeditiously as possible by the sector controllers, who made their decisions as they went along. Therefore, in a problem as complicated as this one, different aircraft did not always follow the same sequence in successive runs due to differences in the decisions made by the controllers in the rapidly changing situations of the problem. Although each console operator handled the same aircraft at the start of each problem, differences in the landing order soon produced variations in the assignment of aircraft identifications in the later stages of each problem. For example, in Phase I the arrival times of one aircraft, chosen at random, in six runs were as follows: 24:26, 25:12, 25.12, 25:30, 25:54 and 27:26.

TESTS CONDUCTED ON PHASE I PROPOSAL

Holding Fixes

In the original proposal, four holding fixes were used, namely, Riverdale marker, Andrews range, Mt. Vernon marker and Springfield marker. Before testing this proposal, it was found desirable to move the Mt. Vernon marker to a point on the southwest course of the Washington range, 11 miles from the outer marker. This relocation was necessary in order to avoid the necessity for using altitude separation between aircraft at Mt. Vernon and aircraft en route from Springfield to the outer marker. The new arrangement provided maneuvering area for adjusting the approach intervals of the latter aircraft. In evaluating this proposal, it was assumed that Riverdale, Andrews, Potomac Heights and Springfield would be used as final clearance limits by ARTC with standard altitude separation provided between aircraft at each fix.

Division of Control

The Washington terminal area was divided into two approach control sectors as previously described and as illustrated in Fig. 7. This division provided each sector with two of the clearance limits listed above. Since altitude separation was used only between the aircraft at each fix, rather than between all aircraft in each sector, each controller had under his control, at times, two streams of traffic proceeding through the same altitude levels. It was the controller's responsibility to maintain approved separation between such aircraft and always to have at his command a safe plan of aircraft diversion which could be employed quickly in case of radar failure.

Arrival Control Procedures - North Landing

Normally, aircraft arriving over Riverdale were vectored on a downwind leg of 180 degrees. Aircraft arriving over Andrews range were vectored on a 190-degree track from Andrews. This was done in order to give such aircraft ample time to descend from the relatively high crossing altitudes required over Andrews. In order to avoid using excessive air space in the flight path of these aircraft, most arrivals over Andrews were requested to reduce to an intermediate speed immediately after leaving the Andrews range. Aircraft arriving over Springfield were vectored on a southeasterly heading toward the final approach course. These aircraft required constant attention to avoid possible conflict with aircraft at Potomac Heights, which might be at the same altitudes as those off Springfield. Aircraft arriving over Potomac Heights were vectored, whenever possible, directly to the outer marker. In other cases, they were vectored into the approach sequence using easterly headings from the Potomac Heights marker to the approach course. In a few instances, where a possible conflict with traffic being vectored from Springfield was apparent, aircraft arriving over Potomac Heights were delayed momentarily by making a 360-degree turn at the fix. The normal flight patterns and minimum altitudes are shown in Fig. 12. Cross-feed patterns are illustrated in Fig. 8.

Inbound Control Procedures - Southeast Landing

Whenever possible, aircraft en route from Lisbon or Beltsville to Riverdale were given a right turn toward a point where the base leg could be started. Aircraft arriving at Riverdale were cleared to leave that fix on a downwind leg of 330 degrees. Aircraft arriving at Andrews were given a 350-degree heading in order to take them well east of the Washington air space reservations. After reaching the vicinity of Riverdale, these aircraft were turned to a downwind leg of 330 degrees. Aircraft arriving at Potomac Heights or Springfield were vectored on a northerly heading until they passed the northwest course of the Washington range, after which they were turned toward the final approach course. Because of this routing, the traffic flow resembled a 2-fix system, since the Andrews traffic had to be posted at Riverdale and the Potomac Heights traffic had to be posted at Springfield. Altitude separation was used between all aircraft in the vicinity of Riverdale and in the vicinity of Springfield. The normal traffic patterns and minimum altitudes used are shown in Fig. 13.

Emergency Procedures

In event of radar failure, the dual-sector system reverted to an inner-outer sector arrangement. The Sector A controller assumed control of the stack at the outer marker and the Sector B controller assumed control of all outer fixes.

At the time of radar failure, aircraft already on final approach were permitted to continue approach provided controllers were certain that such aircraft could maintain more than three miles longitudinal separation from each other while in flight. Other aircraft in Sector A were cleared directly to the outer marker with altitude separation from each other. Aircraft in Sector B were started back toward Springfield and Potomac Heights to hold at these fixes until altitudes became available for them at the outer marker. Since the southwest course of the Washington range was not used as a departure route, it was possible to send aircraft to Potomac Heights for holding at 1,500 feet, without co-ordination with the departure controller. This procedure was useful when an aircraft had to be removed from the final approach path due to a possible traffic confliction.

Standard timed approach procedures were utilized by the outer marker controller in clearing aircraft for ILS approaches. When radar surveillance was restored, aircraft holding in the outer marker stack were fanned out into the east and west sector patterns, and the dual-sector vectoring system was resumed.

Results

The data taken from the number of runs made on this phase of the tests are tabulated in Table V The average delays that each aircraft encountered are shown in Fig 35. The photograph of the screen, in Fig. 14, shows the location of the aircraft in the vectoring pattern at one period during the test. An actual S-t curve, derived from data observed during the problem, is shown by Fig. 15. Flight paths actually used during the test are plotted in Fig. 16. These data were taken from the recording made by the camera during the evaluation.

Observations

The following observations were made during the study on Phase I

1. Due to a lack of sufficient air space in which to vector aircraft from Springfield to the outer marker, the 4-fix operation does not appear practical unless the Mt Vernon marker is relocated. In the tests run on this phase, it was assumed that the Mt. Vernon marker was moved four miles southwest, to Potomac Heights. After studying the flight paths of these tests, it was believed that the marker should be moved an additional three miles southwest in order to maintain adequate separation between aircraft at this marker and aircraft inbound from Springfield. Fig. 13 shows the recommended location of the marker

2. This system would be slightly less adaptable than 2-fix systems for the installation of automatic data transfer equipment, as it would require four posting boards instead of two.

TESTS CONDUCTED ON PHASE II PROPOSAL

Holding Fixes

It was assumed that two low-power VHF omniranges were installed in the vicinity of the outer marker One LVOR was located 4 miles east and 1 1/2 miles south of the outer marker and designated Fix A. The other station was located 4 miles west and 1 1/2 miles south of the outer marker and designated Fix B This installation provided dual holding stacks in proximity to the outer marker and twin holding patterns which paralleled the final approach course. It was assumed that these two fixes are used as final clearance limits by air route traffic control with standard altitude separation provided between aircraft arriving in each sector. Normal holding altitudes at Fix A were 3,000, 4,000 and 5,000 feet. Normal holding altitudes at Fix B were 2,500, 3,500 and 4,500 feet

Division of Control

The Washington terminal area was divided into two approach control sectors as previously described and as illustrated in Fig. 7.

Arrival Control Procedures

This system was adaptable only for landings to the north, and was not evaluated for southeast landings. Normally, aircraft arriving over Riverdale and Andrews were cleared via direct routes to Fix A, while aircraft arriving over Mt Vernon and Springfield were cleared via direct routes to Fix B In order to keep the holding stacks equalized, occasionally it was necessary to cross-feed aircraft from Riverdale direct to Fix B and from Mt. Vernon direct to Fix A, as illustrated in Fig. 17.

Timed approach procedures were used in unloading holding aircraft from the twin stacks. Each holding aircraft received advance notice as to when to leave Fix A or B southbound. Normally, fix departures were staggered alternately from the two fixes. Radar vectoring then was used to establish the approach intervals between aircraft and to turn such aircraft into the final approach course. The area required for adjustment of the approach interval is shown in Fig. 18

Emergency Procedures

In the event of radar failure, aircraft already on final approach, with proper longitudinal separation, were permitted to continue approach. No change of sector jurisdiction was required during non-radar operation. The approach interval was lengthened somewhat in order to have the No. 2 aircraft just leaving the fix southbound at the time the No. 1 aircraft was expected to report over the outer marker, inbound. On receipt of the latter report, the No. 2 aircraft then was cleared for approach. Using this system, it was soon discovered that approach intervals increased progressively, due to increasing lengths of the "trombone" patterns, because aircraft were allowed to leave the holding fixes southbound considerably ahead of the time when they could be cleared for approach. Taking this into consideration and adjusting the fix departure time, it was found that approach intervals during non-radar operations constantly averaged between 2 1/2 and 3 minutes.

Results

Data for the Phase II tests are shown in Table V. The average delays encountered during this phase are shown in Fig. 36. The photograph of Fig. 19 shows a typical problem presented during this phase. Fig 20 shows the recorded flight paths followed by the simulated aircraft during this phase

Observations

The following additional observations were made during the Phase II study

1 This system required a relatively small amount of communications time, as navigation all the way in to the holding fix usually was accomplished by the pilot instead of by the radar controller. This setup greatly reduced the work load of the controller since it was not necessary for him to concentrate on the identification, heading and position of all aircraft inbound

to the holding fixes. Consequently, he was under less mental strain and also had more time to devote to other duties.

2. As may be seen in Fig 20, this system required the smallest amount of maneuvering air space of any system tested. Since all inbound flight routes went directly to the holding fixes, a considerable portion of aircraft descent was accomplished in the holding stacks, instead of on long vectoring routes. In congested areas, this feature is advantageous in avoiding interference with the normal flow of traffic to and from other airports in the vicinity.

3. In this system, radar vectoring usually was employed only for the adjustment of approach intervals along the relatively short flight path from the holding fixes to the outer marker. The arrangement of this approach system, which is illustrated in Fig. 18, permitted considerable flexibility in the adjustment of approach intervals.

4. The rate of aircraft departures from the holding fix at intervals of one departure every 1 1/2 minutes had to be adjusted occasionally to keep the "trombone" approach patterns properly filled. The basic purpose of the close-in dual stack arrangement was to provide a means of limiting the flow of aircraft into the approach channel to a rate compatible with the landing acceptance rate of the system

5. In this phase, control operations reached their peak of efficiency when the number of aircraft in the "trombone" patterns was just sufficient to keep the approach path supplied with aircraft at the minimum spacing interval. As the shortest approach path from a holding fix to the outer marker was approximately 6 miles, while approach speeds varied from 120 to 150 mph, at least 2 aircraft had to be in the approach patterns simultaneously in order to maintain an efficient spacing close to the 3-mile minimum. With three aircraft in the approach patterns, the approach path could be well supplied with aircraft at the minimum interval. Since aircraft could not be accepted at the approach gate (outer marker) at a rate higher than this saturation rate, there was nothing to be gained in speeding up fix departures to get more than three aircraft into the "trombone" patterns. Any further increase in the number of aircraft in these patterns loaded up the communications channels and increased the controller's work load by giving him more aircraft to control and a larger area to watch. This obviated the basic advantages of the twin-stack system By forcing aircraft to fly longer common approach paths, it also tended to lengthen the approach interval.

TESTS CONDUCTED ON PHASE III PROPOSAL

Holding Fixes

It was assumed that Riverdale and Mt Vernon would be used by air route traffic control as final clearance limits, with standard altitude separation provided between aircraft at each fix.

Division of Control

The Washington terminal area was divided into two control sectors as previously explained and as shown in Fig. 7 This division provided each sector with one of the clearance limits listed in the preceding paragraph.

Arrival Control Procedures - North Landing

Aircraft arriving over Riverdale were vectored on a downwind leg of 180 degrees. Aircraft arriving over Andrews range followed a direct course toward Riverdale until radar contact was established, at which time they were turned into the downwind leg of the pattern. If radar contact was established before such aircraft left the Andrews range, these aircraft were vectored on a 190-degree heading to lose altitude, then turned on base leg before they reached the edge of the terminal area. To conserve air space, pilots usually were requested to slow down to an intermediate speed immediately after leaving Andrews range.

Aircraft approaching Mt. Vernon from over Doncaster usually were vectored on an easterly heading toward the final approach course. Aircraft arriving over Springfield usually proceeded directly to the Mt. Vernon marker, at which point they were vectored on a downwind leg of 180 degrees until they could be fitted into the final approach sequence. Normal flight routes are illustrated in Fig. 21. Cross-feeding routes are illustrated in Fig. 8.

Arrival Control Procedures - Southeast Landing

Whenever possible, aircraft en route to Riverdale from Lisbon or Beltsville were given a right turn toward a point where base leg could be started. Aircraft arriving at Riverdale were cleared to leave that fix on a downwind leg of 330 degrees. Aircraft arriving over Andrews followed a direct ADF course to Riverdale, at which point they were turned on a downwind leg of 330 degrees. Aircraft arriving over Springfield or Mt. Vernon were vectored on a northerly heading until past the northwest course of the Washington range station, after which they were turned toward the final approach course. Normal flight patterns and minimum altitudes are the same as those shown in Fig. 13. Cross-feeding routes are illustrated in Figs. 9 and 10.

Emergency Procedures

In event of radar failure, the dual-sector system reverted to an inner-outer sector arrangement The Sector A controller assumed control of the outer marker stack and the Sector B controller assumed control of the outer fixes.

At the time of radar failure, aircraft already on final approach were permitted to continue approach, provided controllers were certain that such aircraft could maintain more than three miles longitudinal separation between each other. Other aircraft in Sector A were cleared directly to the outer marker, maintaining altitude separation. Due to the proximity of Mt. Vernon and the outer marker, it was not considered safe to hold aircraft at these fixes, at the same altitudes simultaneously. This fact presented a problem as to the disposition of Sector B aircraft in the event of radar failure, since they could not be cleared to hold at their previous clearance limit, if other aircraft were cleared to hold at the same altitude levels at the outer marker. In this case, disposition of Sector B aircraft required quick co-ordination with the Center, in determining whether such aircraft could be sent temporarily to Indian Head or, preferably, Springfield These aircraft were re-cleared to the outer marker as soon as suitable altitudes became available for them at that fix.

Standard timed approach procedures were utilized by the outer marker controller in clearing aircraft for ILS approaches. When radar surveillance was restored, aircraft in the outer marker stack were fanned into the east and west sector patterns, and the dual-sector vectoring system was resumed.

Results

Data for Phase III are listed in Table V. The delays encountered are shown in Fig. 37.

Observations

1. Use of Mt. Vernon as a clearance limit in a purely vectoring system was not very satisfactory due to the short distance between Mt. Vernon and the outer marker. This arrangement produced occasional complications in the traffic patterns in the vicinity of Mt. Vernon and, in turn, increased the communications work load to a relatively high figure.

2 Simultaneous holding could not be accomplished at the same levels at the Sector B clearance limit and the outer marker. Hence, this system was less adaptable for non-radar operations than some of the other phases tested

TESTS CONDUCTED ON PHASE IV PROPOSAL

Holding Fixes

It was assumed that the Springfield marker and the Andrews range would be used as final clearance limits by air route traffic control, with standard altitude separation provided at each fix.

Division of Control

The Washington terminal area was divided into two approach control sectors as previously described and as illustrated in Fig. 7. This division provided each sector with one of the clearance limits.

Arrival Control Procedures - North Landing

Aircraft arriving over Riverdale proceeded on a direct course toward Andrews range, until radar contact was established, at which time they were turned on downwind leg. Aircraft arriving over Andrews were vectored on a 190-degree track in order to descend from the relatively high crossing altitudes required over Andrews. In order to avoid using excessive air space in the vectoring of these aircraft, most arrivals were requested to slow down to an intermediate speed immediately after leaving the Andrews range.

Aircraft approaching Mt. Vernon from Doncaster usually were vectored on an easterly heading toward the ILS course. Aircraft arriving at Springfield were vectored on a southeasterly heading toward the final approach course and sometimes turned on a 180-degree downwind leg until they could be fitted into the approach sequence. Normal flight patterns and minimum altitudes are shown in Fig. 22. Cross-feeding patterns are shown in Fig. 8. Because of the disadvantages which soon became apparent in the operation of this system, and the fact that more efficient systems already had been tested, no attempt was made to test the operation of the Springfield-Andrews system in vectoring aircraft to a southeast landing.

Results

Data for Phase IV are listed in Table V. The delays encountered are shown in Fig. 38. A photograph showing typical locations of aircraft in the pattern is shown in Fig. 23. The drawing in Fig. 24 was made from photographs taken during the tests.

Observations

1. The main disadvantage of this system lay in the fact that a minimum altitude of 5,000 feet was required over the Sector A clearance limit at the Andrews range This requirement likewise raised the minimum altitude of all aircraft arriving over Riverdale. As a result, this system had the highest entry altitudes of any system tested.

2. Because of the extremely high entry altitudes, radar coverage was regarded as poor.

3. The large number of altitude vacating reports greatly increased the communications work load.

4. Time required in making the long descents increased delays.

5. The necessity for long common flight paths in Sector A raised the approach interval to the highest recorded in any phase tested

TESTS CONDUCTED ON PHASE V PROPOSAL

Holding Fixes

In the original proposal, two holding fixes were used, namely, the Springfield marker and Mt Vernon marker. However, both of these fixes were on the same side of the ILS course, with the Mt. Vernon marker blocking the normal vectoring path of aircraft approaching from Springfield. For this reason the Mt. Vernon marker was moved to Potomac Heights as previously explained in Phase I

Division of Control

Considerable thought was given to the division of sectors but no satisfactory solution was found because both holding fixes were on the same side of the approach course to Runway 36 and also on the same side of the approach course to Runway 15.

In all other systems tested, the division of sectors shown in Fig. 7 made possible the establishment of two separate traffic patterns which could operate independently up to their confluence on the final approach. Because of the 1-sided arrangement of holding fixes in this proposal, it was not possible to establish any workable clear-cut sector division which would permit two sectors to feed aircraft to the final approach path in an orderly sequence without crossing boundaries or conflicting with aircraft of the opposite sector.

The best compromise was the division illustrated in Fig. 25. This division was based on the proposed criteria regarding air space requirements of holding patterns. It still was inadequate in providing independence for two traffic patterns because the arrangement of clearance limits made it practically impossible to operate either pattern in saturated traffic conditions without crossing the sector boundary lines. This division also ruled out the possibility of using a 2-sector system to vector aircraft for southeast approaches on Runway 15.

Arrival Control Procedures - North Landing

Aircraft arriving at Riverdale proceeded direct to the compass locator at the middle marker, thence directly to Springfield, on ADF courses At some point west of the middle marker they were vectored on a southeast heading toward the final approach course. If possible, aircraft in radar contact over Andrews were turned to a 190-degree heading to lose altitude and were slowed to intermediate speed. Andrews arrivals not in radar contact proceeded on a direct ADF course to Potomac Heights. Whenever possible, aircraft approaching Potomac Heights from the south were vectored toward the final approach course on an easterly heading. Aircraft arriving over Springfield were cleared on an easterly or southeasterly heading toward the final approach course before being fitted into the final approach sequence. Normal flight routes are shown in Fig 26. Cross-feeding routes are illustrated in Fig. 8

Because of the disadvantages which soon became apparent in the operation of this system, and the fact that more workable systems had already been tested, no attempt was made to test the operation of the Springfield-Potomac Heights system in vectoring aircraft to a southeast landing.

Results

Data for Phase V are listed in Table V. Delays encountered are shown in Fig 39.

Observations

1. The functional disadvantage of this system was that the clearance limits for both sectors were located on the same side of the final approach course. This arrangement produced extremely inefficient traffic-flow patterns

as neither pattern had unrestricted access to the final approach path. Because of this lack of flexibility in adjusting approach intervals, the resulting intervals were large.

2. Aircraft in the vicinity of the southwest course of the Washington range required constant attention to avoid confliction between the two patterns. The traffic flow became very complicated in this area. This in turn increased the communications work load considerably.

3 Because of the inevitable overlapping of traffic patterns, it became difficult at times for the Flight Data position to determine whether various altitude levels should be reported as vacant, particularly in the vicinity of Potomac Heights As a result, altitude levels built up to a maximum of 10,500 feet in this phase This, in turn, reduced the percentage of aircraft under radar surveillance, further increasing the communications work load.

4. Because of interference between the flight patterns of the two sectors during heavy traffic conditions, constant concentration and co-ordination was required on the part of both sector controllers in order to avoid traffic conflictions. There were many times when this characteristic of the system would have produced a hazardous situation in case of sudden failure of the surveillance radar.

TESTS CONDUCTED ON PHASE VI PROPOSAL

Holding Fixes

It was assumed that the Springfield marker and the Riverdale marker would be used as final clearance limits by air route traffic control with standard altitude separation provided at each fix

Division of Control

The Washington terminal area was divided into two approach control sectors as previously described and as illustrated in Fig. 7 This division provided each sector with one of the clearance limits.

Arrival Approach Control Procedures - North Landing

Aircraft arriving over Riverdale were vectored on a downwind leg of 180 degrees. Aircraft arriving over Andrews followed a direct ADF course toward Riverdale until radar contact was established, at which time they were turned into the downwind leg of the pattern. If radar contact was established before such aircraft left the Andrews range, these aircraft were vectored on a 190-degree heading to lose altitude, then turned on base leg before they reached the edge of the terminal area. To conserve air space, pilots usually were requested to slow down to intermediate speed immediately after leaving Andrews range. Whenever possible, aircraft approaching Mt Vernon from Doncaster were vectored toward the final approach course on an easterly heading. Aircraft arriving over Springfield were vectored on a southeasterly heading prior to being turned on the downwind leg. Normal flight paths and minimum altitudes are shown in Fig. 27. Cross-feeding routes are illustrated in Fig. 8.

Arrival Control Procedures - Southeast Landing

Whenever possible, aircraft en route to Riverdale from Lisbon or Beltsville were given a right turn to a point from which a base leg could be started. Aircraft arriving at Riverdale were cleared to leave that fix on a downwind leg of 330 degrees. Aircraft arriving over Andrews followed a direct ADF course to Riverdale, at which point they were turned on a downwind leg of 330 degrees. Aircraft arriving over Mt. Vernon followed a direct ADF course toward Springfield. All aircraft arriving at Springfield departed that fix on a northerly heading and continued until they passed the northwest course of Washington range station, after which they were turned toward the final approach course. Normal flight patterns and minimum altitudes are shown in Fig. 28 Cross-feeding routes are illustrated in Figs. 9 and 10.

Emergency Procedures

In event of radar failure, the dual-sector system reverted to the inner-outer sector arrangement. The Sector A controller assumed control of the outer marker stack and the Sector B controller assumed control of the outer fixes

At the time of radar failure, aircraft already on final approach were permitted to continue approach provided controllers were certain that such aircraft could maintain more than three miles longitudinal separation from each other. Other aircraft in Sector A were cleared directly to the outer marker, maintaining altitude separation from each other. Aircraft in Sector B were turned back toward Springfield to hold temporarily until altitudes became available for them at the outer marker

Standard timed approach procedures were utilized by the outer marker controller in clearing aircraft for ILS approaches. When radar surveillance was restored, aircraft holding in the outer marker stack were fanned out into the east and west sector patterns and the dual-sector vectoring system was resumed.

Results

Data for Phase VI are listed in Table V The delays encountered are shown in Fig 40. Fig. 29 shows a typical problem presented during this phase and is a photograph of the display. Fig. 30 was drawn from photographs taken during the tests and shows the flight paths used by the simulated aircraft involved.

Observations

1. This system had the lowest approach intervals, the lowest communications times, the lowest delays and the lowest entry altitudes of any of the 2-fix vectoring systems tested.

2. Because of the balanced arrangement of the holding fixes in relation to the final approach path to Runway 15, this system had the lowest approach intervals of any phase tested, for southeast approaches.

TESTS CONDUCTED ON PHASE VII PROPOSAL

Holding Fixes

It was assumed that an LVOR was installed in the vicinity of Piscataway. This installation, together with Mt. Vernon, formed a symmetrical twin-stack system. These two fixes were used as final clearance limits by air route traffic control, with standard altitude separation provided between aircraft at each fix. Normal holding altitudes at Mt. Vernon were 2,000, 3,000 and 4,000 feet, at Piscataway 2,500, 3,500 and 4,500 feet.

Division of Control

The Washington terminal area was divided into two sectors as previously described and as illustrated in Fig. 7. This division provided each sector with one of the clearance limits. This system was adaptable only for landings to the north and was not evaluated for southeast landings.

Arrival Control Procedures

Aircraft over Riverdale or Andrews proceeded to Piscataway on direct ADF courses. Aircraft from Springfield proceeded to Mt. Vernon on a direct ADF course. Normal flight routes, minimum altitudes and cross-feeding routes are illustrated in Fig. 31

Emergency Procedures

In the event of radar failure, no change in sector jurisdiction was necessary Without radar, approach intervals had to be lengthened somewhat, but still averaged less than three minutes.

When the radar was not in operation, the system was operated as follows

The No 1 aircraft was cleared for approach, and was cleared to descend to final approach altitude as soon as the pilot reported leaving the holding fix. Based on this report, the No. 2 aircraft then was issued a time to leave its holding fix inbound This time, which provided an interval of at least two minutes, was figured so as to place this aircraft not more than one minute past the holding fix at the time the No. 1 aircraft reported passing the outer marker inbound. The No. 2 aircraft reported leaving its holding fix and was held at a minimum holding altitude until the No. 1 aircraft reported passing the outer marker inbound. On receipt of this report, the No. 2 aircraft was immediately cleared for approach and descended to final approach altitude.

Results

Data for Phase VII are listed in Table V. The delays encountered during this phase are shown in Fig. 41. A typical problem presented by this phase is shown in the photograph of Fig. 32. The flight paths used by the simulated aircraft are plotted in Fig 33.

Observations

1. This system required the lowest communications time of any system tested.

2. With this arrangement of fixes, as illustrated in Fig. 34, control operations with radar worked most efficiently when there were at least two and not more than three aircraft in the approach patterns between the holding fixes and the outer marker. Approach intervals were as low as any recorded for any 2-fix system tested

3 The arrangement of the holding patterns in this system was believed superior to the arrangement used in the Phase II twin-stack system in that it produced less interference with Washington departure routes. However, there was a possibility that the Phase VII holding patterns might produce occasional interference with traffic proceeding to and from Andrews via the southern route.

APPENDIX I

Notes on Effect of Work Load on Air Traffic Controllers

Method

In order to determine the effect of a greatly increased work load on controller efficiency, a number of runs were made with a single controller handling all control operations in both sectors. In these tests, the Phase I and Phase II systems were used Control techniques were the same as those previously described for these phases except that all air/ground communications were handled on a single duplex channel.

Results

Data for these tests are compared with data for the corresponding 2-man operations in the following Table VI

TABLE VI

Phase	Landing Runway	No. of Controllers	No of Channels	*Comm. Channel Load %	Total Delays 36 Aircraft Absolute	Total Delays 36 Aircraft System	Ave. Apch. Int.	Ave. A/G Comm. Time per Aircraft
I (Four Fix)	36	1	1	72	559·53	220·43	1·45	1·21
	36	2	2	39	491:54	152·44	1 41	1 26
II (Twin Stack)	36	1	1	67	717 22	326:12	1 54	1:21
	36	2	2	39	574:39	253.29	1.48	1:29

*Average percentage of time each communications channel was in use, as determined by the formula

$$L = \frac{C}{RN} \qquad (2)$$

where

L = Communications channel load
C = Total communications time
R = Total running time of problem
N = Number of communications channels

Conclusions

1. In making the original evaluation runs of Phases I through VII, the number of aircraft handled simultaneously by one controller averaged three, and occasionally reached four. The purpose of studying 1-man operation was to find out whether efficiency would drop when the controller had a steady

work load of six aircraft.

The controllers who made these runs had acquired a considerable degree of skill before they tackled 1-man operation of this saturated traffic problem. Although they managed to keep the traffic situation under control at all times, both the approach intervals and delays increased. Average communications time per aircraft decreased slightly due to the fact that weather, wind and runway information usually was given to six aircraft simultaneously In the 2-man operations, this information normally was given to only two or three aircraft at a time.

2. The drop in over-all efficiency was caused by the fact that the single controller was so occupied in keeping all aircraft properly identified, in handling the almost doubled communications load and in keeping all flight progress strips properly posted, that he was unable to devote sufficient time to the precise spacing of aircraft on the final approach Therefore, it appears that, from the standpoint of control efficiency, six aircraft are too many for one man to control simultaneously in a vectoring system of this type, using present separation standards and without radar identifications.

3. The human element is one of the most important variables in the traffic control system and probably one of the least understood. Different controllers vary widely in efficiency depending on training, temperament and recent experience Even the same controller may show a considerable day-to-day or hour-to-hour variation While it is not believed that simulation test runs can reproduce all of the factors which make up the job and atmosphere of actual IFR traffic control, it is believed that if a certain increase in work load results in a decrease in controller efficiency during simulation tests, then the added strains and distractions of such an increase during actual traffic control would likely result in an even greater decrease in efficiency. It is important, then, that any system be designed to avoid over-loading controller personnel much beyond the point at which their peak efficiency is reached. This may be done by restricting the number of aircraft released to approach control at one time. In order to avoid starving the approach system, this number should be large enough to keep the approach gate supplied with a steady stream of aircraft at the minimum approach interval. It can be determined approximately by the following empirical formula.

$$N = \frac{\left(\frac{60D}{S}\right) + L}{I} \qquad (3)$$

where

N = Optimum number of aircraft under approach control

D = Distance of normal vectoring path from farthest ARTC clearance limit, to the approach gate, in miles

S = Approach speed of slowest aircraft using the system in miles per hour (Note The quantity $\frac{60D}{S}$ indicates the number of minutes required for this aircraft to proceed from clearance limit to approach gate)

L = Maximum time, in minutes, required for an aircraft to leave a holding pattern at an ARTC clearance limit This is normally three minutes for a standard 2-minute race track pattern, or two minutes for a standard 1-minute race track pattern

I = Approach interval in minutes. For mixed aircraft of the types used in the Washington simulation tests, three miles separation produced a theoretical approach interval of 1 1/2 minutes.

Example: The vectoring path from the farthest ARTC clearance limit to the outer marker is 12 miles. The minimum approach speed is 120 mph. A 2-minute holding pattern is used at the clearance limit (L = 3). The desired approach interval is 1 1/2 minutes. Substituting these values in Equation (3),

$$N = \frac{\left(\frac{60 \times 12}{120}\right) + 3}{1.5} = 6$$

Therefore, six aircraft between the outer limits of the holding patterns and the outer marker would saturate the system. Any further increase in the number of aircraft would tend to increase the approach control work load, without increasing the efficiency of the system.

Even with only six aircraft cleared to approach control simultaneously, there are occasions when all six might be inbound into the same sector. The purpose of the cross-feed system as used in the proposals tested is to provide a means to alleviate this surge by transferring excess aircraft to the control of the other sector. This procedure tends to equalize the work load and prevent overloading one controller and one control frequency to the point where efficiency is impaired.

Another problem encountered by the controller in attempting to obtain the maximum efficiency of the system is the determination of the effect of headwind on the separation required between aircraft. This problem is well illustrated by Fig. 42. In the case shown, a slow aircraft is followed by a faster aircraft. A larger separation is required over the outer marker when a headwind exists over that required during a calm wind condition in order to maintain the required 3-mile separation at touchdown. Under present conditions, the separation on the approach path must be estimated by the controller and this estimate normally is made with a large safety factor, thus increasing the average approach interval.

TABLE V

Summary of Data

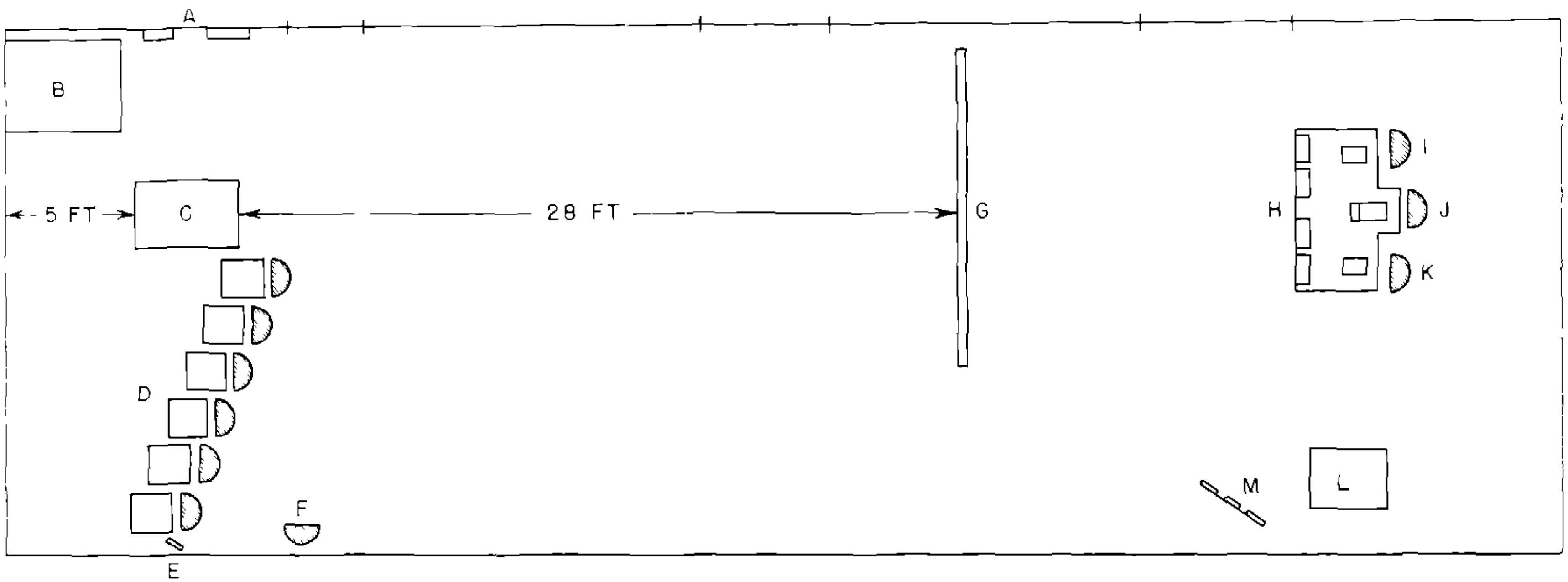
Evaluation of Air Traffic Control Procedures
Washington Terminal Area

Phase No	I		II	III		IV	V	VI	
Holding Fixes	SRI - RVD - POT - ADW		A + B LVOR'S	MTV - RVD		SRI - ADW	SRI - POT	SRI - RVD	
Landing Runway	36	15	36	36	15	36	36	36	1
Average Approach Interval (Min/Sec)	1 41	1 53	1 48	1 53	1 56	1 59	1 54	1 42	1 4
Average A/G Communications Time per Aircraft (Min/Sec)	1 26	1 32	1 29	1 43	1 44	1 40	1 40	1 37	1 3
Communications Channel Load East Sector*	39%	36%	35%	41%	40%	40%	40%	45%	37
Communications Channel Load West Sector*	40%	37%	38%	44%	45%	40%	42%	44%	45
Average Entry Altitude	4300	4760	4977	5511	5590	5808	5478	5386	463
Maximum Entry Altitude	7000	7000	7500	8500	8000	10500	10500	7500	650
Total Absolute Delays	491 54	589 47	574 39	666 14	654 11	639 13	639 52	505 16	543 2
Total System Delays	152 44	250 37	235 29	327 04	315 01	300 03	300 42	166 06	204 1
Changes Required in Air Navigation Facilities	Relocation of MTV		Installation of 2 LVOR'S	None		None	Relocation of MTV	None	
Estimated Interference with Andrews Traffic	None		Possible Confliction with Holding at ADW	None		None	None	None	
Adaptable for S E Approaches	Yes		No	Yes		No	No	Yes	
Simplicity of Control Procedures	Good		Excellent	Fair		Fair	Poor	Good	
Co-ordination Work Load	Good		Excellent	Fair		Fair	Poor	Good	
Adaptability for Automatic Data Transfer	Fair		Good	Good		Good	Poor	Good	
Probable Radar Coverage of Maneuvering Airspace	Good		Good	Good		Poor	Fair	Good	
Adaptability for Non-Radar Operations — Arrivals	Fair		Excellent	Good		Fair	Poor	Good	
Adaptability for Non-Radar Operations — Departures	Good		Fair	Good		Good	Good	Good	

* Communications Channel Load = $\frac{\text{Average Time Duplex Channel in Use}}{\text{Average Running Time of Problem}}$

LEGEND

ADW - Andrews
MTV Mt Vernon
POT - Potomac Heights
SRI - Springfield
DCA - Washington Air
PIS - Piscataway
RVD - Riverdale



LEGEND

A POWER SWITCHES
B TIMING UNIT
C PROJECTOR RACK
D OPERATOR CONSOLES
E CLOCK
F COORDINATOR
G SCREEN

H CONTROL DESK
I "A" SECTOR CONTROLLER
J FLIGHT DATA POSITION
K "B" SECTOR CONTROLLER
L RECORDER
M RECORDING CLOCKS

(OPERATING POSITIONS ARE SHADED)

FIG I NAVASCREEN LAYOUT FOR WASHINGTON TERMINAL AREA STUDY

FIG. 2 SIMULATED CONTROL TOWER WITH PICTORIAL DISPLAY OF PROBLEM

FIG. 3 CONSOLES AND OPERATORS SIMULATING AIRCRAFT MOVEMENTS AND PILOT'S COMMUNICATION

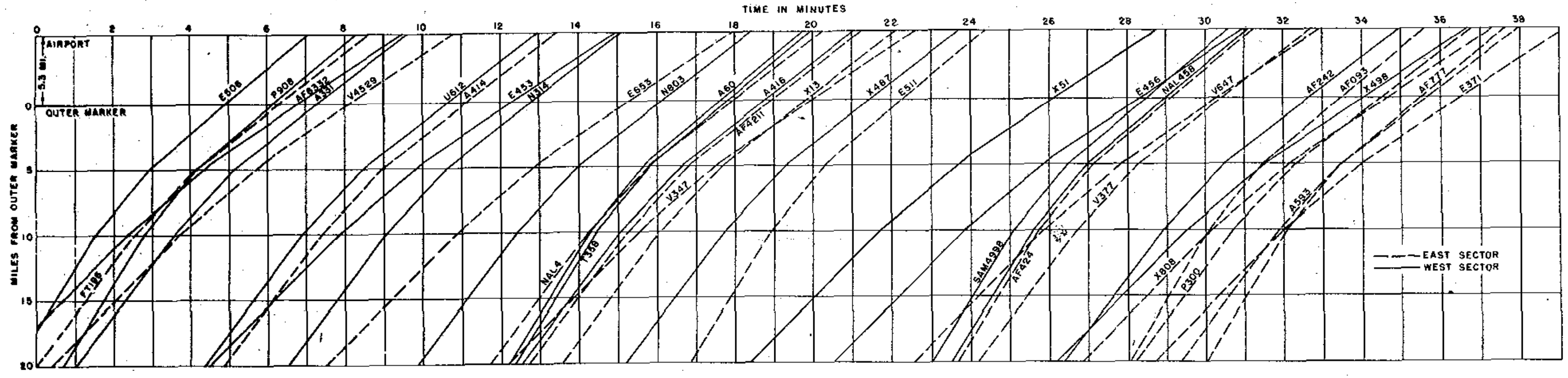


FIG. 4 BASIC S-T CURVE, WASHINGTON TRAFFIC PROBLEM

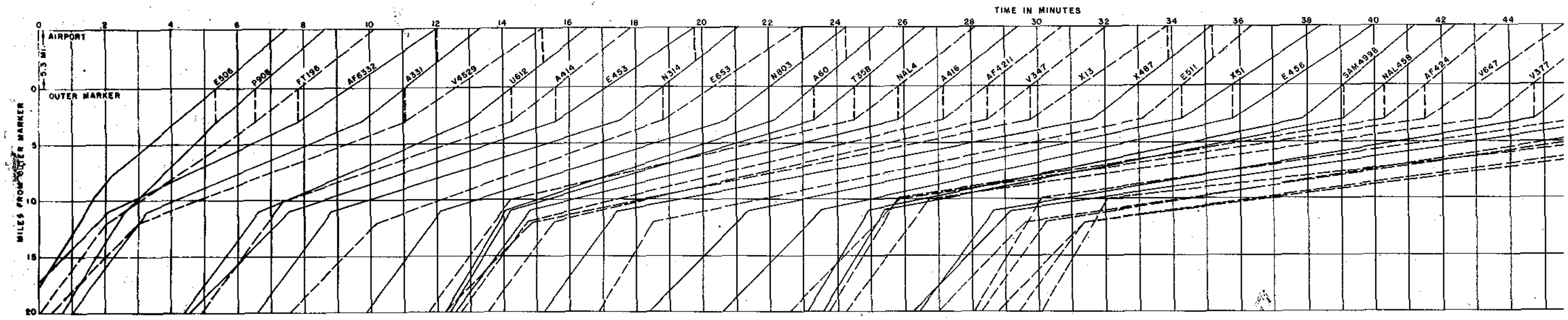


FIG. 5 OPTIMUM TRAFFIC CURVE ADJUSTED FOR 3 MILE LATERAL SEPARATION, 1000 FT. ALTITUDE SEPARATION, AND 500 FPM DESCENT RATE

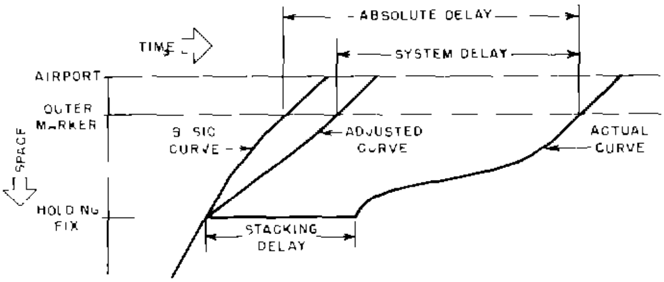
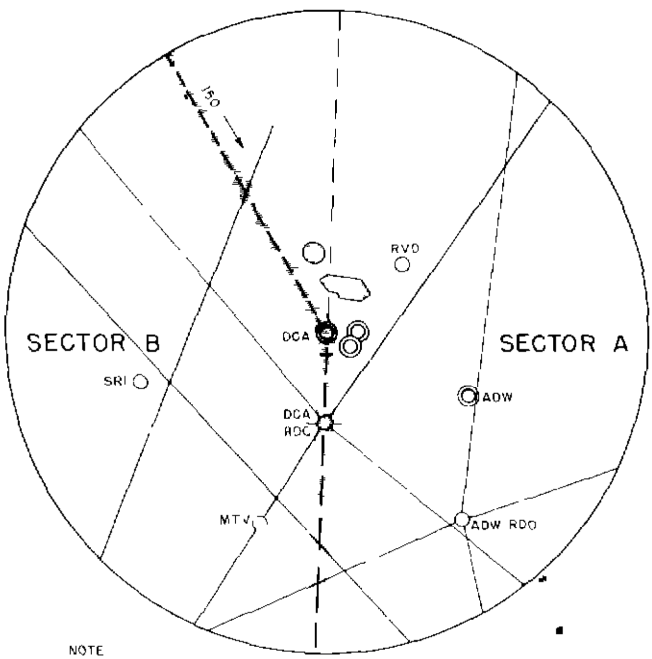


FIG 6 BASIC, ADJUSTED, AND ACTUAL SPACE-TIME CURVES FOR A SINGLE AIRCRAFT, SUPERIMPOSED IN ORDER TO SHOW THE RELATIONSHIP BETWEEN ABSOLUTE DELAY, SYSTEM DELAY, AND STACKING DELAY



NOTE
THIS DIVISION WAS USED IN ALL PHASES OF THE EVALUATION WITH THE EXCEPTION OF PHASE 5 AND PROVIDES TWO APPROACH CONTROL SECTORS WITH ACCESS TO THE FINAL APPROACH PATHS OF RUNWAY 36 AND RUNWAY 15

FIG 7 STANDARD SECTOR DIVISION

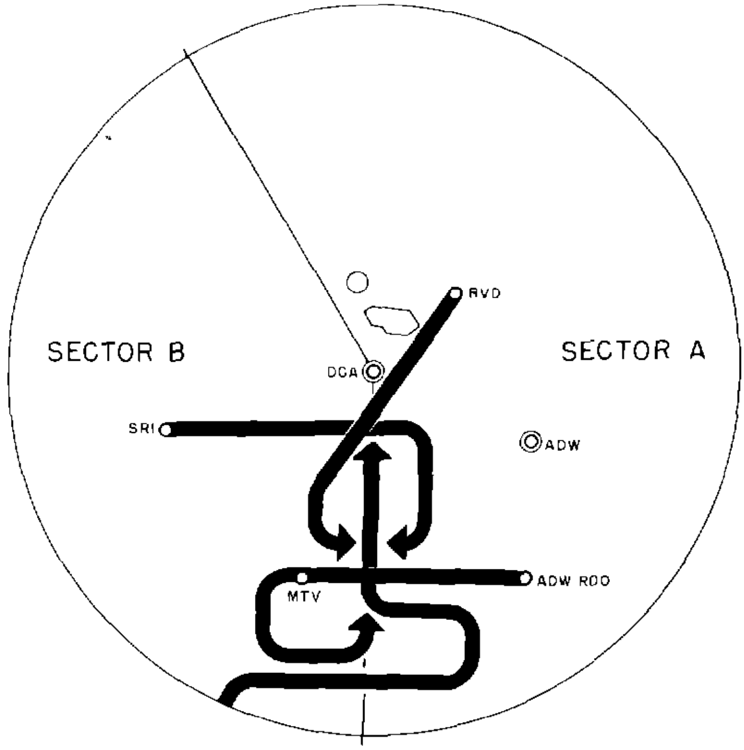


FIG 8 SECTOR CROSS-FEEDING
ROUTES, NORTH LANDINGS

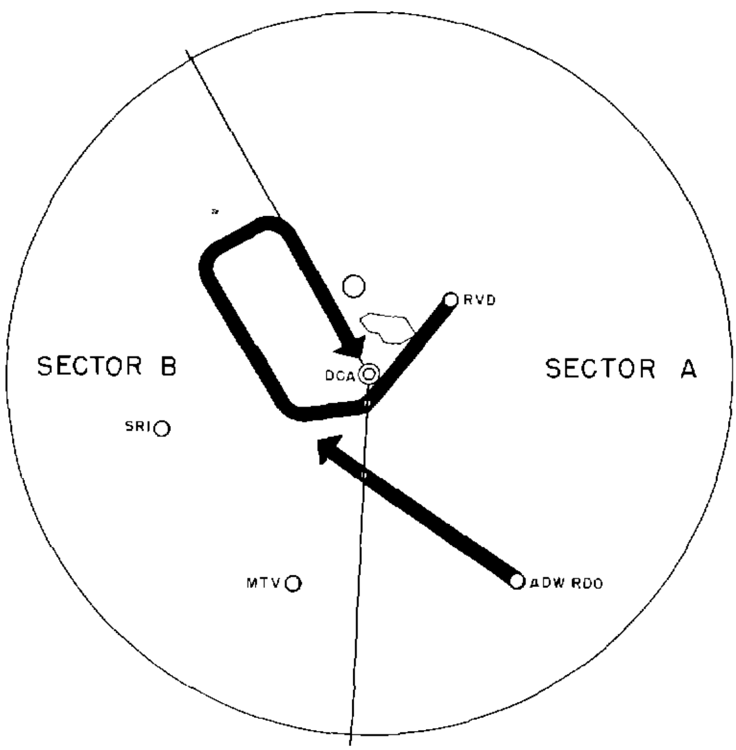


FIG 9 SECTOR CROSS-FEEDING ROUTES,
SOUTHEAST LANDINGS

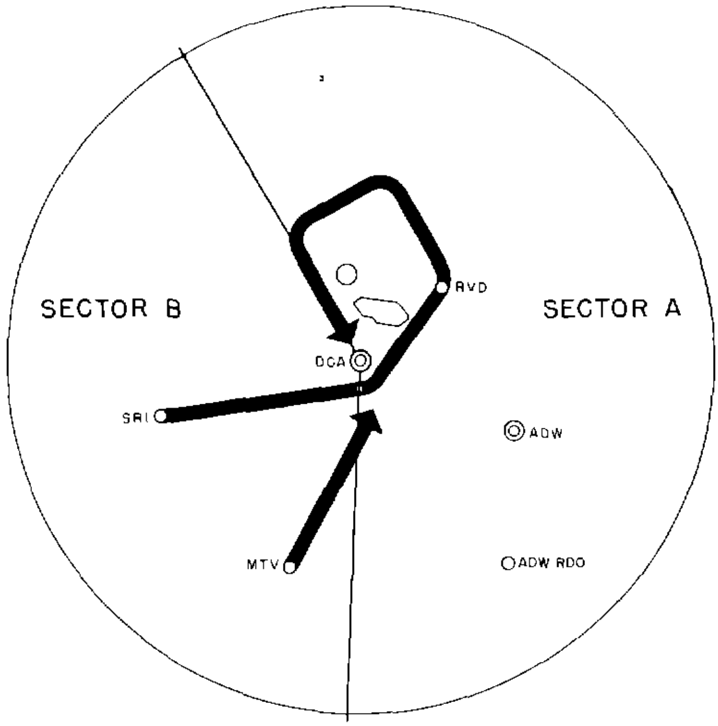


FIG 10 SECTOR CROSS-FEEDING ROUTES, SOUTHEAST LANDINGS

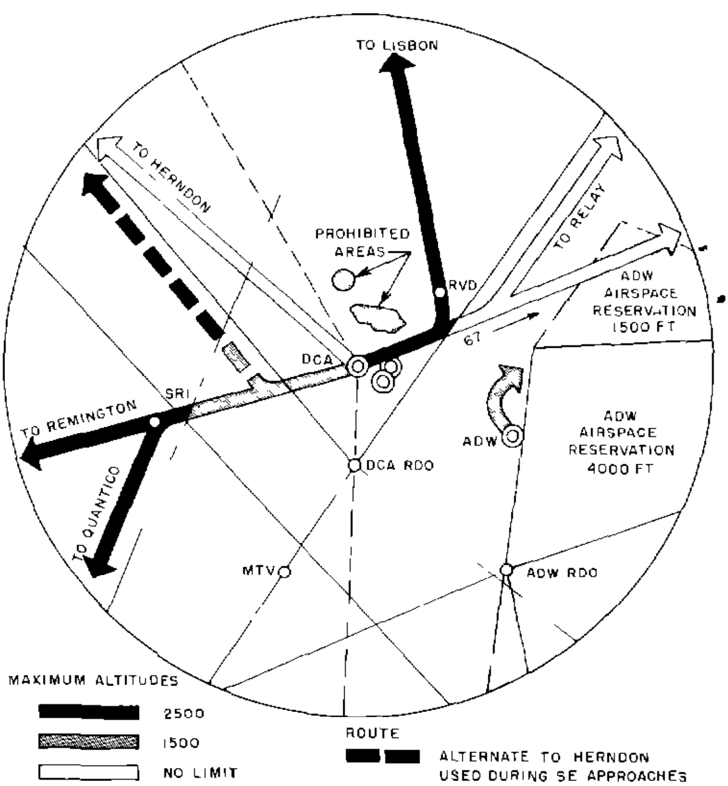


FIG 11 DEPARTURE ROUTES AND RESTRICTIONS

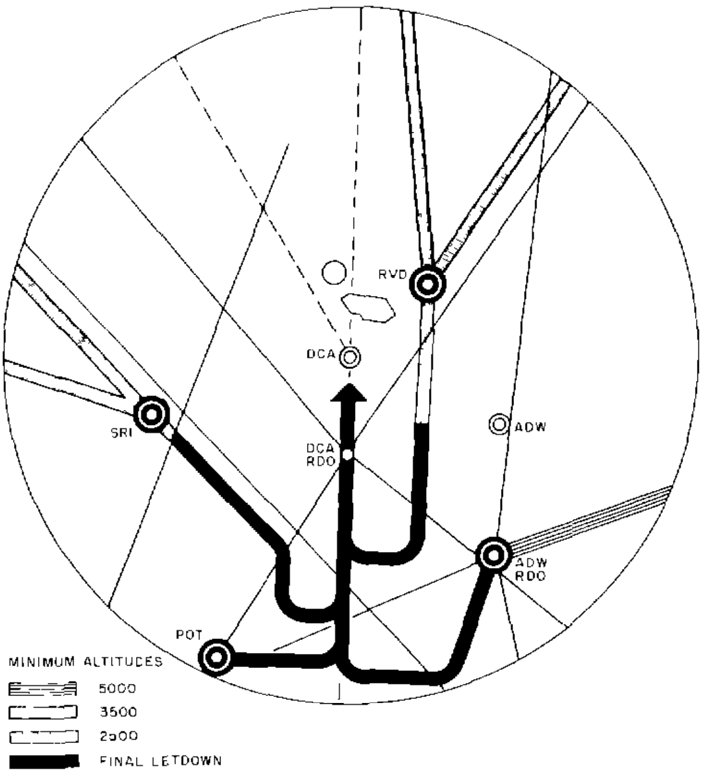


FIG 12 FLIGHT PATTERNS, NORTH LANDINGS (PHASE I)

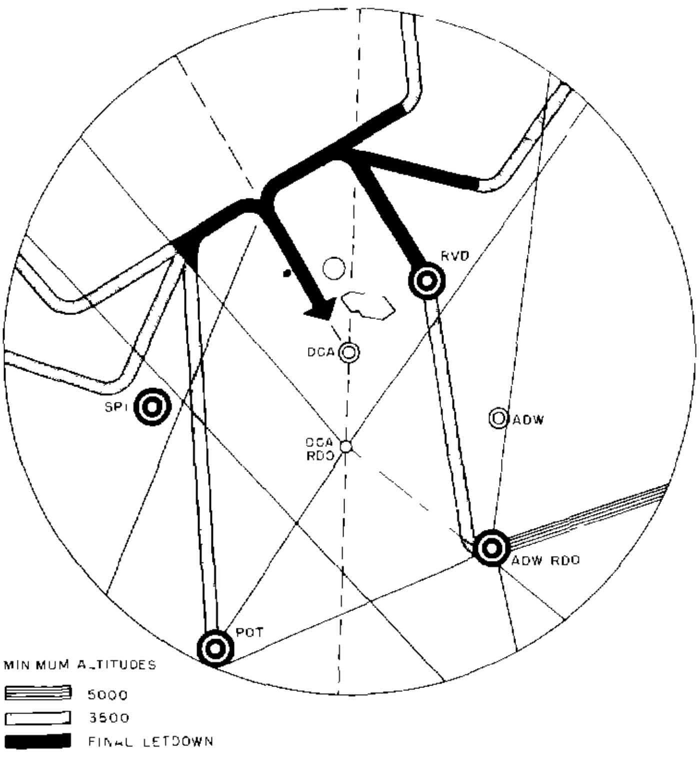


FIG 13 FLIGHT PATTERNS, SOUTH-EAST LANDINGS (PHASE I)

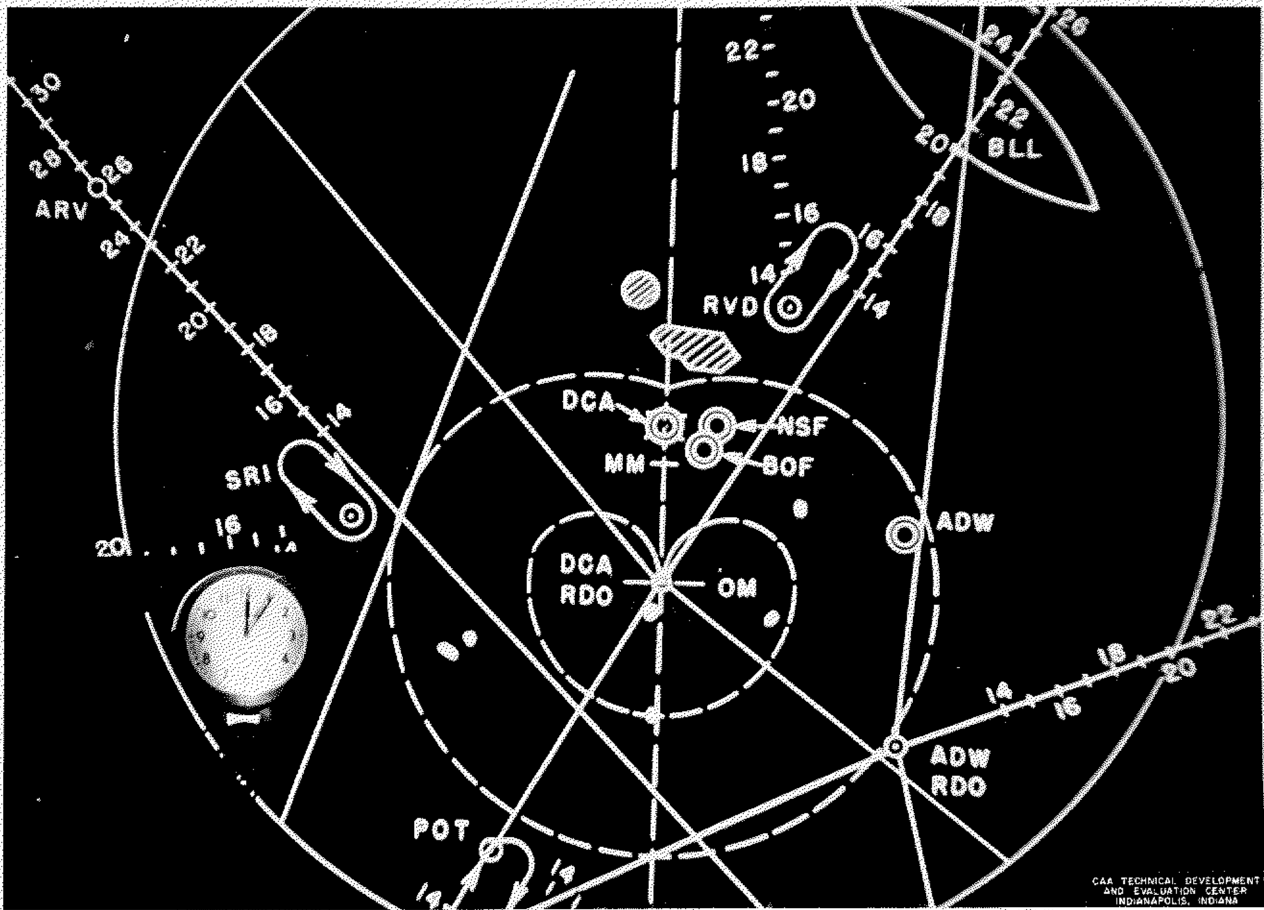


FIG. 14 AIRCRAFT IN VECTORING PATTERNS (PHASE I)

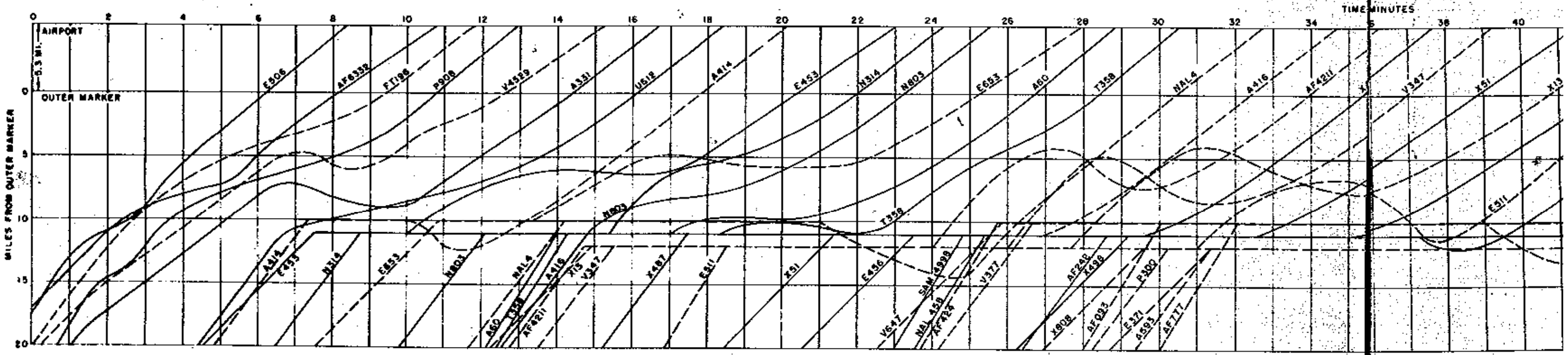


FIG. 15 ACTUAL TRAFFIC CURVE, PHASE I, RUN I, RECORDED BY MOTION PICTURE

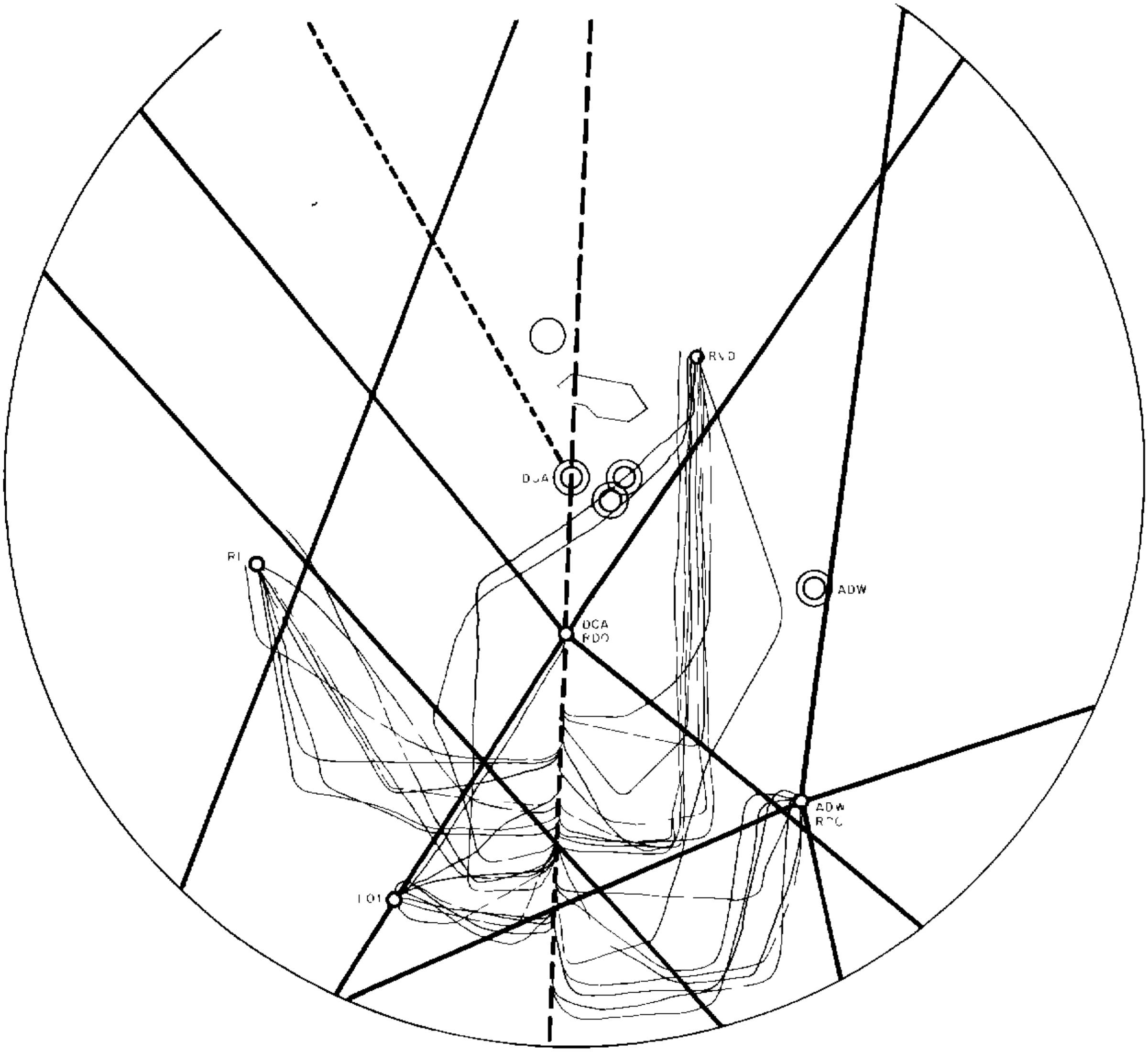


FIG 16 RECORDED NAVASCREEN FLIGHT PATHS (PHASE I)

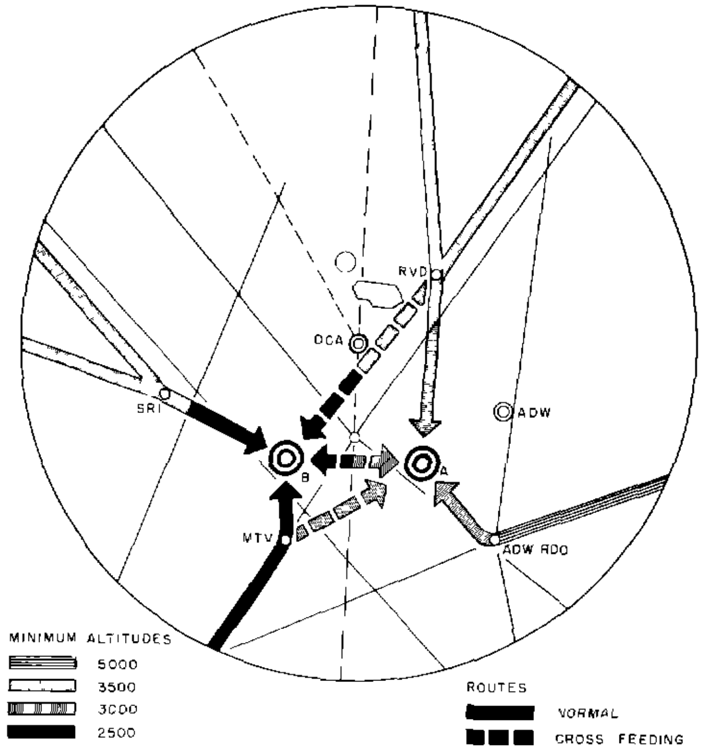
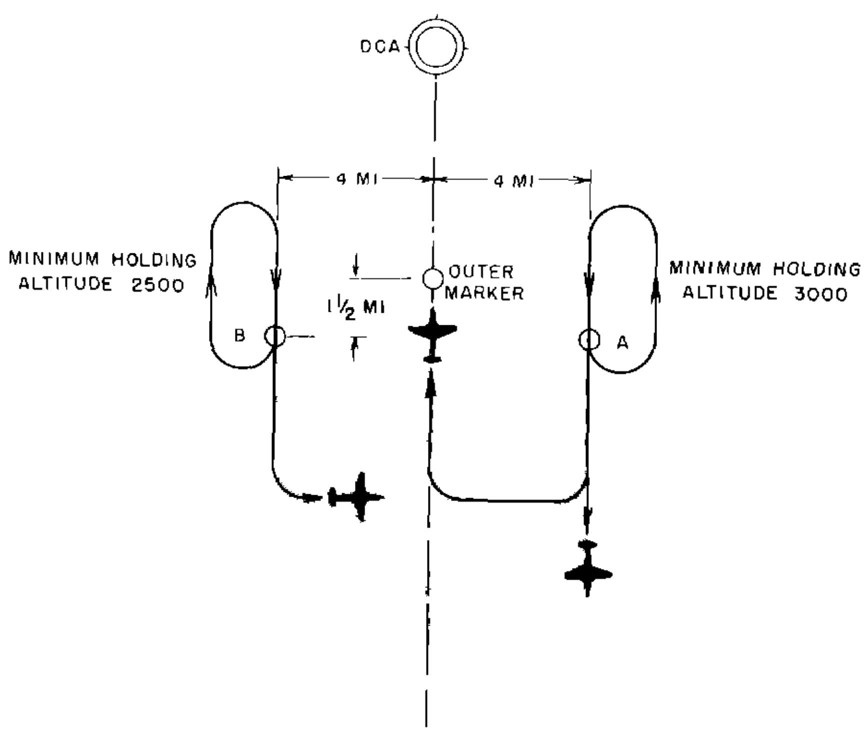


FIG 17 TWIN-STACK FEEDING SYSTEM (PHASE 2)



NOTE
SHADING INDICATES AREA NORMALLY USED FOR ADJUSTMENT OF APPROACH INTERVALS

FIG 18 TWIN-STACK APPROACH SYSTEM (PHASE 2)

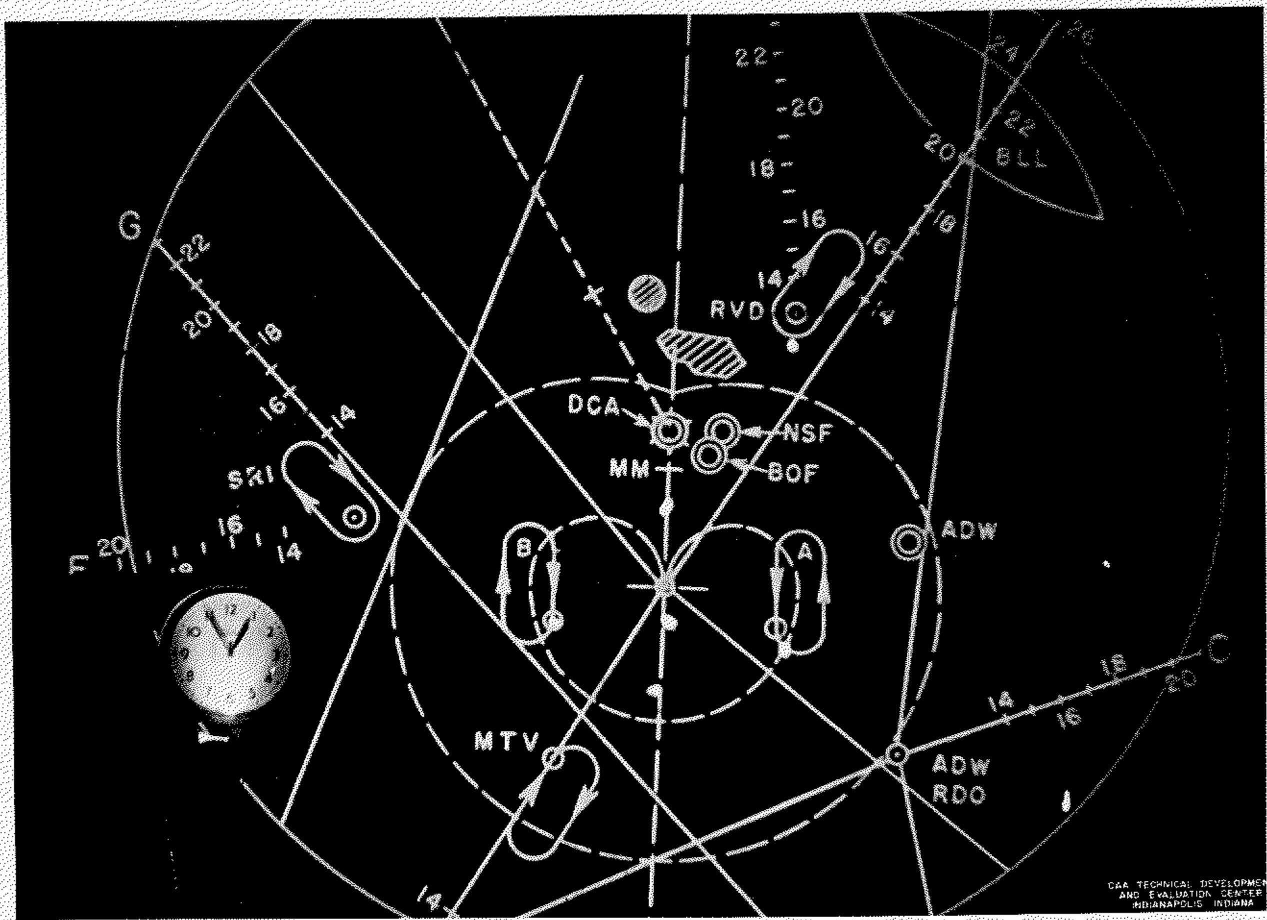


FIG. 19 AIRCRAFT IN FEEDING AND APPROACH PATTERNS (PHASE 2)

NOTE:

ONE AIRCRAFT IS LEAVING RIVERDALE ENROUTE TO STACK "A". ANOTHER IS CROSSING THE ILS AND COMES SOUTH OF THE MIDDLE MARKER ON THE CROSS-FEEDING ROUTE TO STACK "B". ONE AIRCRAFT IS ON FINAL APPROACH; ANOTHER IS TURNING ON FINAL ABOUT 4 MILES SOUTH OF THE OUTER MARKER. ONE AIRCRAFT IS LEAVING STACK "A" SOUTHBOUND; ANOTHER IS HOLDING IN THE "B" PATTERN.

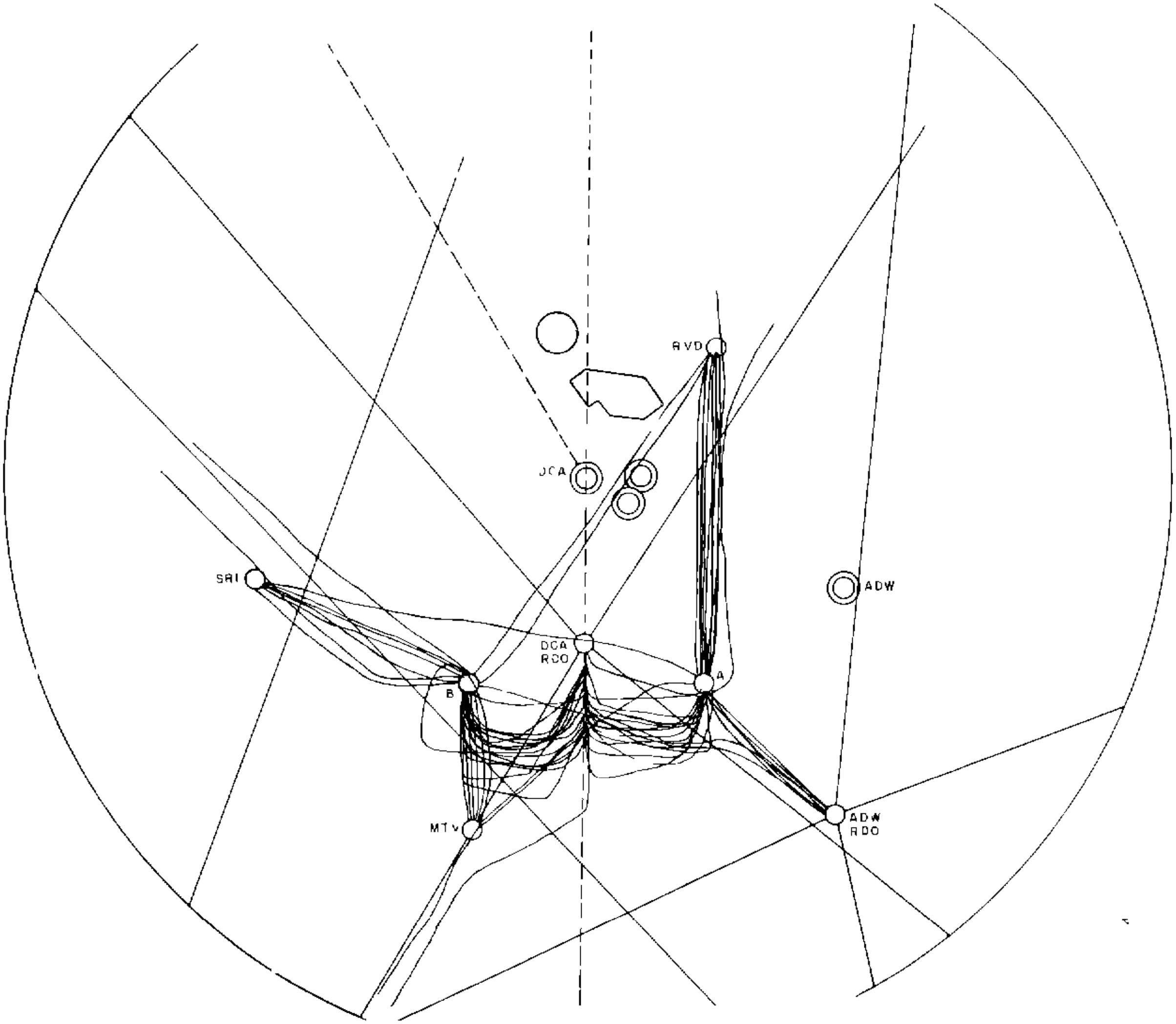


FIG 20 RECORDED NAVASCREEN FLIGHT PATHS (PHASE 2)

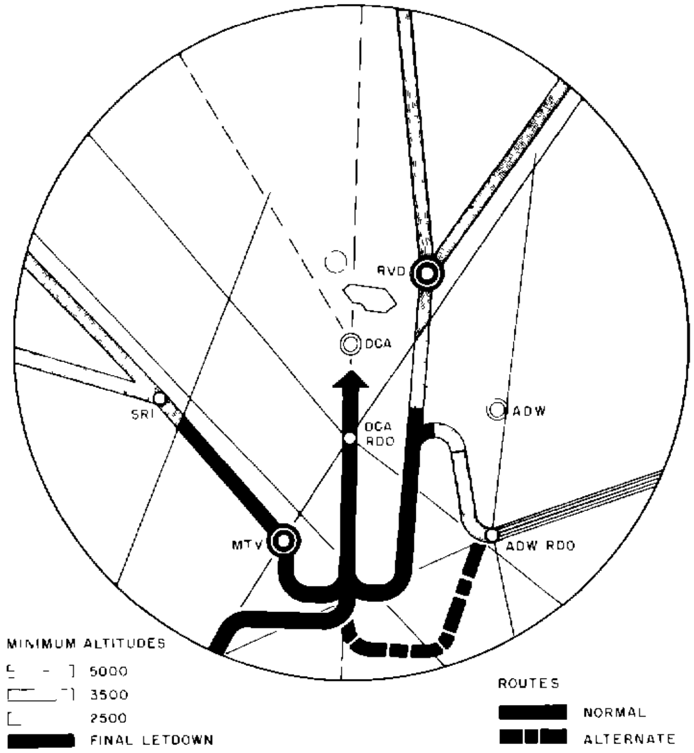


FIG 21 FLIGHT PATTERNS, NORTH LANDINGS (PHASE 3)

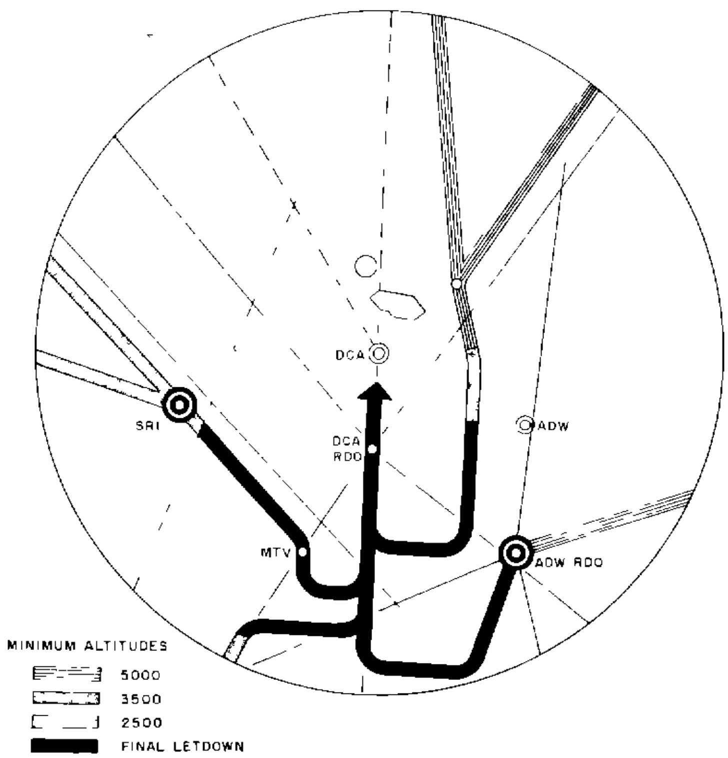


FIG 22 FLIGHT PATTERNS, NORTH LANDINGS (PHASE 4)

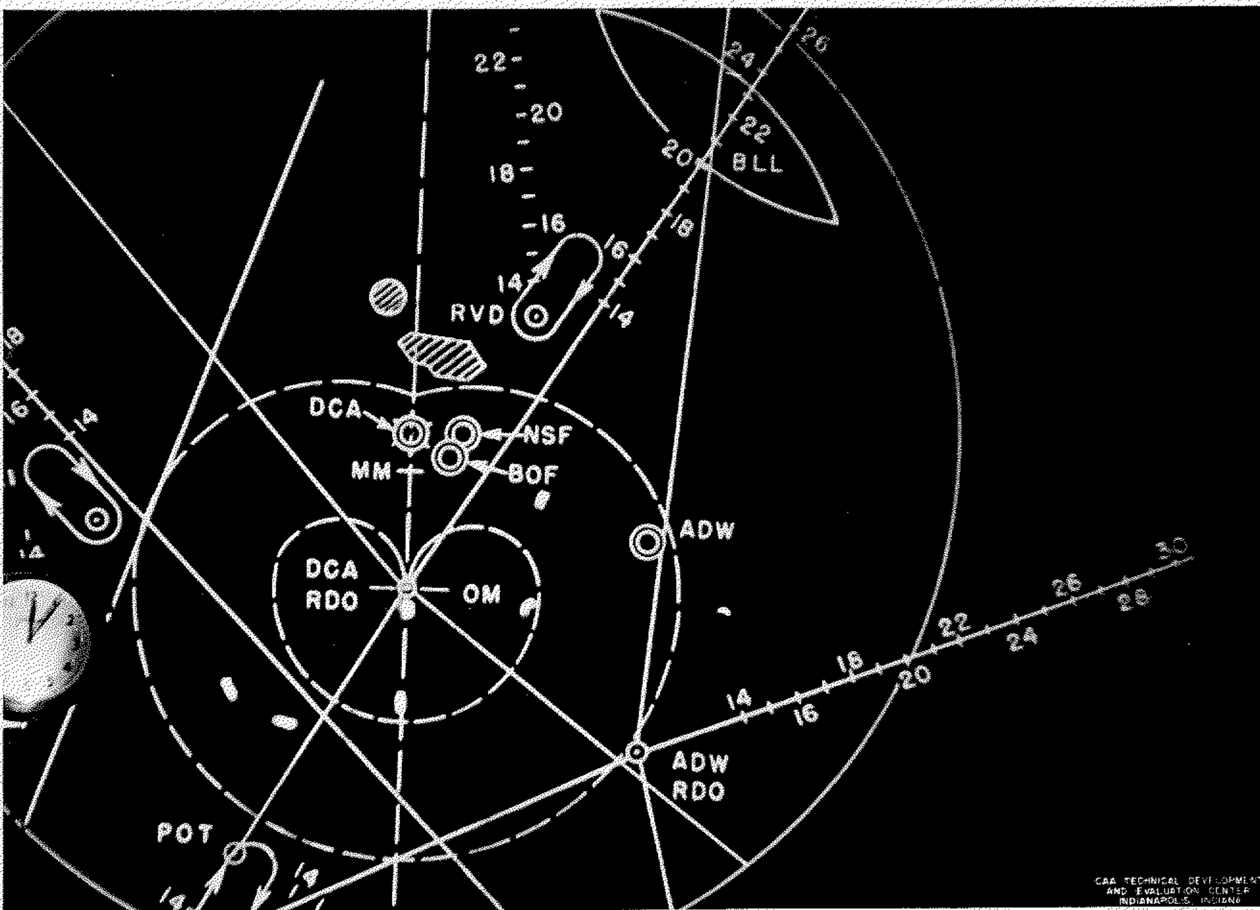


FIG. 23 AIRCRAFT IN VECTORING PATTERNS (PHASE 4)

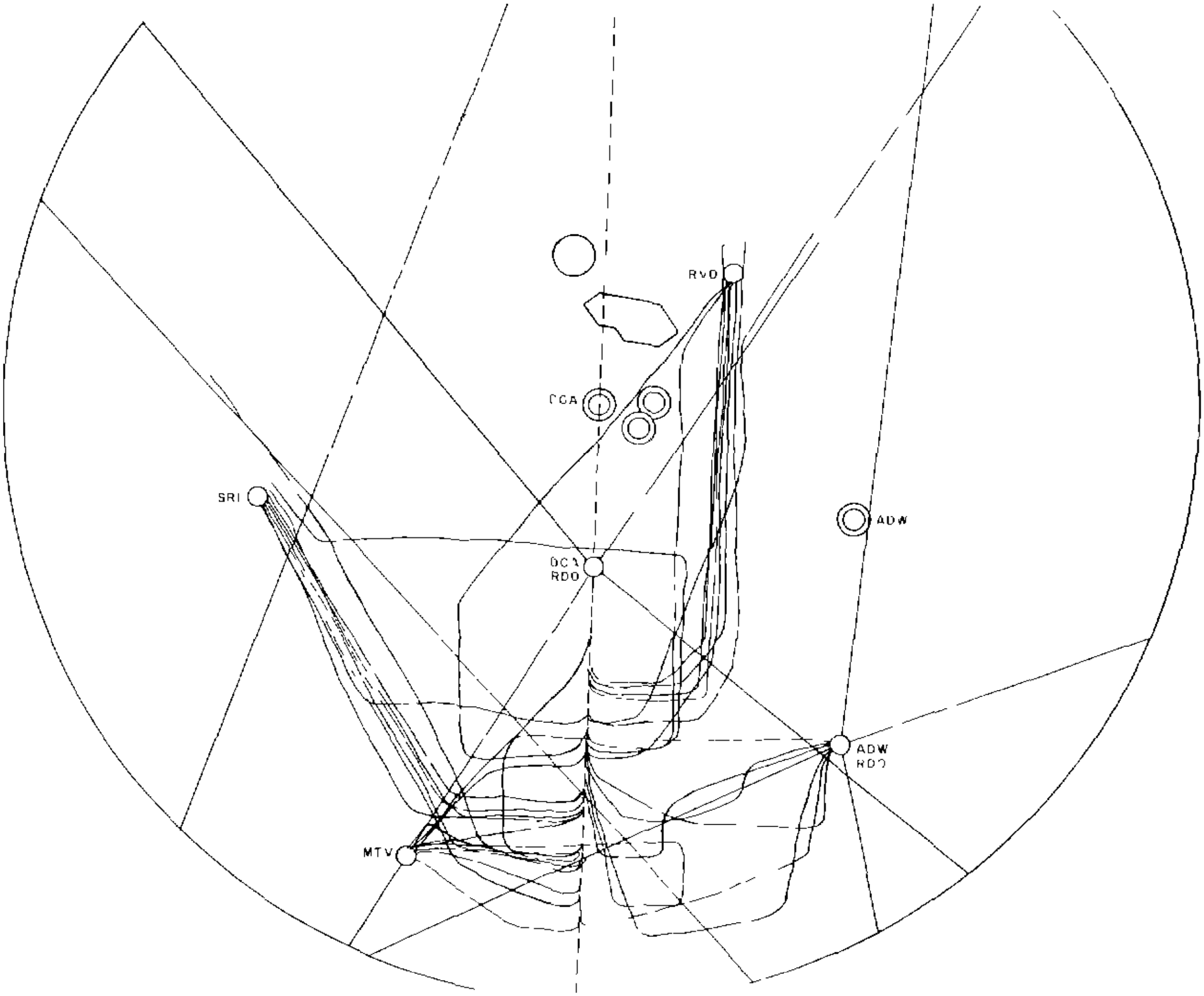


FIG 24 RECORDED NAVASCREEN FLIGHT PATHS (PHASE 4)

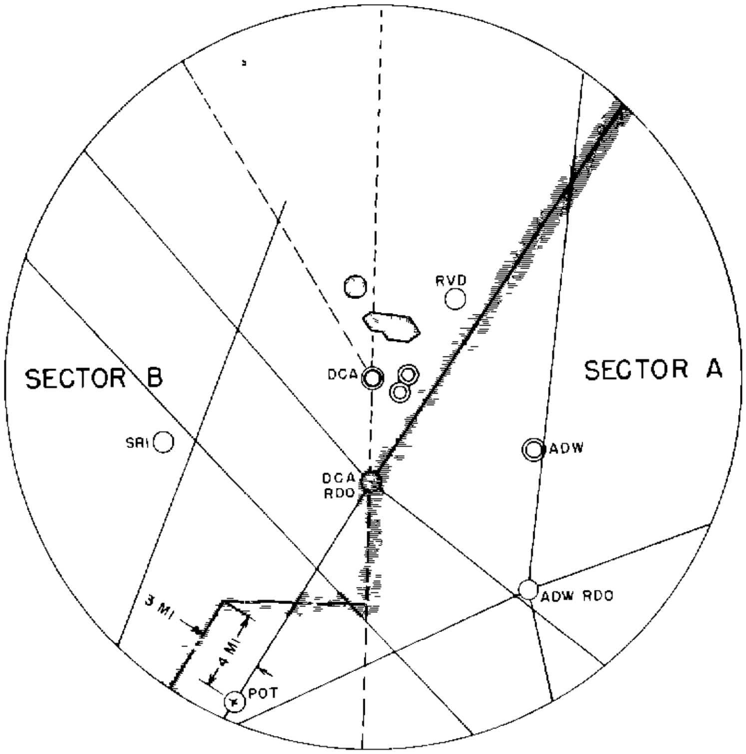


FIG 25 SECTOR DIVISION (PHASE 5)

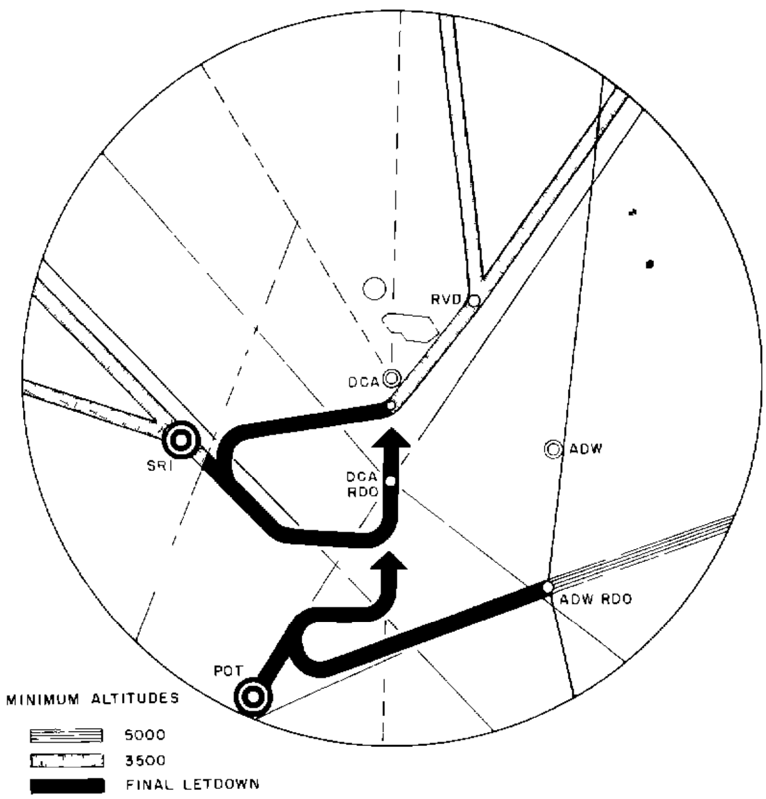


FIG 26 FLIGHT ROUTES (PHASE 5)

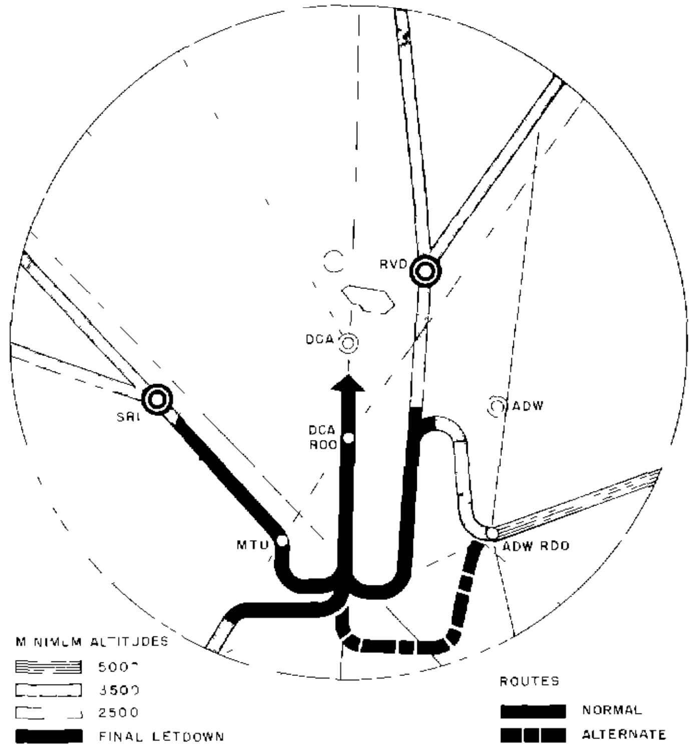


FIG 27 FLIGHT PATTERNS, NORTH LANDINGS (PHASE 6)

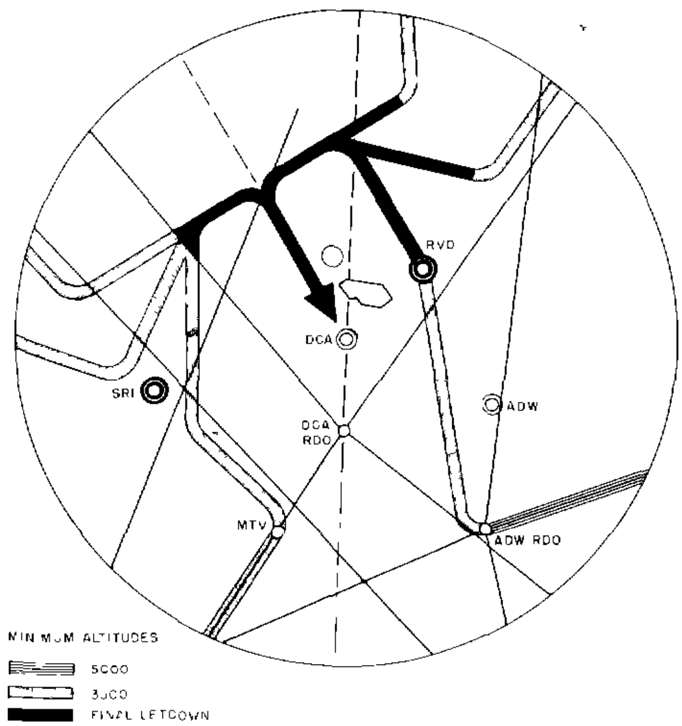


FIG 28 FLIGHT PATTERNS, SOUTHEAST LANDINGS (PHASE 6)

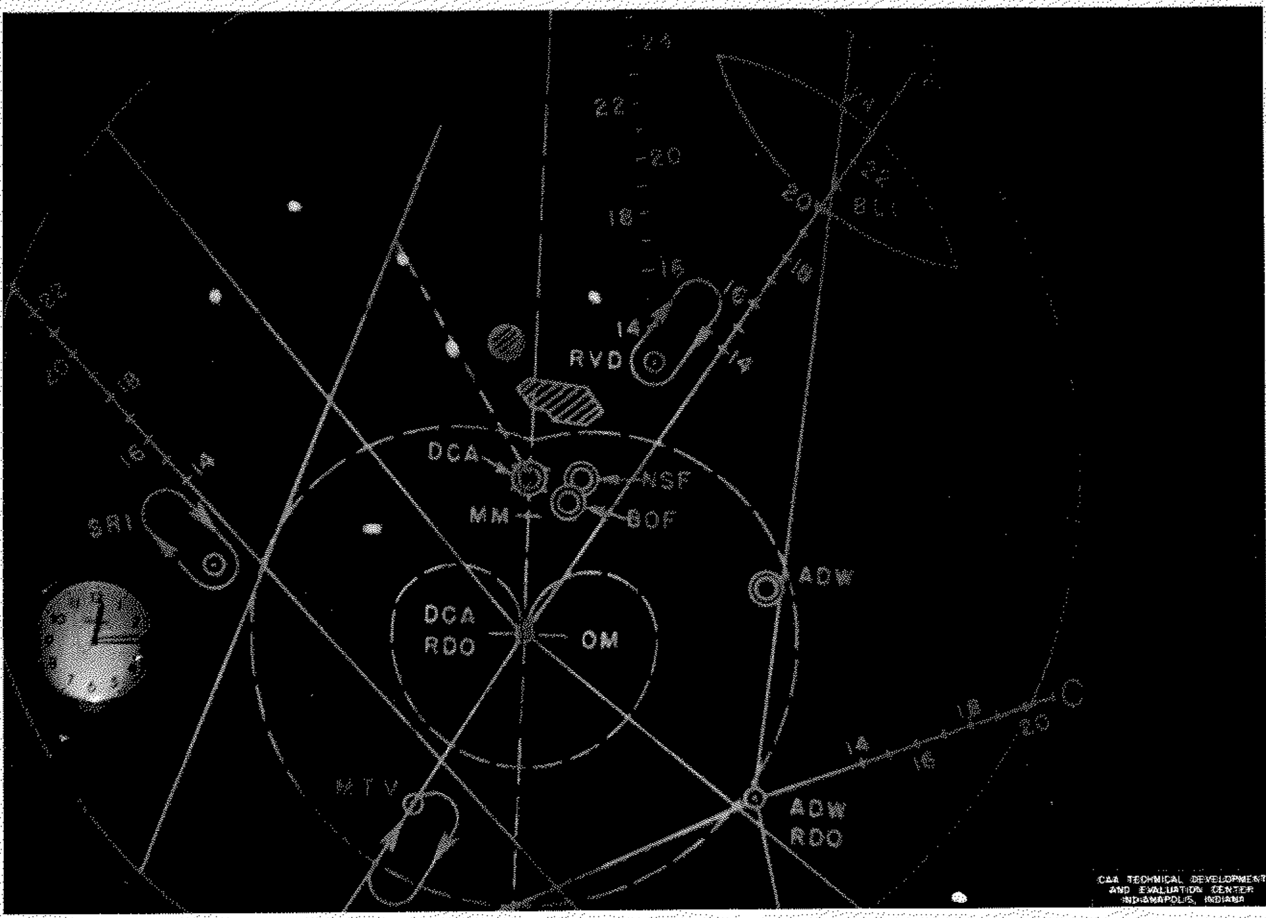


FIG. 29 AIRCRAFT IN VECTOR PATTERNS FOR SOUTHEAST LANDINGS (PHASE 6)

NOTE:

FOUR AIRCRAFT ARE IN THE SECTOR "B" PATTERN NORTHWEST OF THE WASHINGTON AIRPORT. ONLY ONE IS IN THE SECTOR "A" PATTERN. THIS AIRCRAFT HAS JUST LEFT RIVERDALE ON THE DOWNWIND LEG. ANOTHER AIRCRAFT, ABOUT 7 MILES EAST OF SPRINGFIELD, IS BEING CROSS-FED INTO THE SECTOR "A" PATTERN.

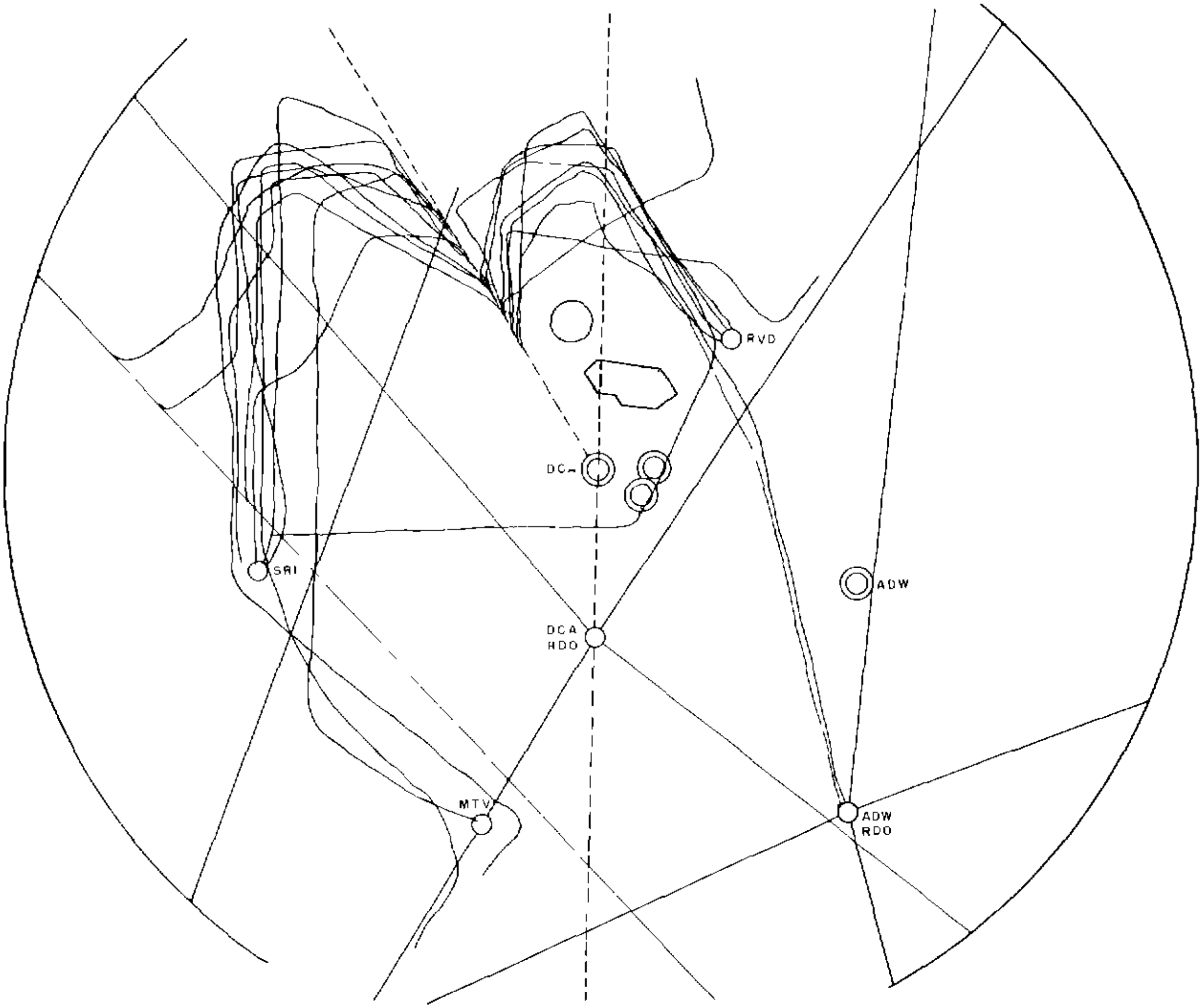


FIG 30 RECORDED NAVASCREEN FLIGHT PATHS (PHASE 6)

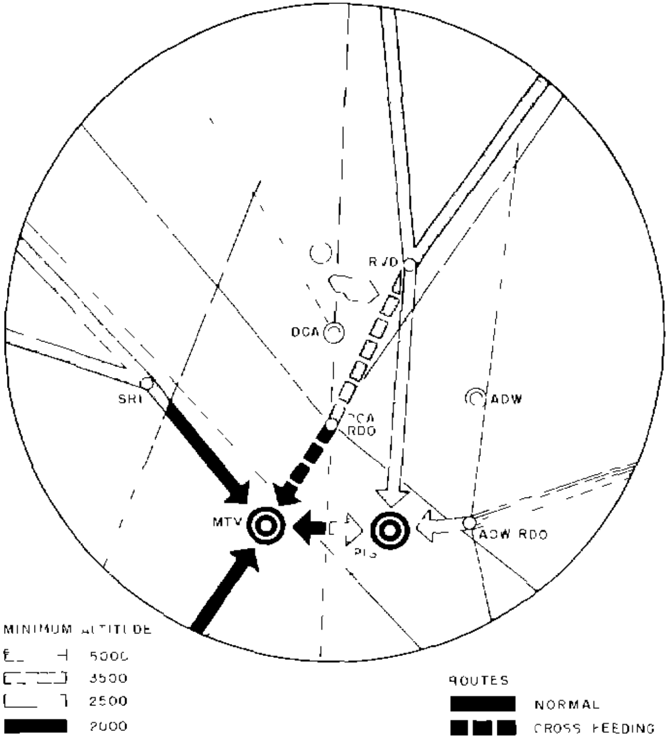


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FIG 31 TWIN-STACK FEEDING SYSTEM (PHASE 7)

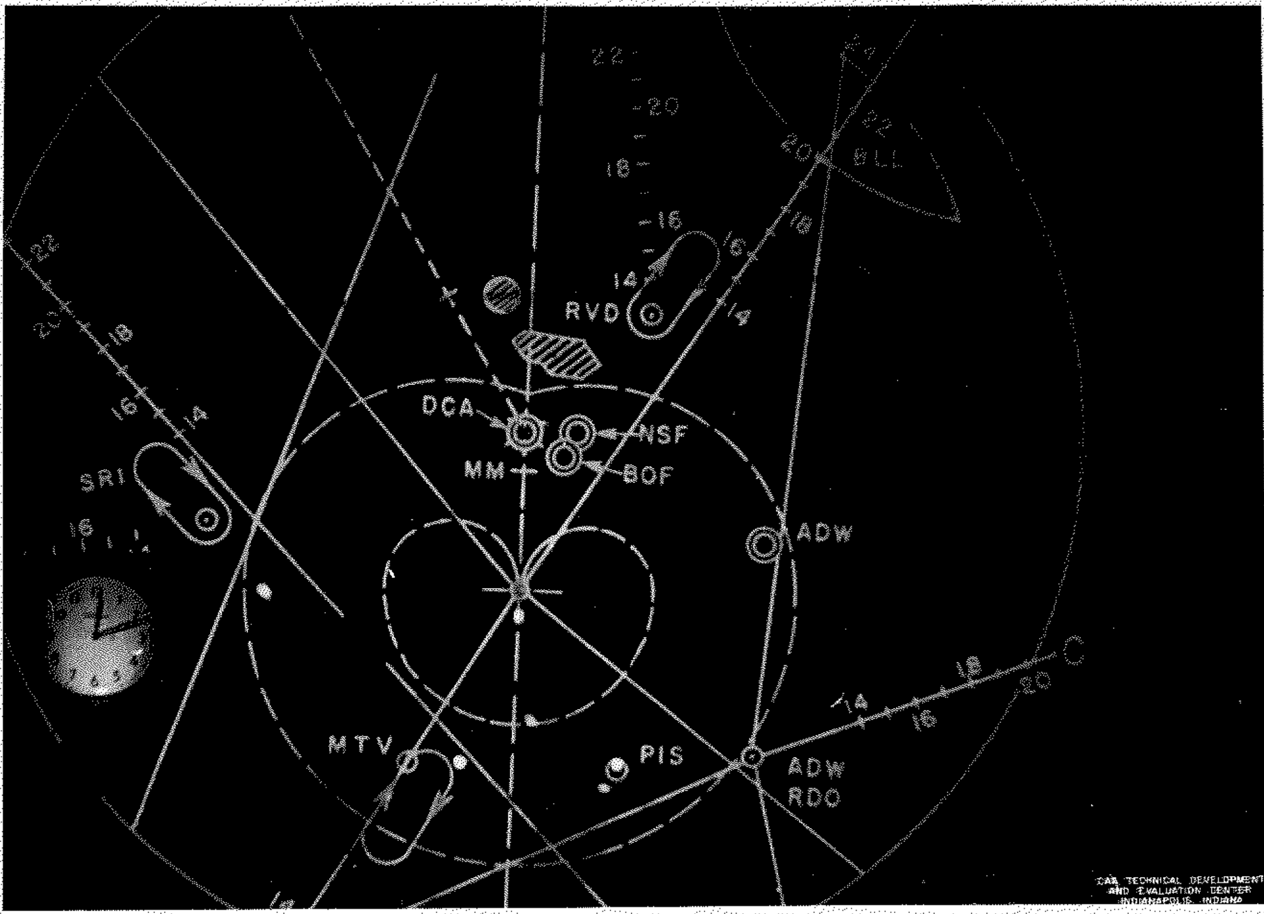


FIG. 32 AIRCRAFT IN FEEDING AND APPROACH PATTERN (PHASE 7)

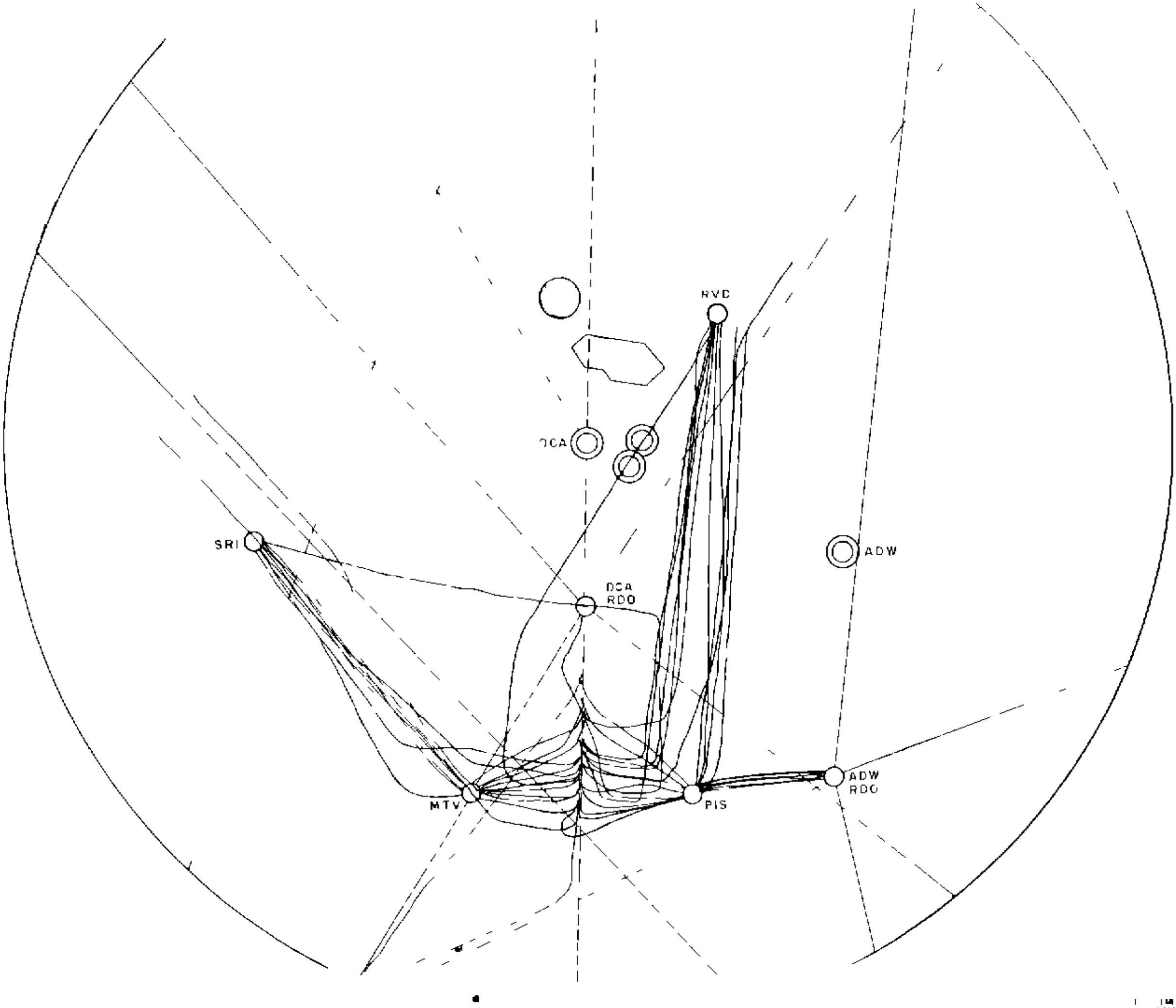
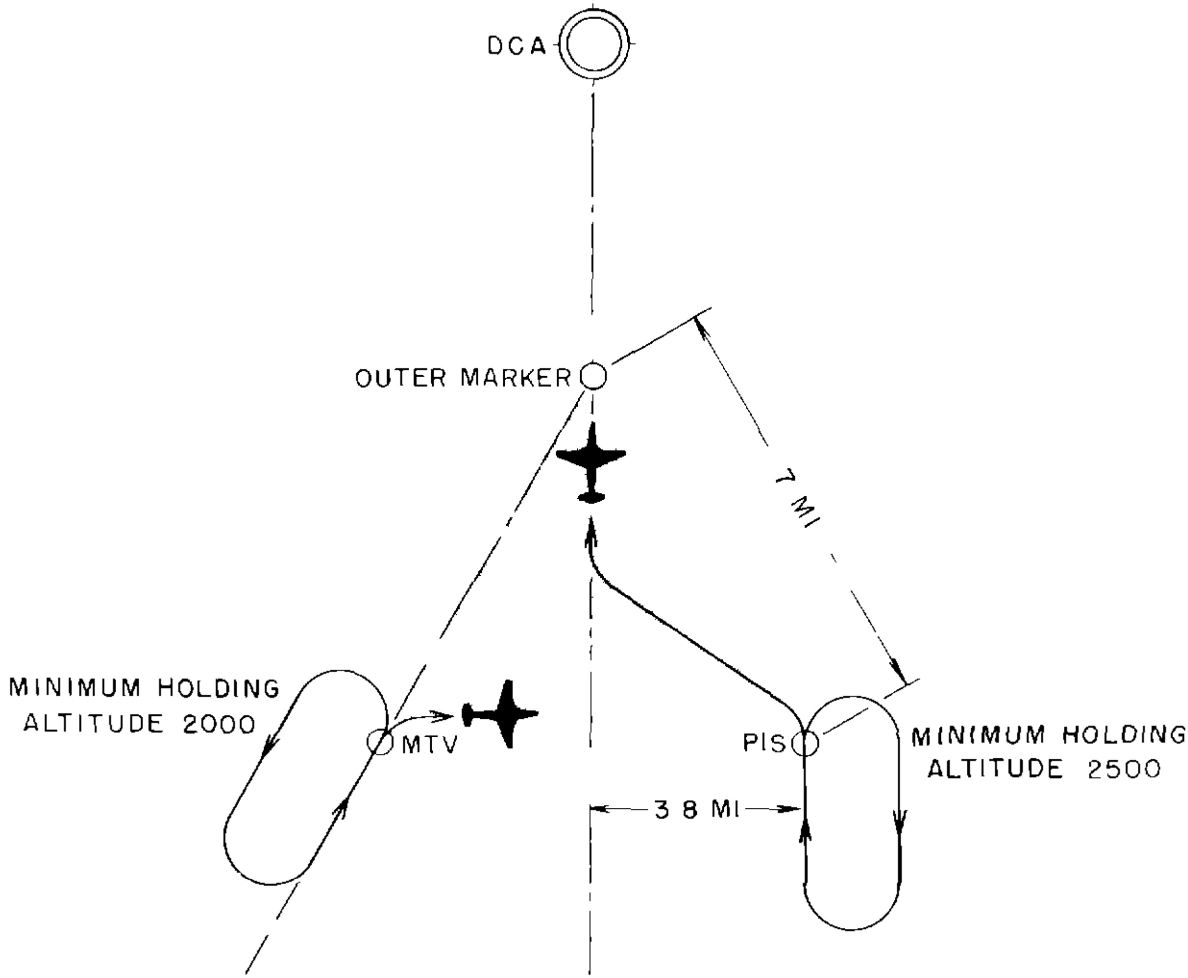


FIG. 33 RECORDED NAVASCREEN FLIGHT PATHS (PHASE 7)



NOTE
SHADING INDICATES AREA NORMALLY USED
FOR ADJUSTMENT OF APPROACH INTERVALS

FIG 34 TWIN-STACK APPROACH SYSTEM (PHASE 8)

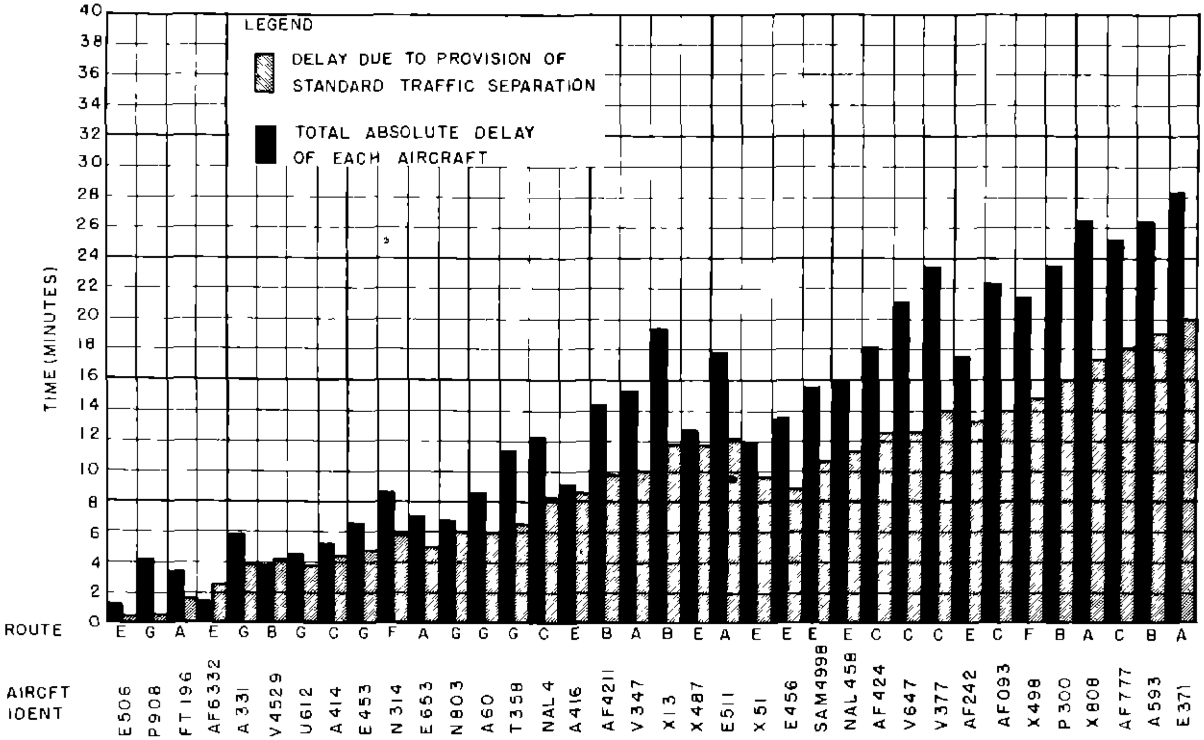


FIG 35 DELAY CHART (PHASE I)

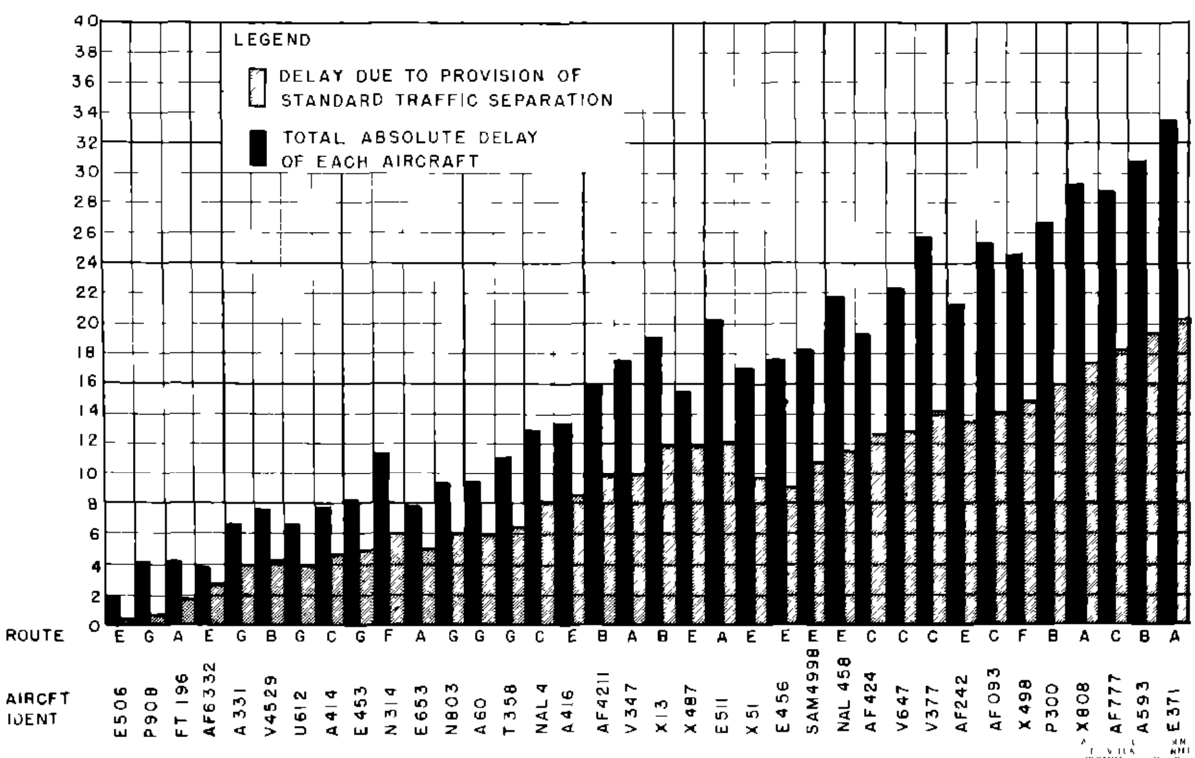


FIG 36 DELAY CHART (PHASE 2)

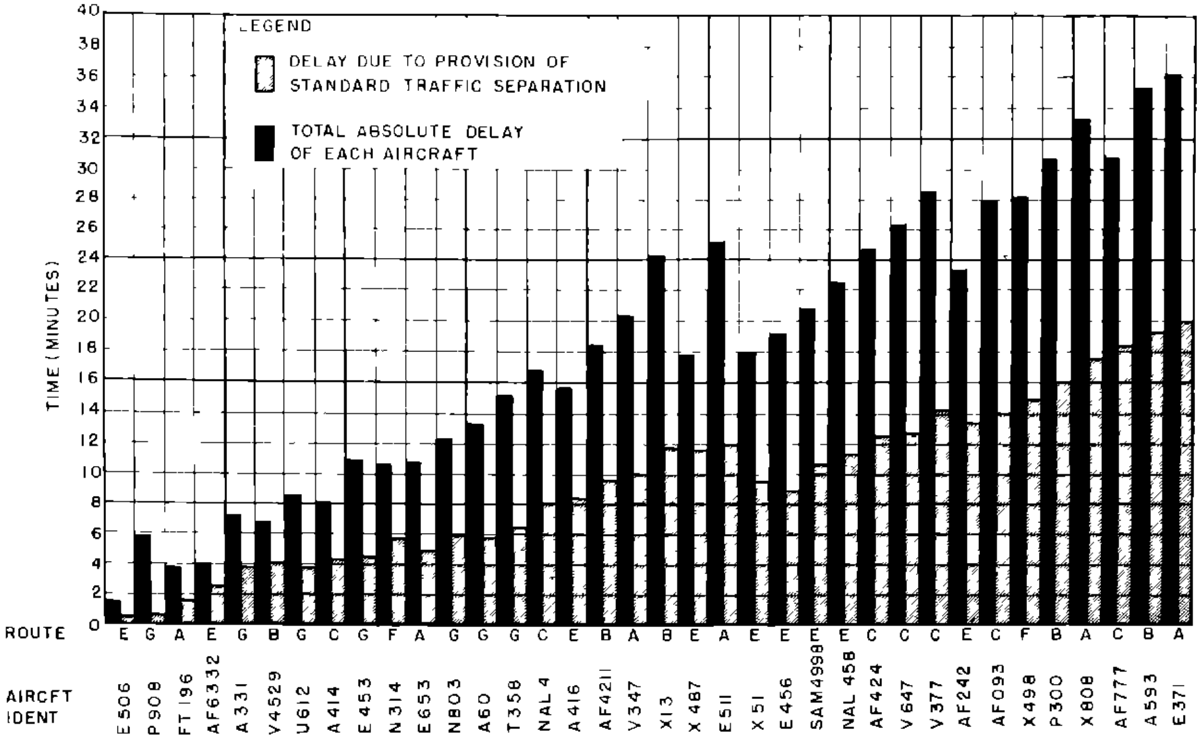


FIG 37 DELAY CHART (PHASE 3)

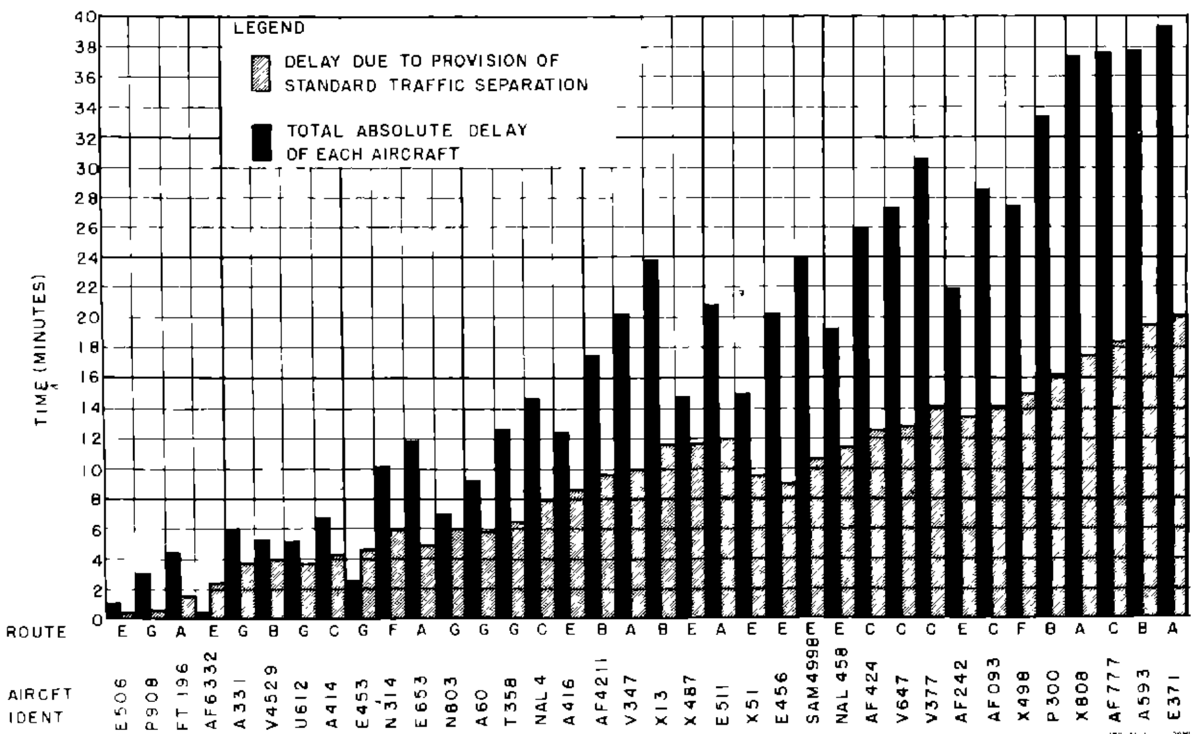


FIG 38 DELAY CHART (PHASE 4)

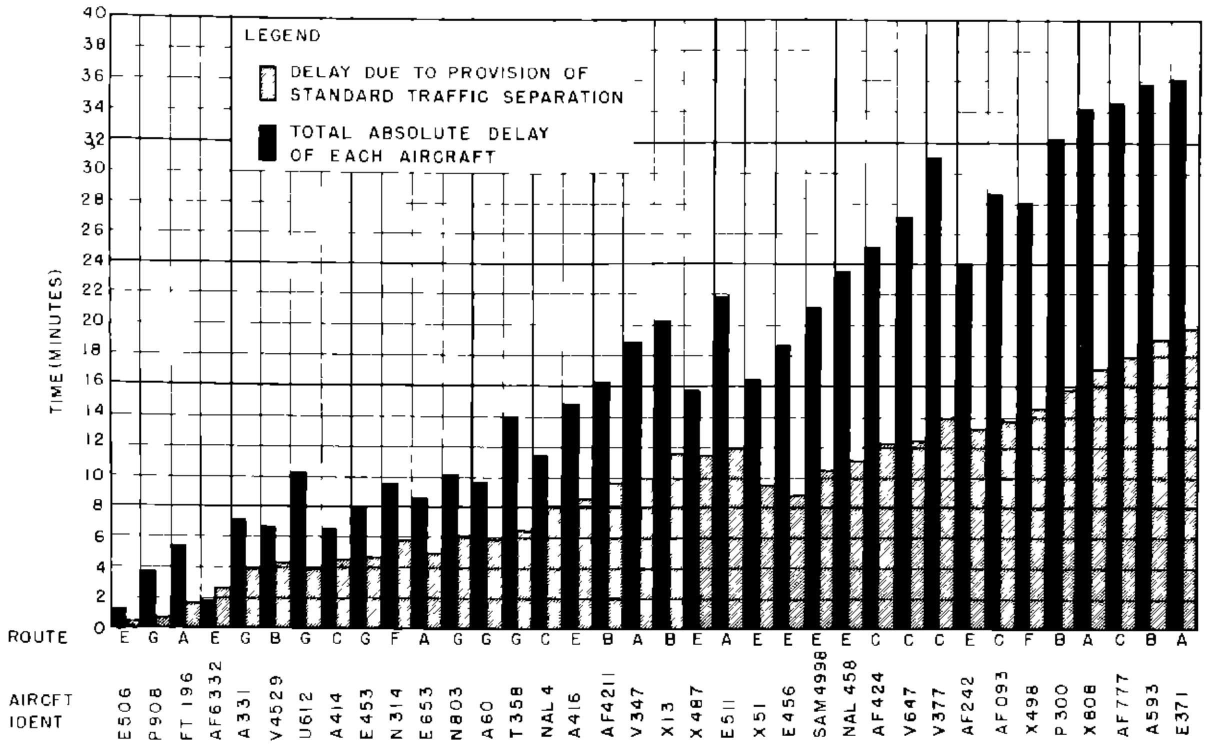


FIG 39 DELAY CHART (PHASE 5)

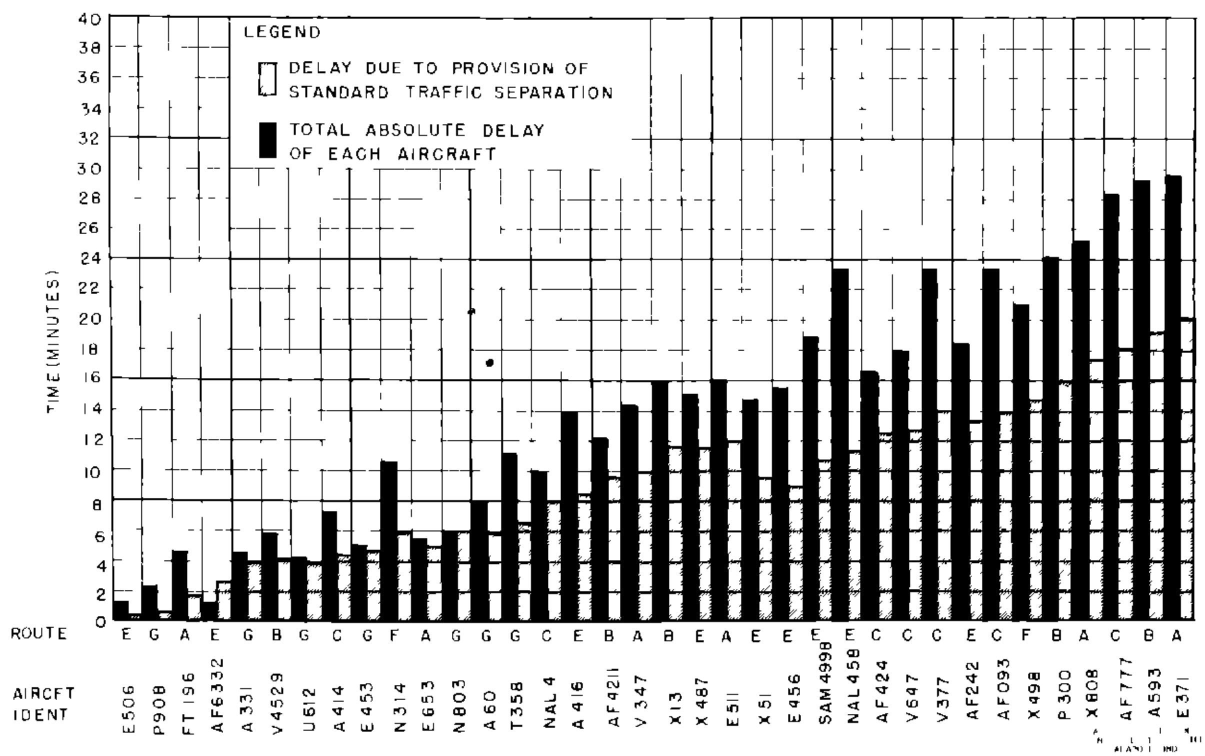


FIG 40 DELAY CHART (PHASE 6)

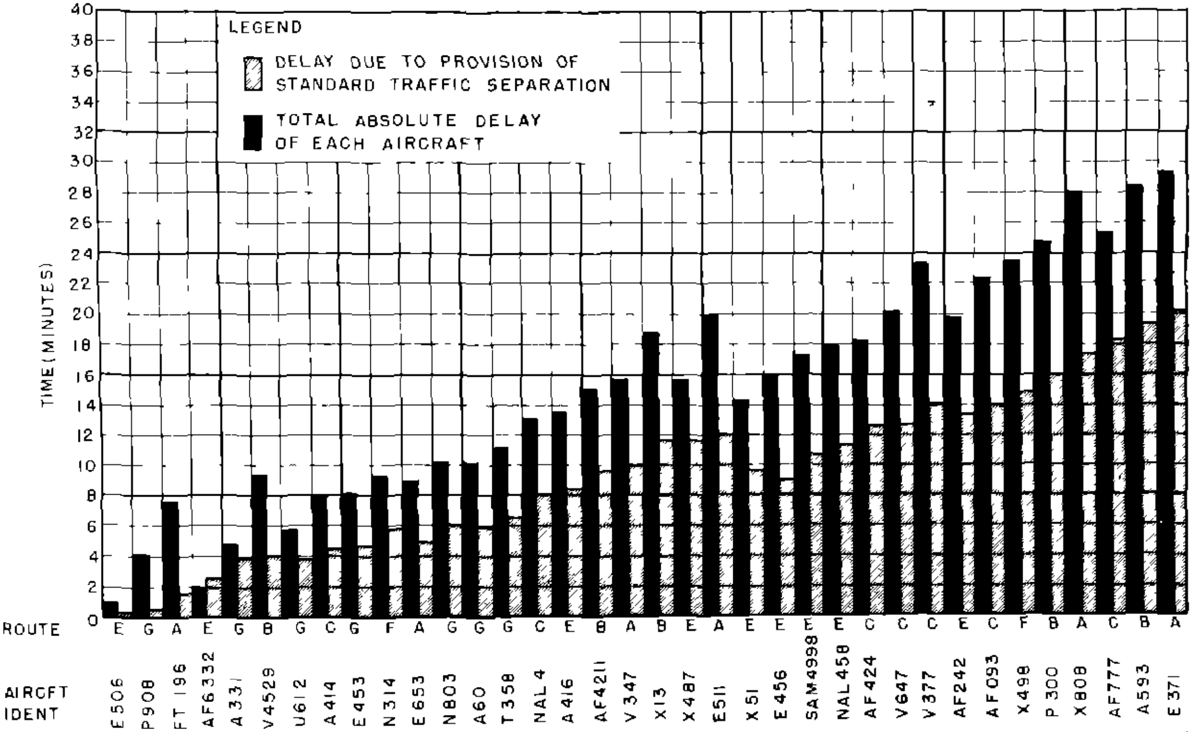


FIG 41 DELAY CHART (PHASE 7)

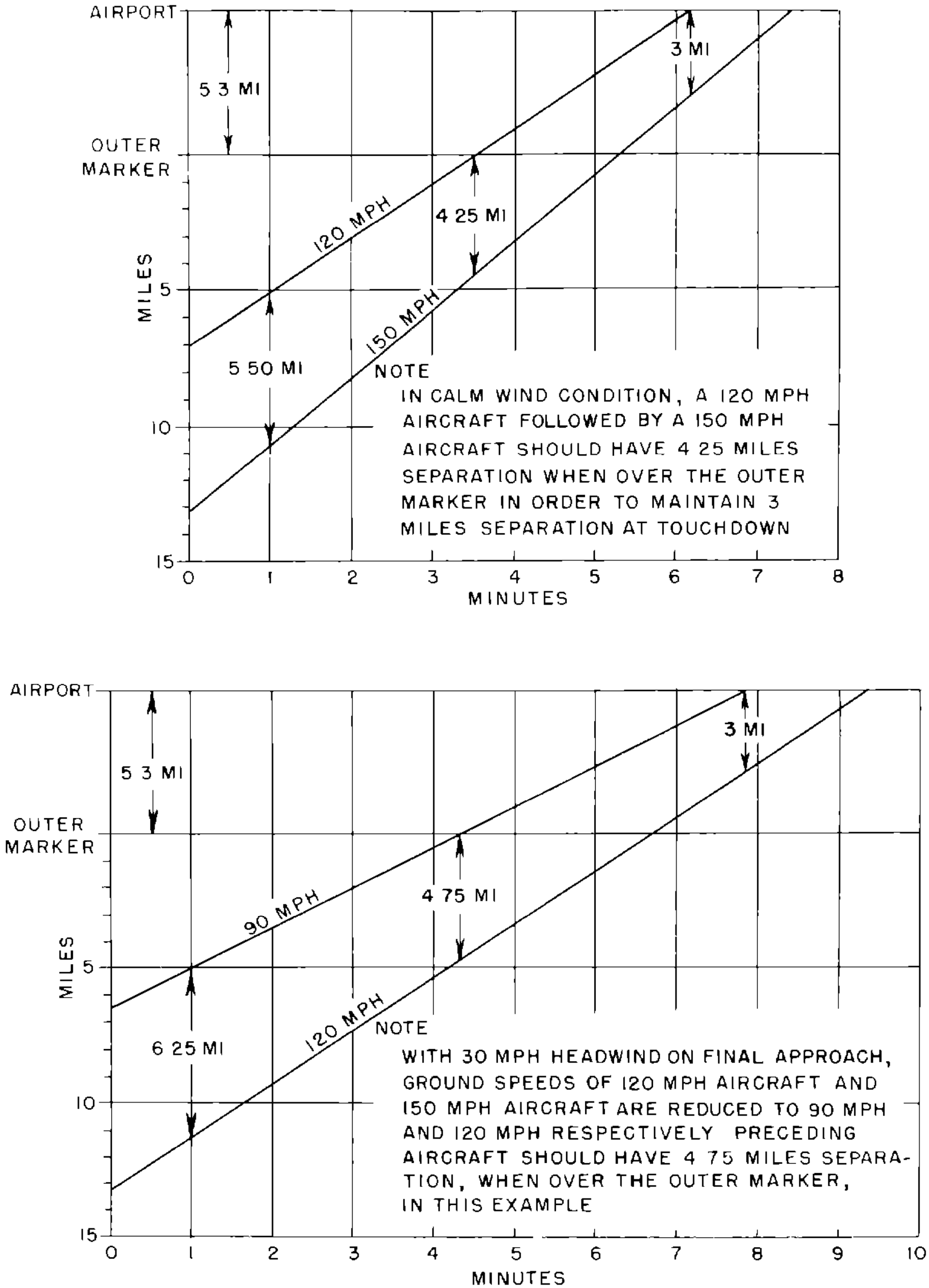


FIG 42 EFFECT OF HEADWIND ON SEPARATION REQUIRED BETWEEN AIRCRAFT ON ILS APPROACH AT WASHINGTON NATIONAL AIRPORT