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FINAL REPORT

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ATC CONCEPTS FOR SUPERSONIC VEHICLES

PART 1

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Test and Evaluation Division

National Aviation Facilities Experimental Center

Atlantic City, New Jersey

FINAL REPORT

ATC CONCEPTS FOR SUPERSONIC VEHICLES - PART I

PROJECT NO. 150-512-01X
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August 1966

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ABSTRACT

This report describes dynamic simulation studies which are a part of a joint Federal Aviation Agency (FAA) and National Aeronautic and Space Administration (NASA) simulation program to determine what impact the Supersonic Transport (SST) will have on the Air Traffic Control (ATC) System, as well as the Air Traffic Control System impact on the supersonic transport operating characteristics.

The simulation studies conducted at NAFEC, tested three ATC systems; Present, Experimental and Pictorial Display. These systems investigated current and special control procedures, increased separation standards, high and low priority handling, and pictorial display navigation capability for SSTs. A supersonic transport flight simulator located at NASA, Hampton, Virginia, and the FAA ATC simulators at Atlantic City, New Jersey, were tied together for these studies. Actual performance and handling characteristics of a fixed and variable sweep supersonic transport configuration were simulated.

Results showed that penalties in the form of delay and reduced operation rates were incurred by other air traffic in each system in which increased separation standards and high priority treatment were provided to the SSTs. Low priority treatment and present day separation standards offer the most acceptable compromise between rigid SST priority and the flexibility needed by the ATC system. Current Air Route Traffic Control Center sectors were found to be too small for efficient control of aircraft operating at supersonic speeds.

author

INTRODUCTION

Purpose

The purpose of this program is to determine the effects of the Supersonic Transport (SST) on Air Traffic Control (ATC) system requirements and to determine the effects of the ATC systems on SST design requirements and operating techniques.

Background

The Federal Aviation Agency (FAA) and the National Aeronautics and Space Administration (NASA), Langley Research Center, Hampton, Virginia, In January 1963, established a joint simulation program to study problems anticipated in introducing the SST into the ATC system. The program, divided into three parts, calls for the investigation of SST operations in an ATC system of today (Part I), 1970 (Part II), and 1975 (Part III).

A supersonic transport flight simulator at the NASA Langley Research Center and the ATC simulator at the FAA National Aviation Facilities Experimental Center (NAFEC), Atlantic City, N. J., were used in studying the anticipated problems. Various air traffic situations that included SSTs were used to investigate present ATC procedures, experimental ATC procedures, and pictorial display (PD) navigation routes.

Performance and handling characteristics of a variable sweep and a fixed wing SST design were simulated. These configurations were flown in the NASA simulator by Trans-World Airlines, United Airlines, NASA and FAA pilots.

By means of a continuing series of SST studies, it is anticipated that compatible traffic control procedures can be devised for commercial and military supersonic operations in domestic and oceanic control areas.

Results of the Part I simulation studies which started in May 1963 and were concluded in January 1966, are presented in this report.

Project Objectives

1. To determine the effects of the SST on ATC system requirements.
2. To determine the effects of the ATC system on SST design requirements and operating techniques.
3. To develop and study various control procedures and determine

which procedures offer near optimum handling of SSTs in the enroute and terminal areas.

4. To determine what effects the SST will have on controller workload.

5. To determine what effects the SST will have on other traffic.

SIMULATION PROCEDURES

Test Environments

New York, N. Y. and Oakland, Calif., test environments were used in these studies. The New York ATC simulation environment, as shown in Figures 1 and 2 consisted of two areas, each approximately 400 by 400 nautical miles. They included portions of the New York, Boston, and Cleveland Air Route Traffic Control Centers (ARTCC), the New York Oceanic Control Sectors, and the John F. Kennedy (JFK) Approach Control and Tower complex.

The Oakland ATC simulation environment shown in Figure 3, consisted of an area approximately 400 by 400 nautical miles, encompassing portions of the Oakland, Seattle and Salt Lake City ARTCCs. The San Francisco (SFO) and Oakland (OAK) Approach Control and associated tower complexes were also included.

Control quarters for the air traffic control simulation environment is shown in Figure 4. The control positions were all manned by experienced and qualified Air Traffic Control Specialists (ATCS).

Traffic Load

New York Areas The simulated traffic in the New York areas consisted of approximately 140 aircraft operations within a 90-minute test period, thereby creating a moderately dense traffic situation.

Oakland Area The Oakland/San Francisco traffic sample consisted of 120 aircraft operations within a 90-minute time period, representing a heavy density traffic situation. Traffic samples for both the simulated areas contained civil SST's, civil and military subsonic jets, turbo-props, and conventional type aircraft. SST type aircraft operated into and out of JFK and SFO airports only.

ATC Simulator

The dynamic ATC simulator is composed of radar target generators (pilot consoles), surveillance radar simulators, radar displays, flight

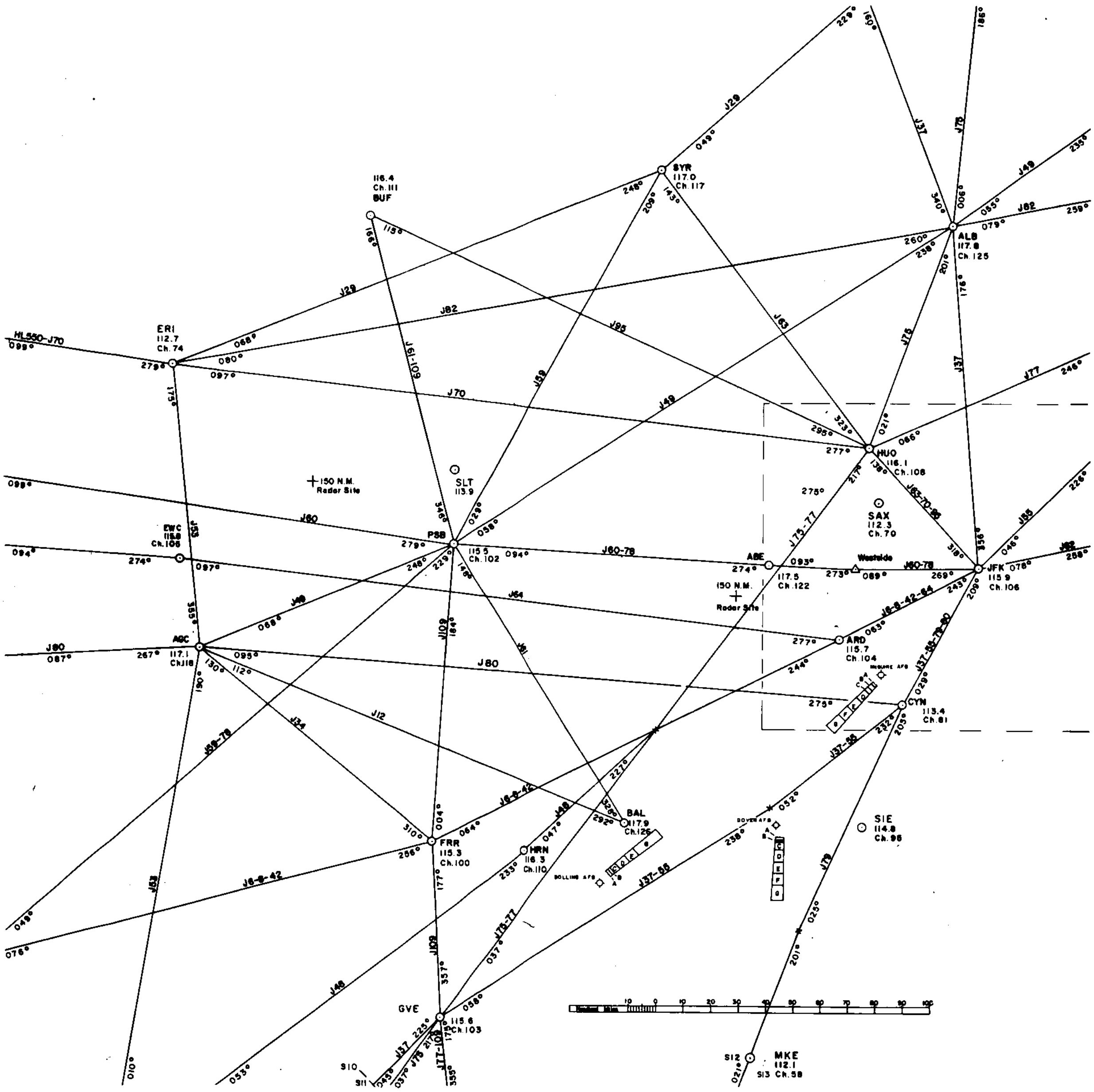

FIG. 1 NEW YORK TEST ENVIRONMENT

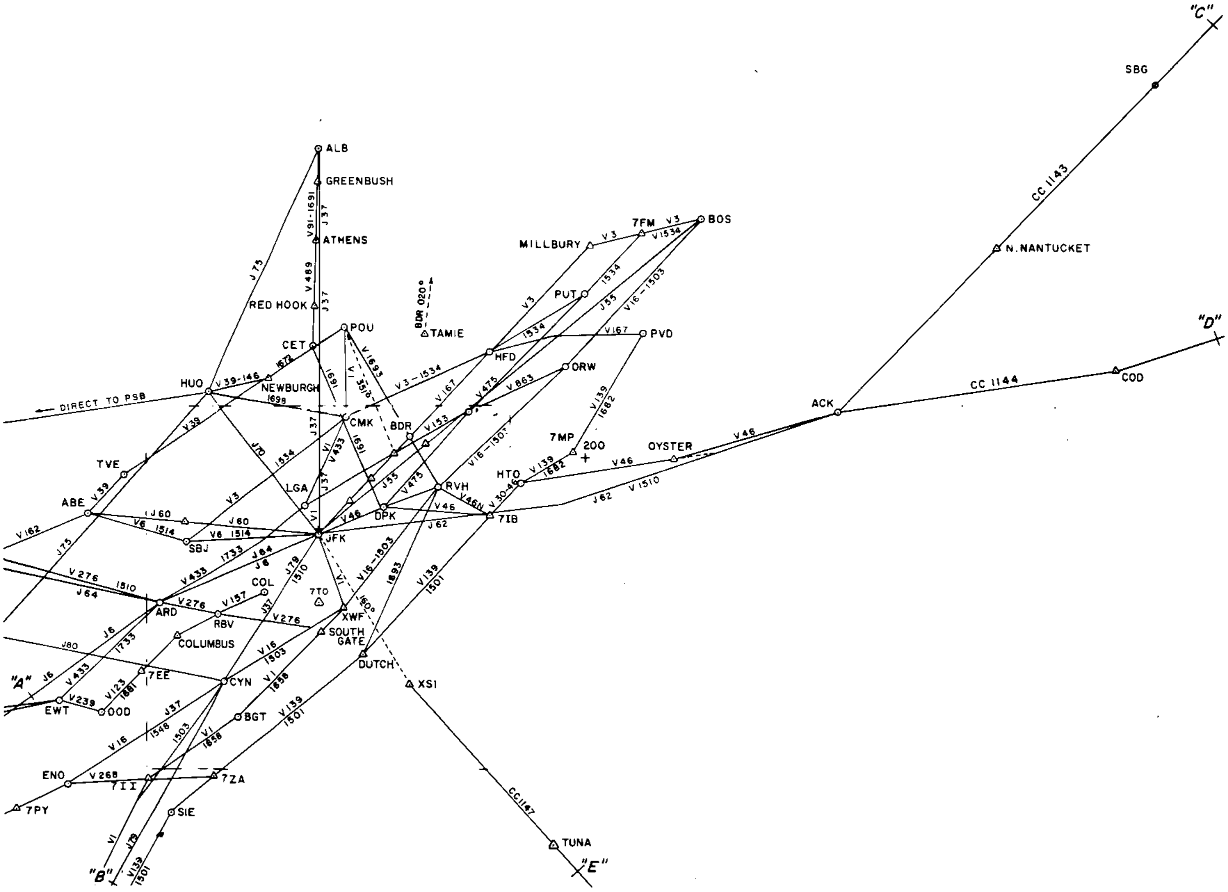

FIG. 2 NEW YORK OCEANIC TEST ENVIRONMENT

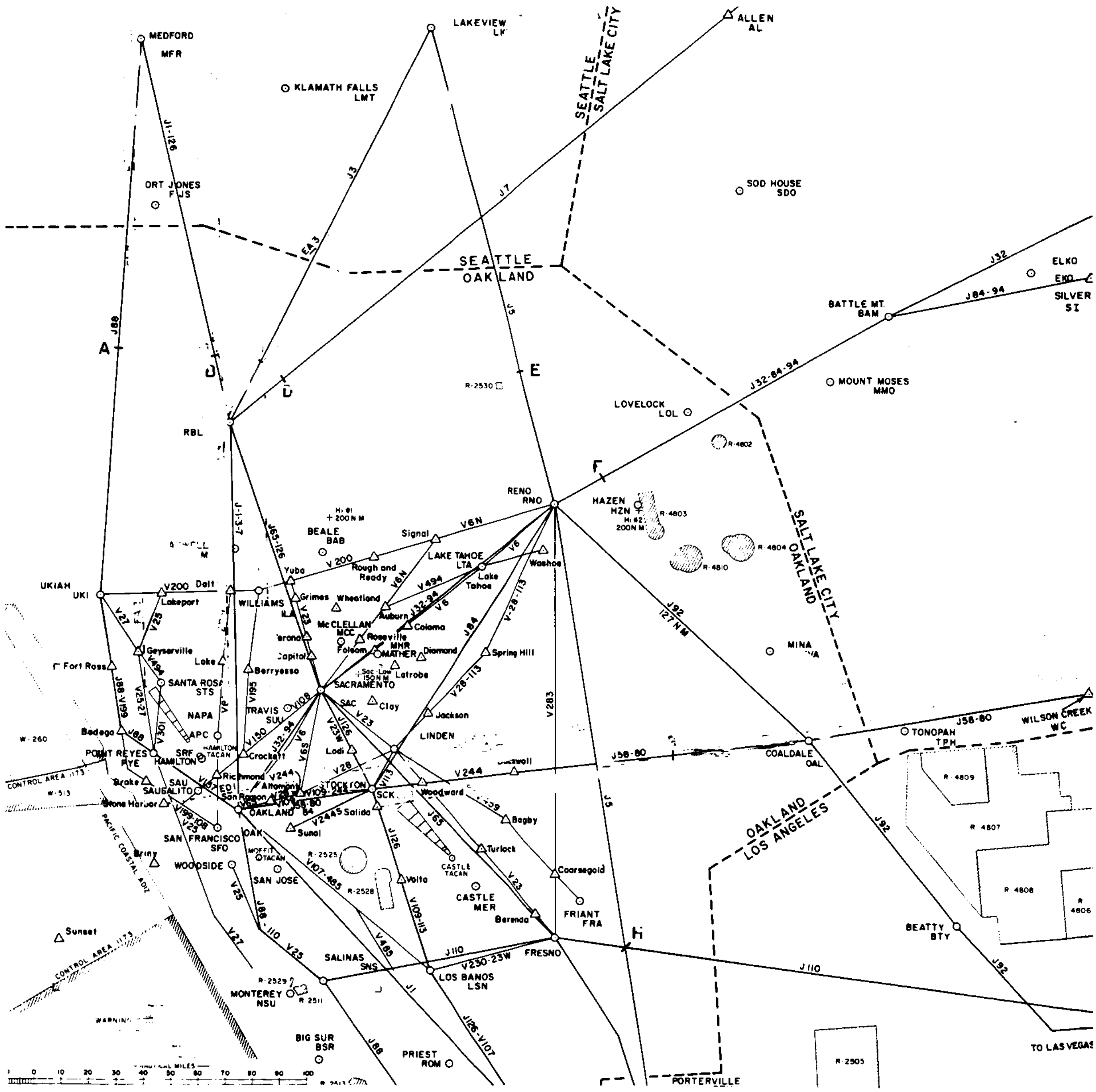

FIG. 3 OAKLAND TEST ENVIRONMENT

FIG. 4 AIR TRAFFIC CONTROL SIMULATION FACILITY

data displays, communication systems and a data collection system. All of the 104 pilot consoles (FIG. 5) are capable of duplicating the operating profile of most existing aircraft; sixty of the 104 consoles are capable of simulating profiles representing SST performance.

The radar target generated by each pilot console is shown on radar scopes or scan converted displays in the simulated ATC facility. The characteristics of Air Route Surveillance Radar (ARSR) or Airport Surveillance Radar (ASR) type equipments are displayed to the controllers as skin paint targets and/or radar beacon targets.

Communications between console pilots and controllers, responsible for aircraft separation, provide a realistic ATC environment. The data collection system records test measurements as required by the study.

Supersonic Transport Flight Simulator*

A plan view of the fixed-base supersonic transport simulator is shown in Figure 6. The flight compartment is similar to that of current jet transport aircraft with seating for the pilot, copilot, flight engineer, navigator, and a jump seat for an observer. The flight instrumentation is also similar to that used in current jet transport aircraft with instrument ranges modified only to cover the higher altitude and Mach number operation of the SST. An interior view of the flight compartment is given in Figure 7.

Accessory equipment needed for navigation, communication recording, and power requirements is located in a room behind the cockpit. The equipment, as shown in Figure 6 (a), provides for simulation of ground-based navigation aids including up to six VHF Omni-range (VOR) stations with Distance Measuring Equipment (DME), beacons, and a simulated Instrument Landing System (ILS). The communications console shown in Figure 6 (b), provides the switching capability required for the simulated VHF radio communication between the pilots and air traffic controllers. For HF communications, such as company reports, the operator at this station serves as the ground contact. A dual-channel tape recorder is provided for preserving air-to-ground and ground-to-air communications. The two X-Y recorders shown in Figure 6 (c) provide for continuous ground track recording over full-scale ranges, 40 to 4,000 nautical miles on each side.

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*Sawyer, R. H. and others, "A Simulator Study of the Supersonic Transport in the Air Traffic Control System," paper, NASA, Langley, Va., May 11, 1964.

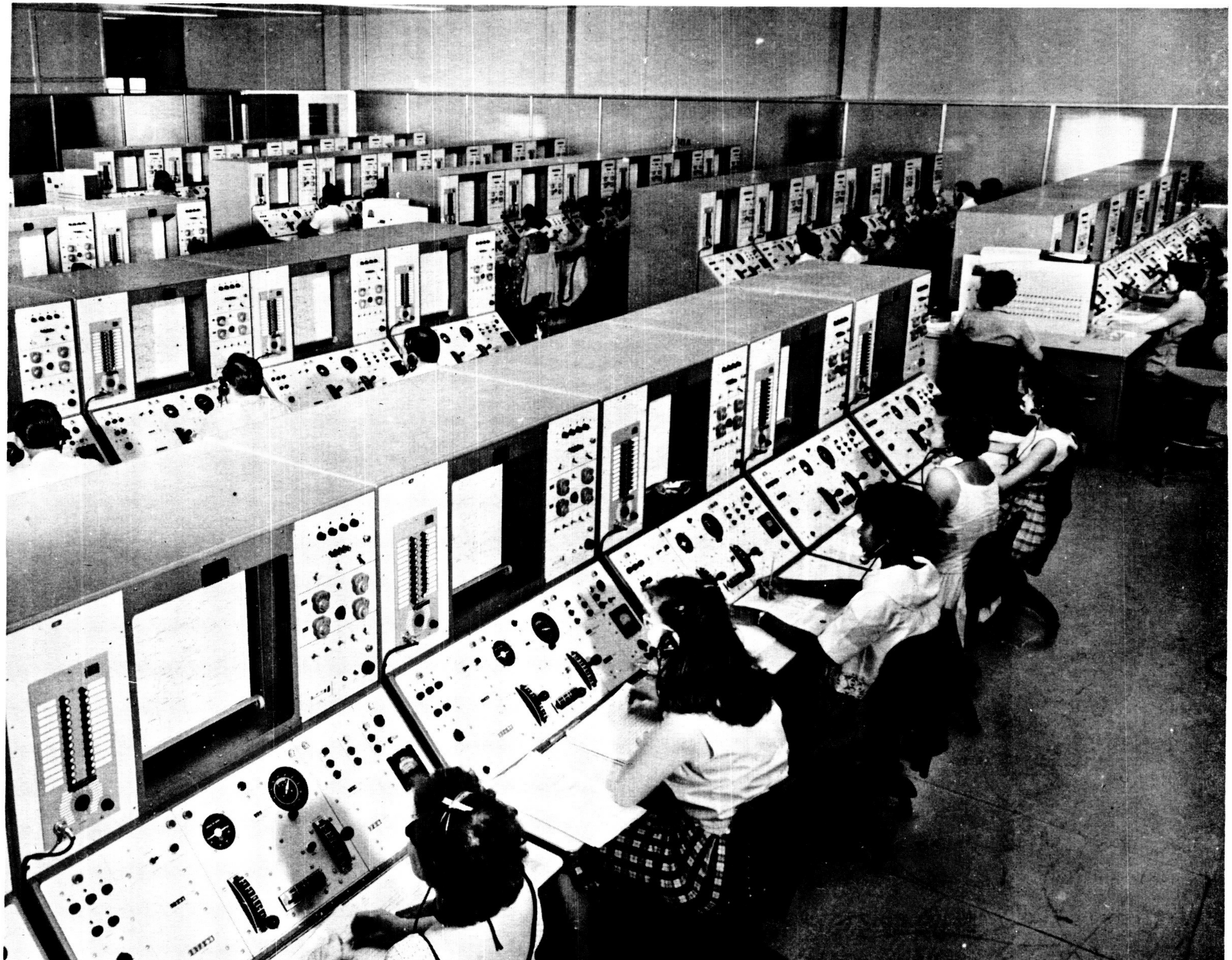


FIG. 5 RADAR TARGET GENERATORS (PILOT CONSOLES)

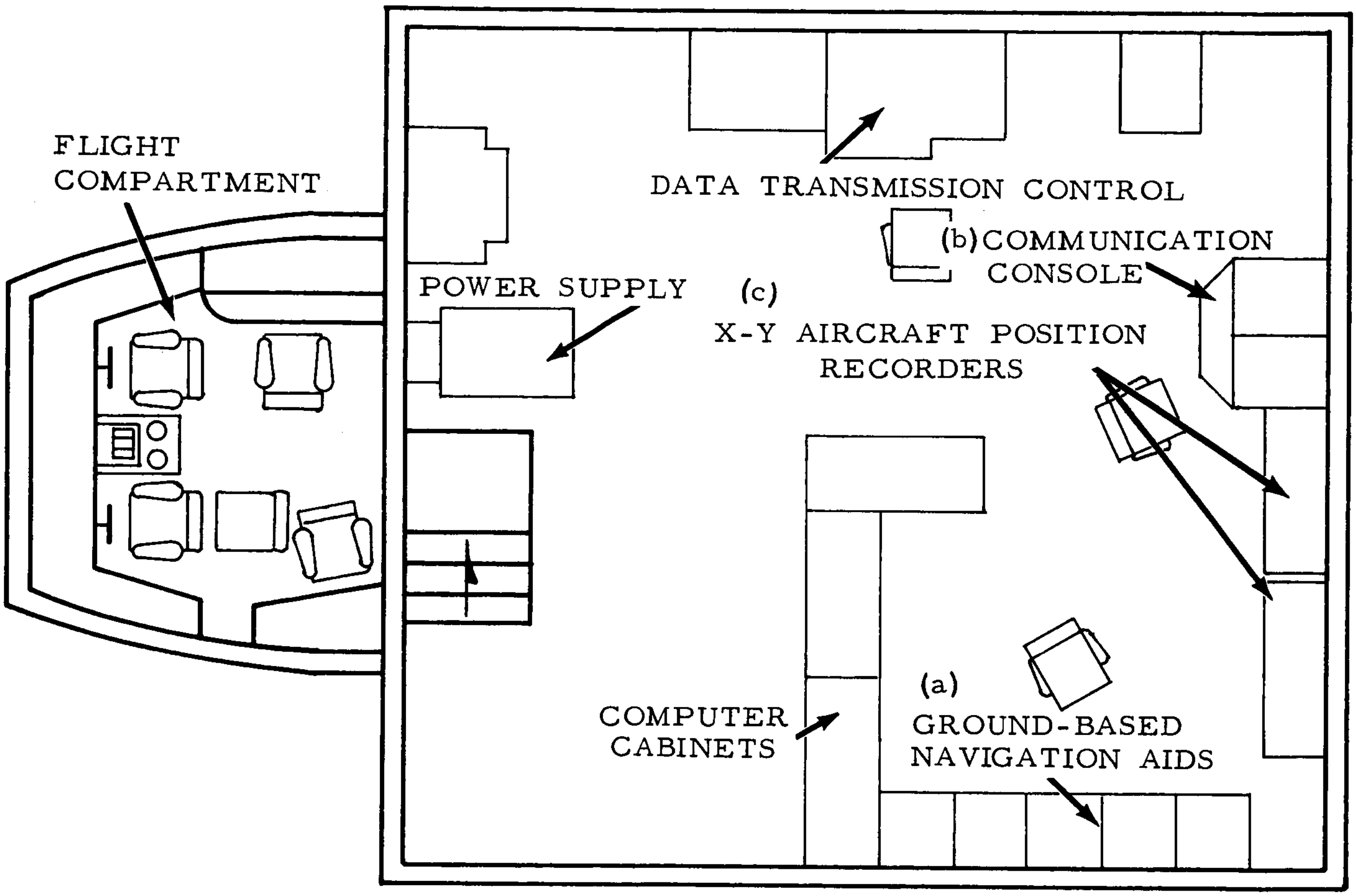


FIG. 6 FIXED-BASE SUPERSONIC TRANSPORT FLIGHT SIMULATOR

FIG. 7 FIXED-BASE SUPERSONIC TRANSPORT SIMULATOR FLIGHT COCKPIT

In addition to the above equipment, five analog computers are programed to solve six-degree-of-freedom motion equations for an aircraft having the characteristics of supersonic transport design. Signals from the pilot's control motions are converted into the proper aircraft instrument indications by means of this analog computer program.

The computer program is scaled to cover a Mach number range from 0 to 4.0 and an altitude range from sea level to 100,000 feet. The characteristics of the engine, autopilot, and other aircraft systems are also programed in the analog computer. Engine thrust and fuel flow characteristics are expressed as a function of Mach number, altitude, and throttle position for four independent engines. The equations representing the autopilot provide for the conventional modes of Mach-hold, and altitude-hold.

The SST flight simulator ground coordinates (X-Y) and altitude (Z) information are digitized and transmitted to the ATC simulation facilities at NAFEC via leased private telephone lines. A block diagram of the data transmission system is shown in Figure 8.

Supersonic Transport Profile - Mach 3.0

Two SST aircraft design configurations were simulated, both having a design cruise Mach number of 3.0. Configuration "A" was a variable-sweep wing design with after burning turbojet engines and Configuration "B" was a fixed delta-wing design with duct-burning turbo-fan engines. Both configurations had the same take-off thrust-to-weight characteristics (FIG. 9). Configuration "A" had a transonic acceleration capability somewhat higher than Configuration "B", as the engines were sized for cruising without after-burning rather than for transonic acceleration capability. The wing loading at maximum gross weight for the variable-sweep wing design was nearly double that of the delta-wing design.

The climb and descent profiles for the SST are constrained by the engine, structural, and sonic boom overpressure limitations as depicted in Figure 10 (a) and (b). For Configuration "A", after take-off and initial acceleration, the SST was scheduled to climb at 360 Knots Calibrated Air Speed (KCAS) until the sonic boom boundary of 2.0 pounds overpressure per square foot was reached. The sonic boom profile was then followed until 570 KCAS was attained. Climb was then continued at this airspeed until cruise conditions were reached. A representative climb profile and flight path is shown in Figure 11.

For descent, a deceleration phase was performed at cruise altitude until the SST reached 340 KCAS. This airspeed was held constant in

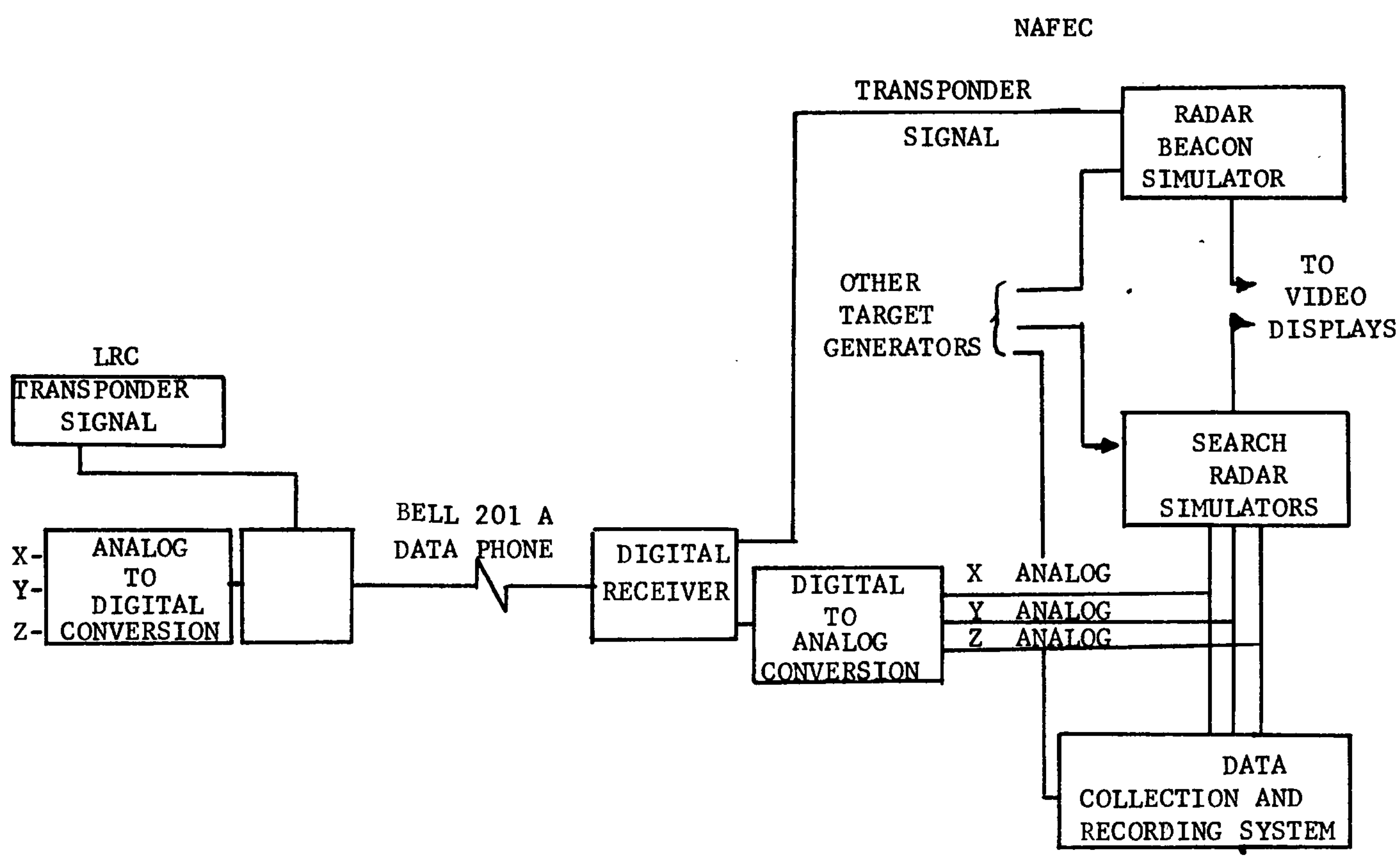
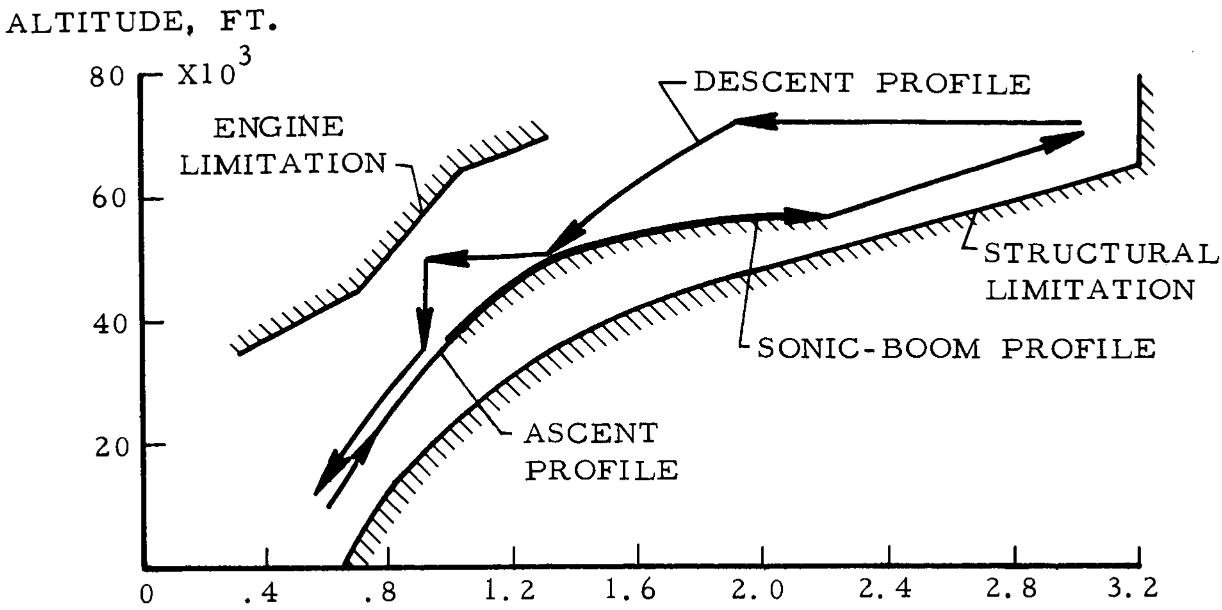


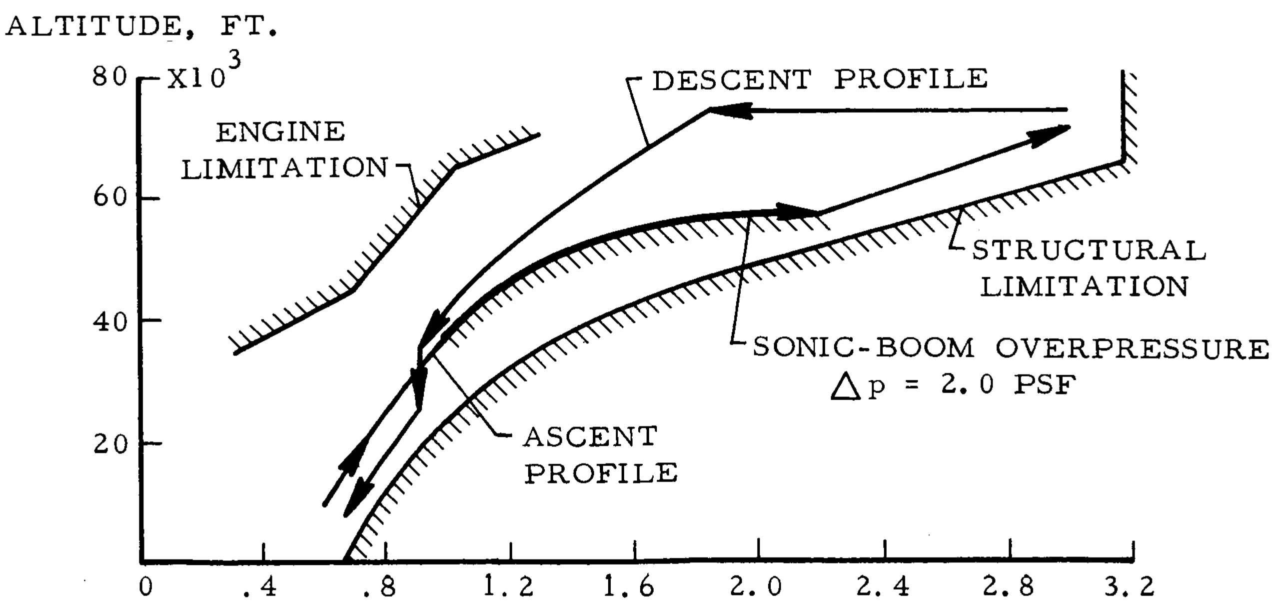
FIG. 8 BLOCK DIAGRAM OF DATA TRANSMISSION SYSTEM

	Configuration	
	A	B
$\left(\frac{T}{W}\right)$ To, dry	0.32	0.32
Min. transonic acceleration, ft/sec^2	1.6	1.4
Wing loading, lb/sq ft	107	56

FIG. 9 GENERAL CHARACTERISTICS OF SST CONFIGURATIONS



(a) CONFIGURATION A.



(b) CONFIGURATION B.

FIG. 10 MACH 3.0 SUPERSONIC TRANSPORT CLIMB AND DESCENT PROFILES

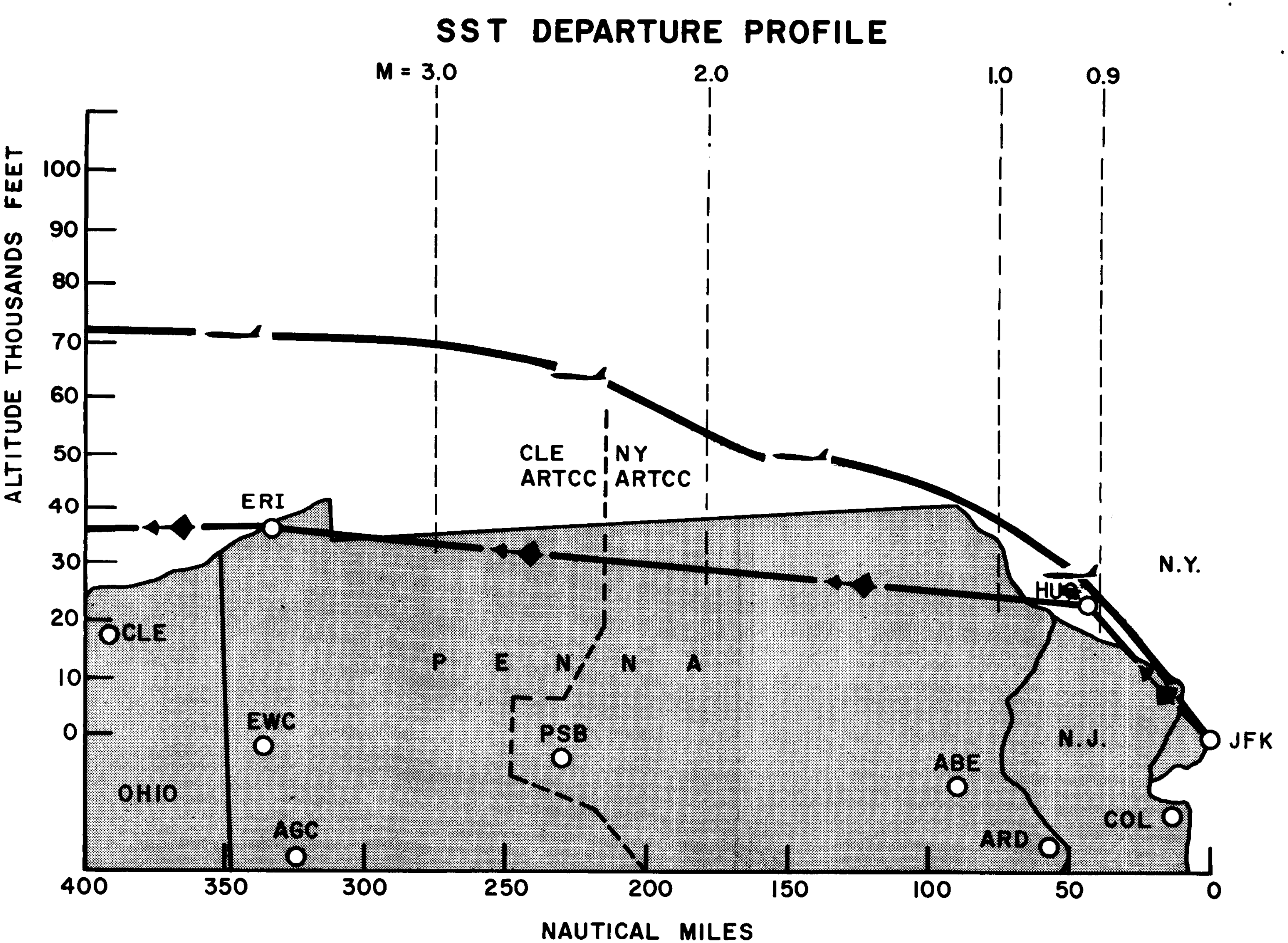


FIG. 11 A REPRESENTATIVE MACH 3.0 SST CLIMB PROFILE AND FLIGHT PATH

descent to Flight Level (FL) 500 where level off was initiated to avoid creating a sonic boom greater than 1.5 pounds overpressure per square foot. After deceleration to a Mach number of 0.9, descent was reinitiated holding this Mach number until 340 KCAS was reached. This air speed was used in the remainder of the descent until reduction to terminal/ approach speed was necessary. The climb and descent profiles used for Configuration "B" were similar to those of Configuration "A" except that speeds of 325 KCAS and 500 KCAS were held constant during the climb. The descent profile differs from Configuration "A" in that 300 KCAS was maintained and there was no level off at FL500. A representative descent profile and flight path is shown in Figure 12.

Supersonic Transport Profile - Mach 2.2

A Mach 2.2 supersonic transport design configuration of the Concorde type was also simulated. A representative climb profile and flight path is illustrated in Figure 13. After takeoff and initial climb out to 5,000 feet and 375 KCAS, the aircraft then continued to climb at this constant airspeed to FL290. It passed through Mach 1.0 during this climb at FL320, some 60 NM (or 8 minutes) after takeoff and reached Mach 1.13 at FL390. The aircraft then accelerated to Mach 1.8 in a climb to FL450 over the next 100 NM (or 7 minutes). Acceleration then continued in a constant airspeed climb at 530 KCAS to Mach 2.2 at FL540 in the added distance of 200 NM (or 12 minutes). The climb continued at Mach 2.2 to the initial cruise altitude of FL570. This climb-out procedure was completed in a distance of 470 NM (or 33 minutes) after takeoff. The aircraft then entered into a cruise climb configuration for approximately two hours at Mach 2.2 gaining altitude up to approximately FL630 at end of cruise.

At approximately 200 NM from destination, the descent commenced (FIG. 14) with a deceleration rate constant at 450 KCAS down to Mach 1.6 at FL500 in approximately 40 NM (or 2 minutes). This was followed by level deceleratation at FL500 down to Mach 0.95 in an added distance of 40 NM (or 2.5 minutes). The aircraft then descended to Mach 0.95 to FL300 over a distance of 50 NM (or 5 minutes) and then decelerated to terminal speed of 260 KCAS.

Operational Assumptions

It was assumed that:

1. Adequate radar and radio coverage existed throughout the geographic area simulated.

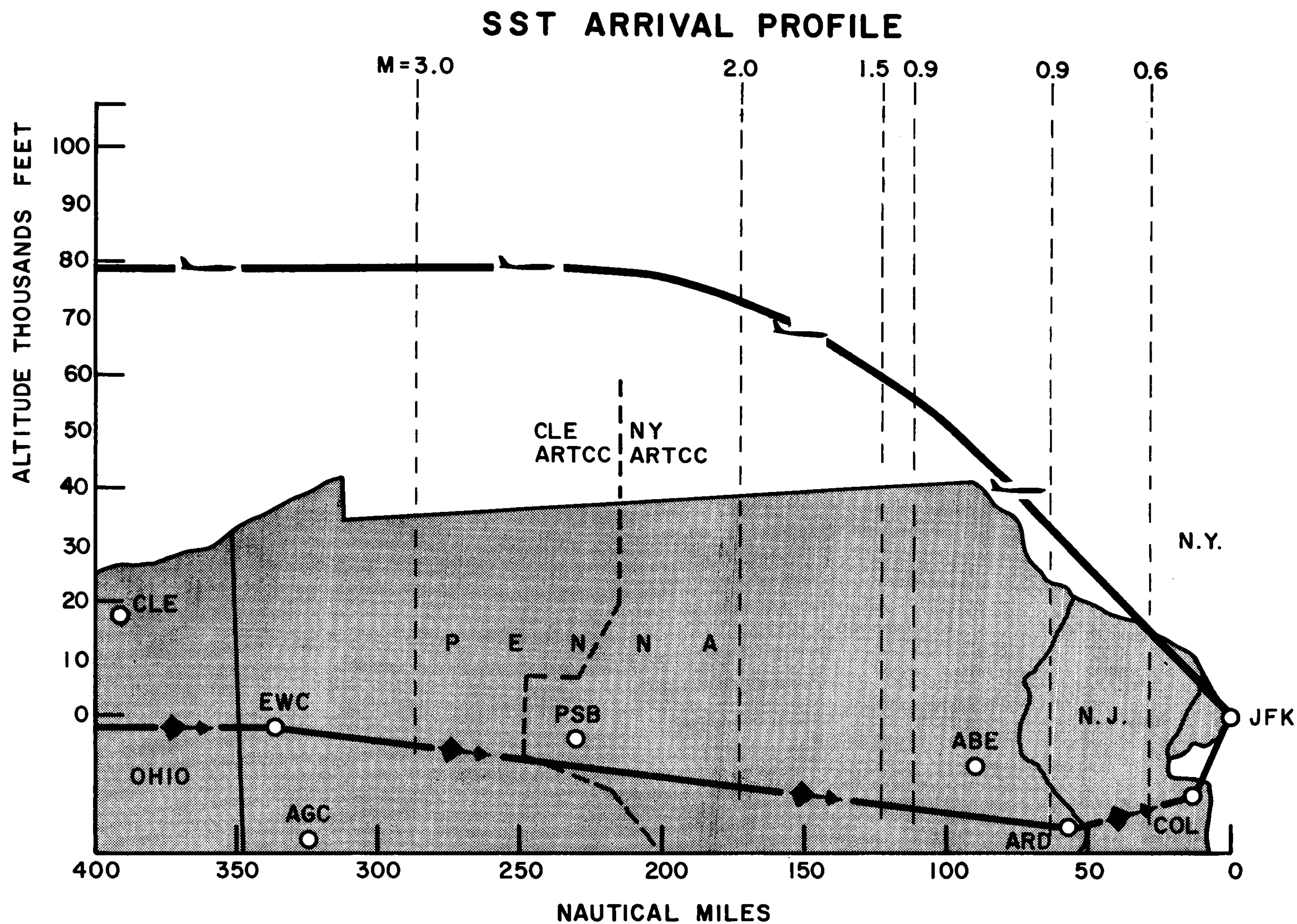


FIG. 12 A REPRESENTATIVE MACH 3.0 SST DESCENT PROFILE AND FLIGHT PATH

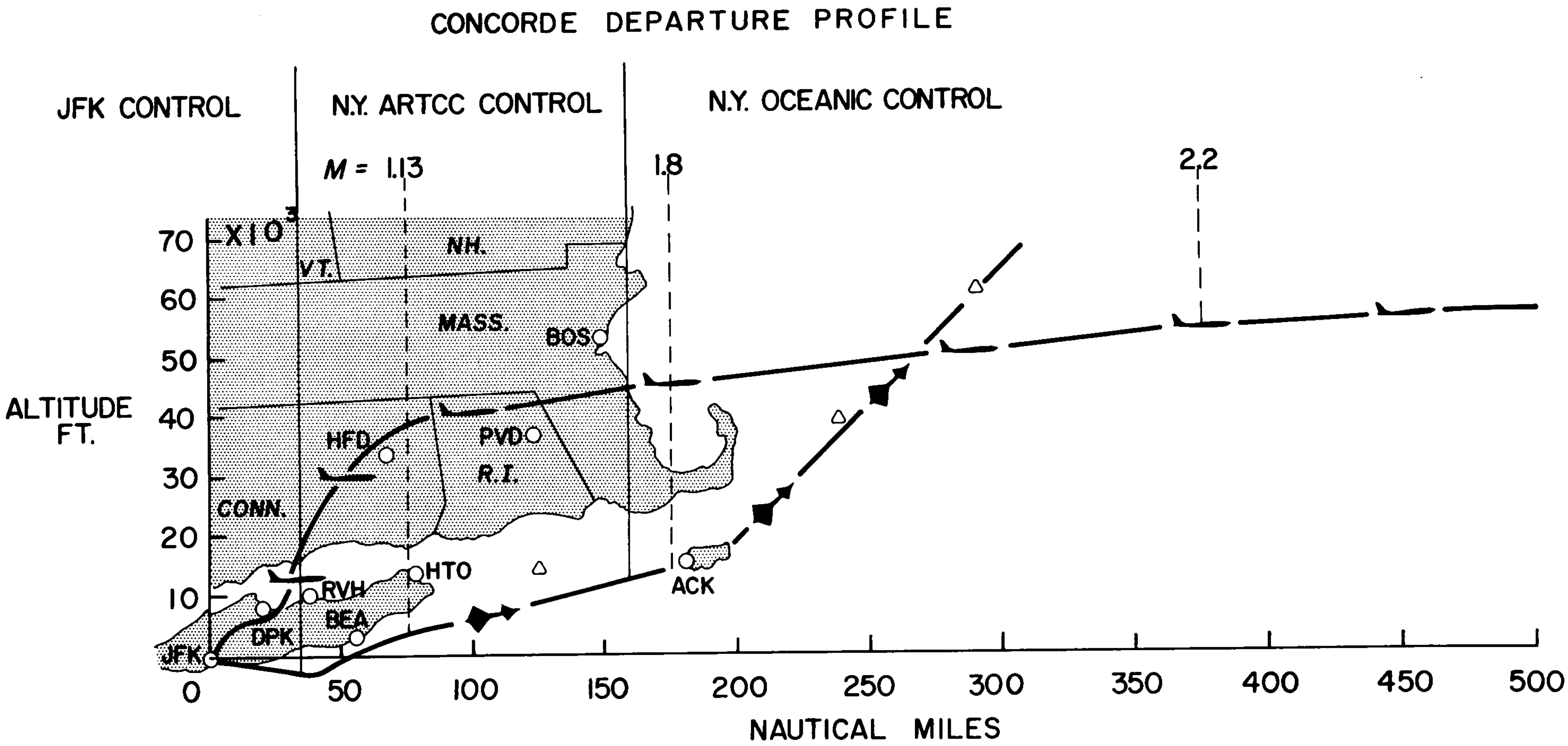


FIG. 13 A REPRESENTATIVE MACH 2.2 SST CLIMB PROFILE AND FLIGHT PATH

CONCORDE ARRIVAL PROFILE

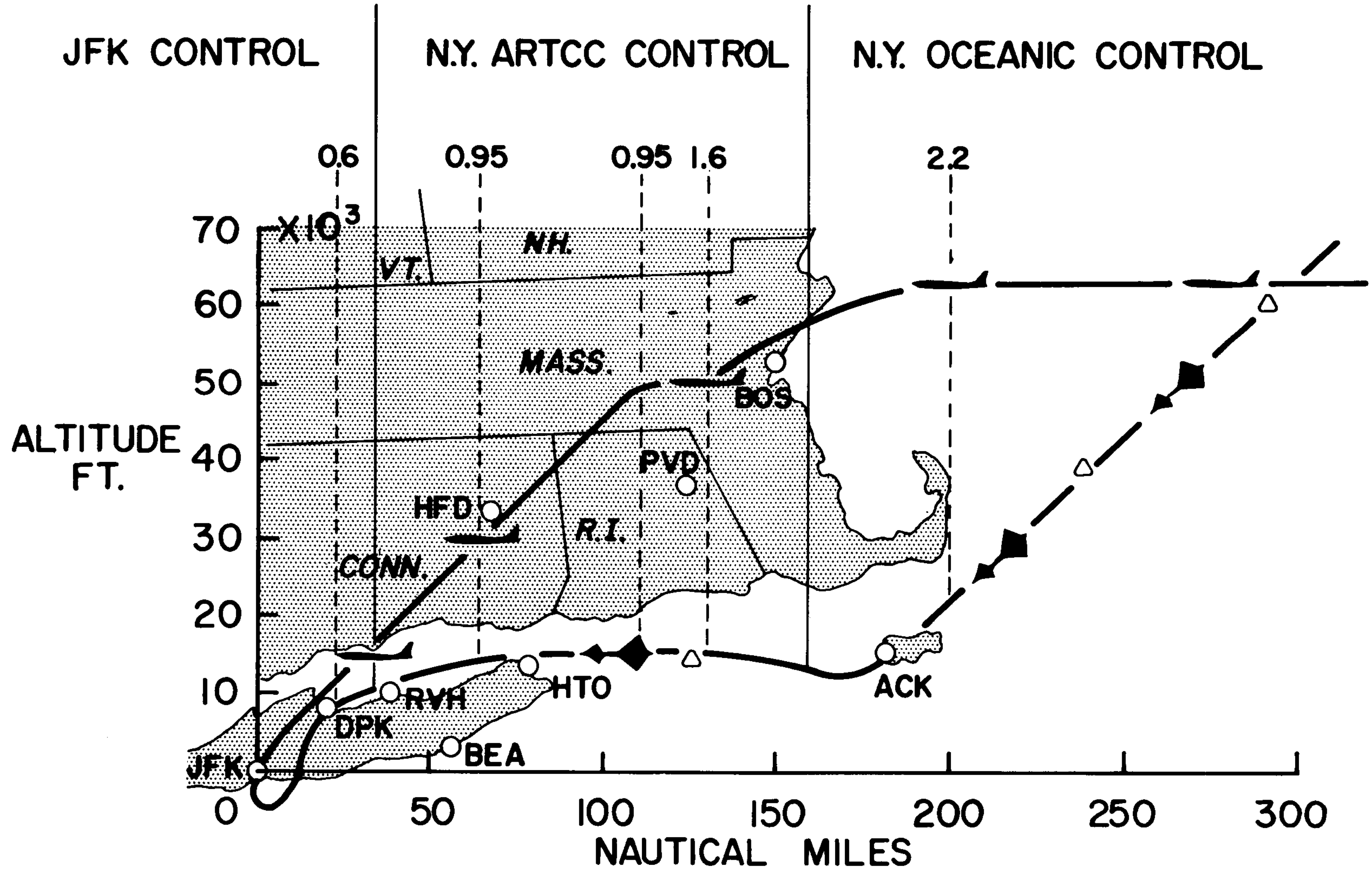


FIG. 14 A REPRESENTATIVE MACH 2.2 SST DESCENT PROFILE AND FLIGHT PATH

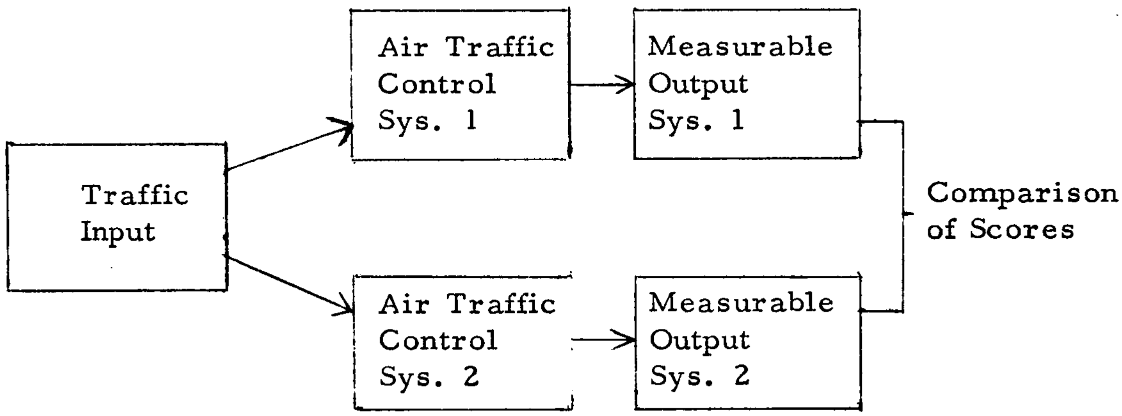
2. Navigational facilities were suitable for navigation at all altitudes.

3. An all-weather landing system existed at the destination airport.

4. SST flight plans were filed one hour prior to Estimated Time of Departure (ETD). ATC clearances were requested 30 minutes before ETD; clearances were delivered no later than 10 minutes prior to ETD, and engines were started 10 minutes before ETD.

Test Method

In comparing ATC Systems, a simple input-output test technique is used as shown below:



The measurable output is recorded in the form of "System Efficiency Measures" and "Controller/Pilot Workload Measures." Statistical comparison can be made between the measures from two or more ATC systems. In this context, any change or variation made in procedures, geography, navigation aids, etc., constitutes a system change. In these tests, limitations prohibited the study of all desired changes simultaneously. Therefore, plans were developed which would meet the basic objectives but which would also permit exploration of other control techniques as the studies progressed.

The general objective of these studies was to determine the relative effects of the integration of supersonic transport type aircraft, with those aircraft now operating in the air traffic system. This was primarily accomplished by applying various air traffic control methods to SST type aircraft and measuring the effects on the ATC system.

Data Collection and Treatment With the exception of radio communications, which were recorded on magnetic tape, data for these measures were acquired by manual recordings made by the simulator pilots on prepared data acquisition forms. Each item was then extracted from these forms and compiled. Data for each measure was subjected to statistical tests to determine if significant differences were attained at either the .05 or .01 levels of confidence. Statistical techniques known as the "analysis-of variance" and the "t-Test" were used in the analysis of these data.

Objective data was not collected during the PD portion of these studies. This was a short probe of an exploratory nature, and was subjected to various environmental changes. Therefore, only gross and very limited comparisons were attempted between this system and other systems. References to PD results are based on subjective opinion derived from observations by the Project Staff, and the opinions expressed by the participating controller personnel.

The primary method of evaluating ATC systems or control procedures was a comparison of system scores based on the following:

1. System efficiency

2. Controller and pilot workload

The measures associated with the above were:

<u>System Efficiency Measures</u>

1. En route holding delay to arrival aircraft

2. Terminal holding delay to arrival aircraft

3. Ground delay to departure aircraft

4. Total delay

5. Airport operations rate

6. SST time-in-system

<u>Controller and Pilot Workload</u>

1. Number of communications

2. Duration of communications

3. Number of radar vectors required

4. Number of altitude changes required

DISCUSSION

Ground Test Procedures

Studies were conducted which investigated various handling procedures of the SST while operating at the airport. Comparative tests were made in which SSTs were afforded no priority, low priority, and high priority treatment.

No Priority In those tests in which the SSTs received no special treatment the SST parking area was assumed to be at the main terminal. Taxiing to the departure runway or to the parking area was assumed to have been accomplished via the same taxi routes as those used by other aircraft. During those tests the SST departures were required to wait their turn for takeoff regardless of delay incurred.

Low Priority Tests conducted under this condition were identical to the tests conducted in the No Priority system with the following exception: Controllers retained the prerogative of delaying the SST for other traffic, with maximum delays, 10 minutes.

High Priority During those tests in which the SSTs received high priority, SST parking areas were assumed to be so located on the airport that an SST could taxi directly to the takeoff runway for an immediate departure. An arrival, upon landing, could taxi directly to the parking area. The SST departures received no ground delay except for that caused by wake turbulence safety measures.

Wake Turbulence Wake turbulence separation criteria was used in all studies to simulate avoidance of the wing tip vortices that would be created by the large SST aircraft operating at slow speeds. This safety measure was applied by requiring all aircraft to wait a specific time before landing or taking off behind an SST. The standard separation in the early studies was four minutes, which was later reduced to three minutes and then to one minute. The one minute wake turbulence separation was used in most of the studies.

Results

Priority Comparisons The primary measures used in the comparison of High Priority versus Low Priority for SSTs operating on the surface of the airport, showed no significant difference in the total ground delay expended (all departures). However, it was apparent that in the Low Priority condition, there were many cases wherein the controller did not exercise his delay prerogative, thus creating a wide range of scores throughout the Low Priority condition. While there was no difference in the amount of delay, there was a two per cent increase in the number of aircraft delayed in the Low Priority condition. This is attributable to the controllers being permitted to also delay the SSTs in the Low Priority condition.

The amount of ground delay imposed on the SST aircraft, however, did increase from zero in the High Priority condition, to 2.4 minutes in the Low Priority condition. High Priority treatment for SST aircraft will not, in itself, necessarily increase the total system delay. However, the use of priority transfers delay to other aircraft.

Wake Turbulence Three different SST wake turbulence separation criteria were tested and their results are as follows:

1. No aircraft would take off or land with less than one minute separation from an SST operation. This separation criteria caused no change in the basic airport arrival rate of 42.5 per hour, as the present runway separation rules preclude this minimum with present aircraft speeds.

2. No aircraft would take off or land with less than three minutes separation from an SST operation. This criteria resulted in a decrease in the arrival rate to 37.5 per hour.

3. No aircraft would take off or land with less than four minutes separation from an SST operation. This criteria resulted in an even further decrease in the arrival rate to 33.25 per hour, or approximately 22% decrease from the basic arrival rate.

It should be noted that the decrease in hourly rates were not the result of wake turbulence separation only, but a combination of the wake turbulence separation criteria and increased separation criteria used in the Experimental System, described under Terminal Test Procedures.

Terminal Test Procedures

General Three systems, Present, Experimental, and Pictorial Display were designed to test and determine:

1. What effects, if any, the introduction of the SST into the present-day ATC system would have on terminal controller workload.

2. What effects the SST would have on subsonic aircraft operation within a terminal complex.

General SST operational requirements, established by NASA to be compatible with the operating characteristics of SST aircraft in the terminal area were as follows:

1. ATC was required to notify the pilot at least 5,000 feet prior to level-off to prevent flying through the desired altitude, because of the SSTs high rate of climb between 4,000 feet and FL400.

2. Descent rates from outer fixes were assumed to be of the same order as those for current subsonic jets.

3. Maneuverability in the terminal area was assumed to be the same as for current subsonic jets.

4. From a fuel standpoint, preferred altitudes for holding was assumed as being between 13,000 and FL250. SSTs holding speed was 250 KIAS at any altitude at or below FL450.

All traffic, subsonic and SST, was controlled in accordance with ATP 7110.1B, Local Letters of Agreement and Facility Memoranda. Certain deviations from these procedures were made in controlling the SST in the Experimental and Pictorial Display Systems. Arrival and departure operations, representative of present-day traffic at both the JFK and SFO Airports, were used.

Present System This study consisted of tests which required SST arrivals and departures to comply with present-day terminal operating procedures at the respective airports. Established Standard Instrument Departures (SIDs) and arrival routes were utilized as shown in Figures 15, 16, 17, and 18. No preferential treatment was given to SST aircraft, with the control and separation standards (radar and vertical) the same as those applied to subsonic aircraft. These tests provided measurements on system efficiency and controller workload.

Experimental System This study consisted of tests in which the ATC system provided SST aircraft with preferential treatment and increased separation standards, as illustrated in Figure 19. The arrival and departure routes used in the Present System were also used in this system. Preferential altitudes at the outer fixes were provided, as requested by the pilot. The two preferred altitudes

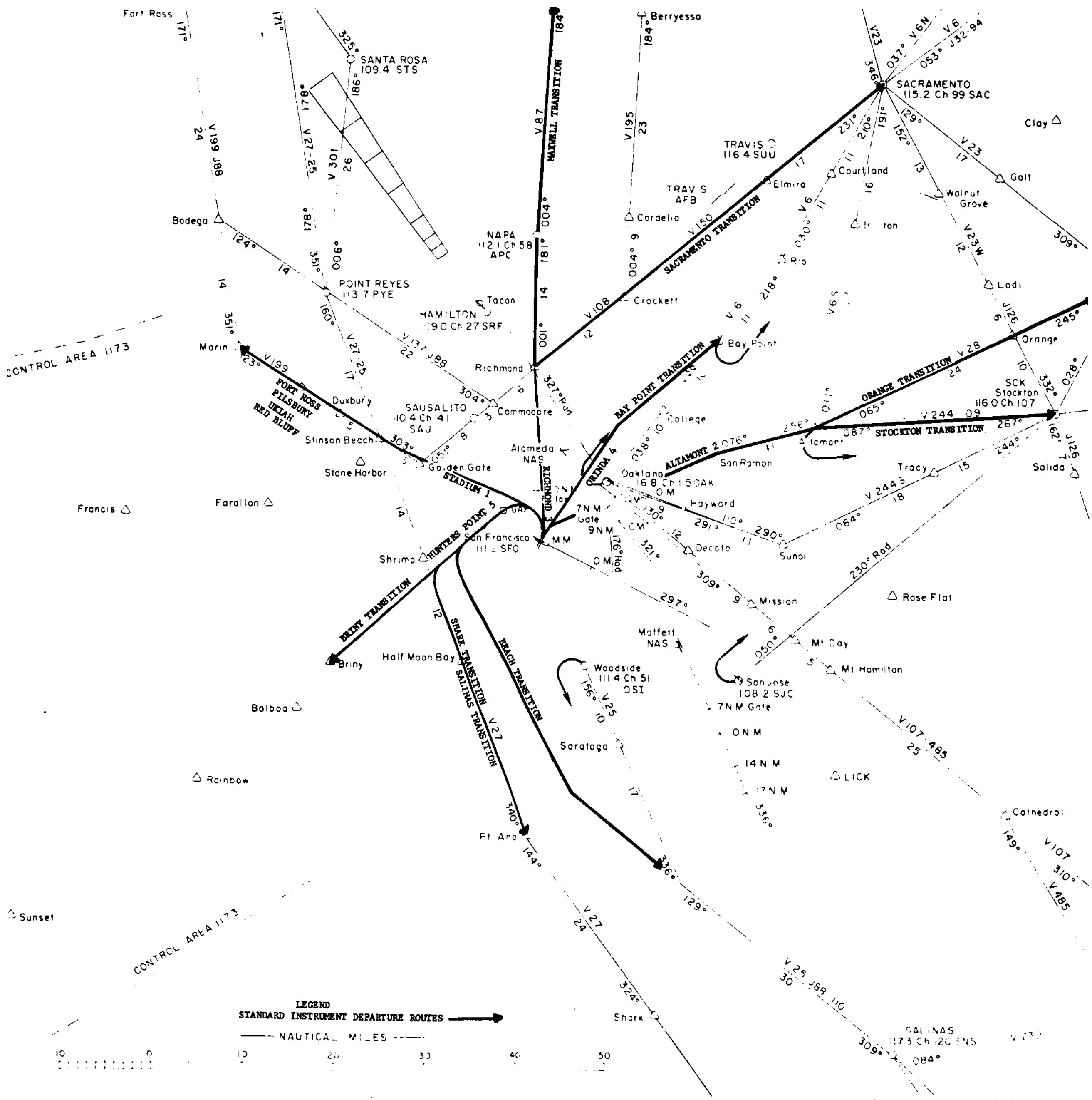


FIG. 15 SFO STANDARD INSTRUMENT DEPARTURE ROUTES

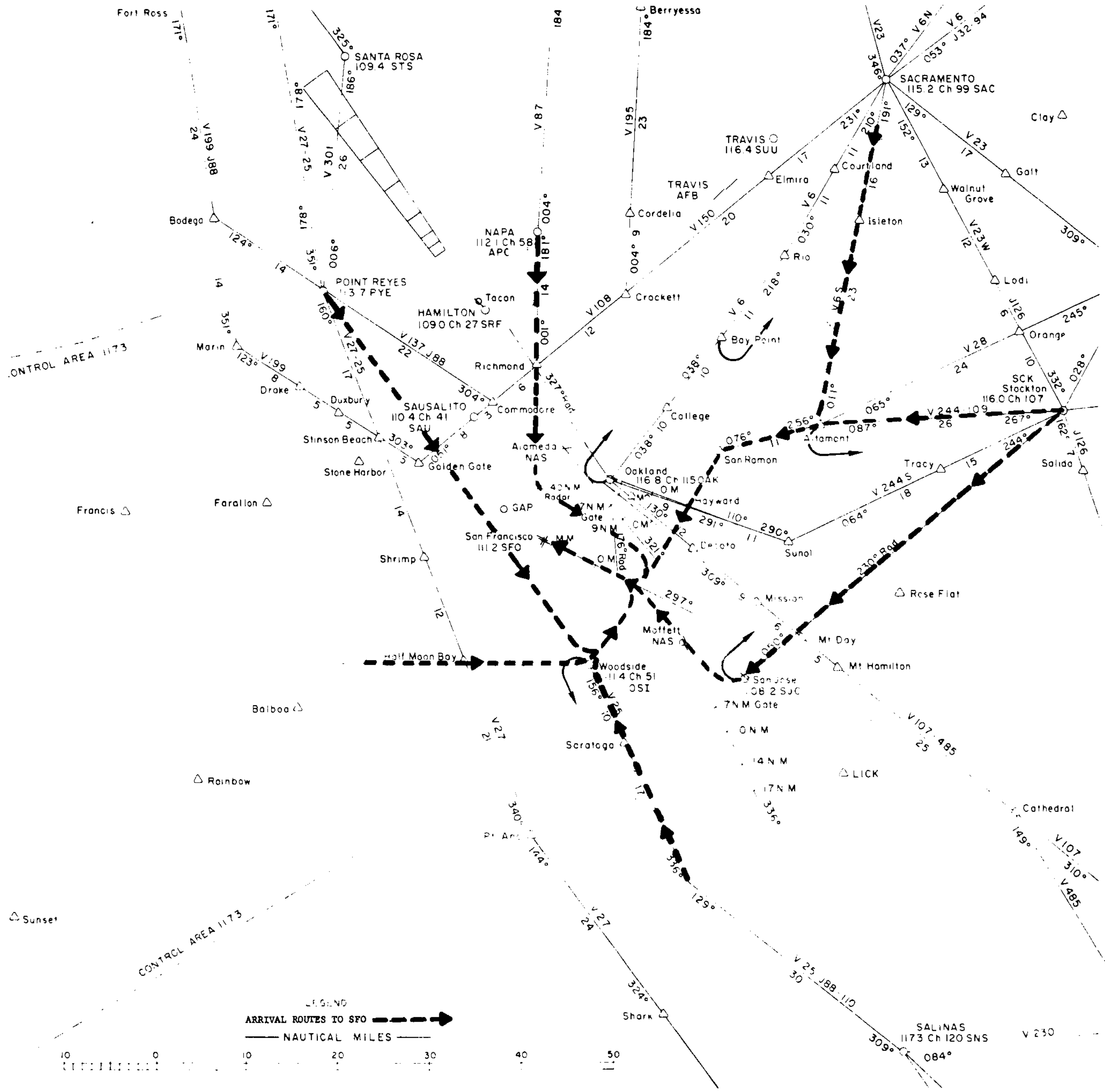


FIG. 16 SFO TERMINAL ARRIVAL ROUTES

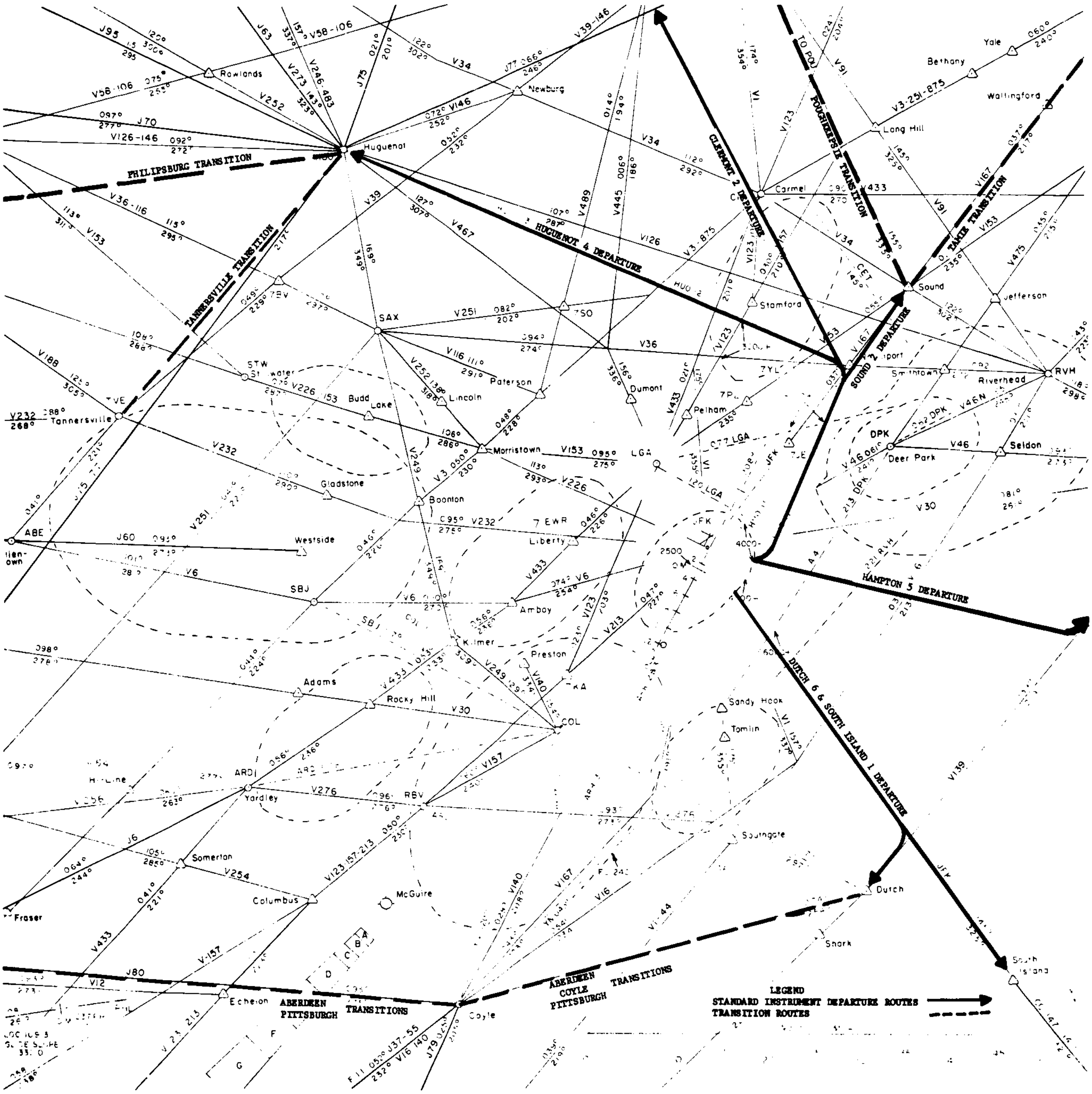


FIG. 17 JFK STANDARD INSTRUMENT DEPARTURE ROUTES

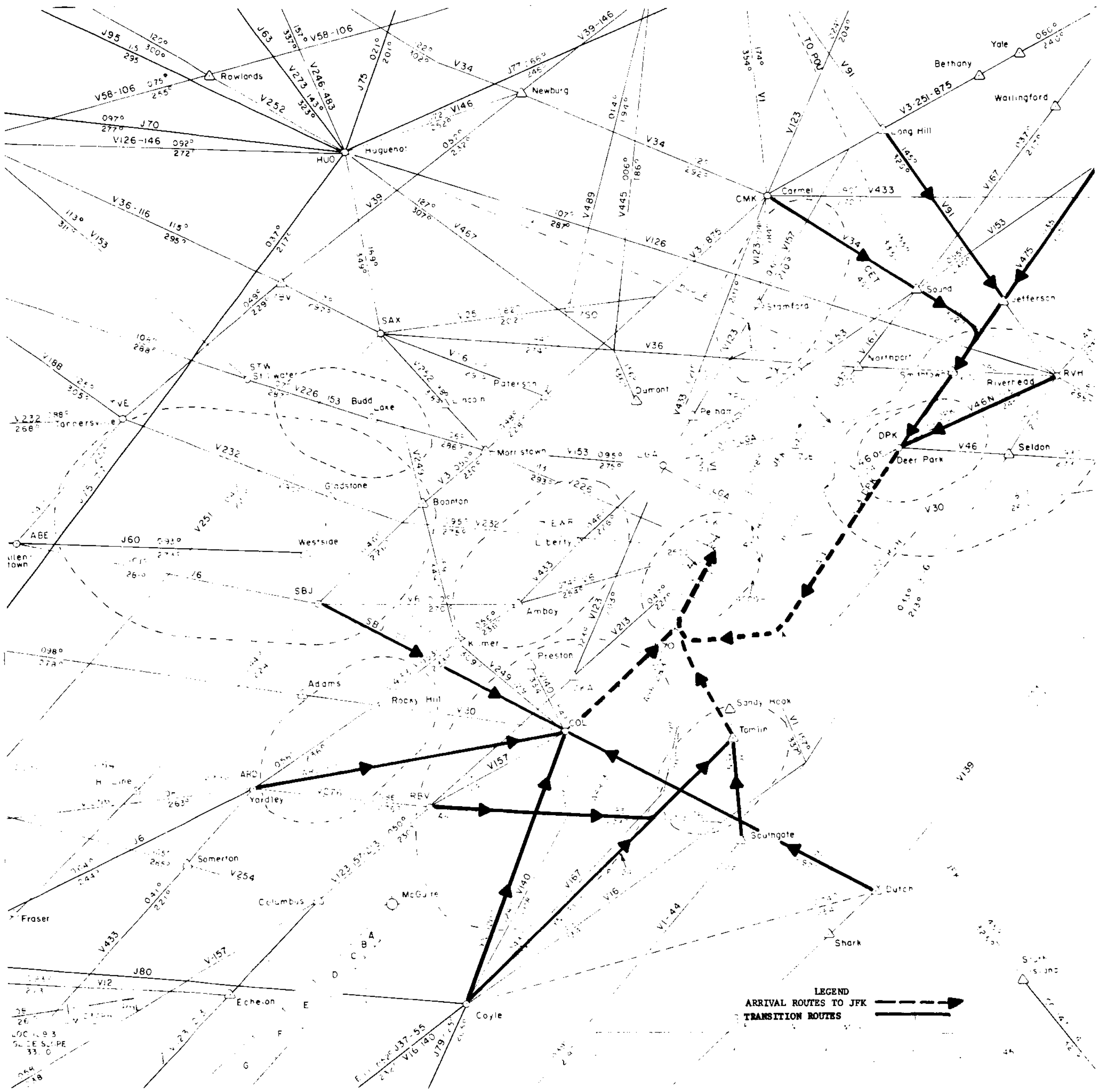


FIG. 18 JFK TERMINAL ARRIVAL ROUTES

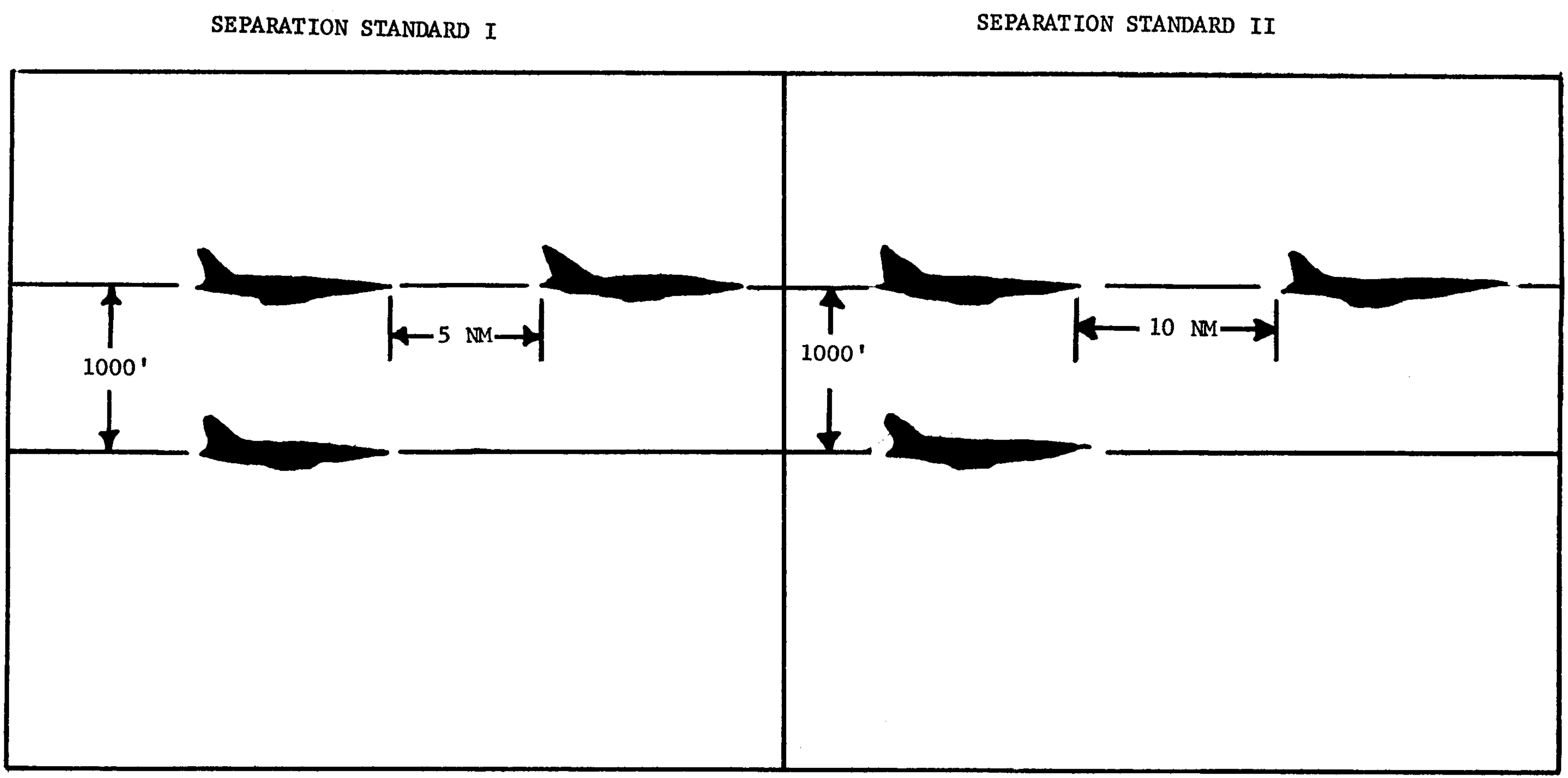


FIG. 19 TERMINAL EXPERIMENTAL SEPARATION STANDARDS

were FL250 and 13,000 feet, as indicated by the NASA SST profile. SID routes and associated altitude restrictions were not used for SST departures. Terminal radar departure controllers were required to establish SSTs on course with a minimum number of vectors.

Pictorial Display (PD) System During this study, PD flight paths were used for SST arrivals and departures in the terminal complex. Tests were made and data collected to determine the value of PD in integrating the SST into the ATC system, and also to determine the capability of the system to accept this operational concept in a terminal control area with high density traffic. As a result, procedures for the control of SST aircraft varied from those in other studies. Controllers did not vector SST aircraft. They were assigned PD routes, to and from the airport, and were completely responsible for their own navigation. Present-day separation standards, altitude and/or radar, were provided SST aircraft assigned PD routes in accordance with procedures in ATP 7110. 1B.

The routes were designed with some independence from the normal routes (FIGS. 20 and 21). Arrival flight paths were independent to a point within the approach control area where they were combined with the normal vector routes of subsonic aircraft. The PD departure paths were separated from, and parallel to, current SID routes to a point in the center area where SSTs were normally above subsonic traffic.

Priority Conditions The Experimental and PD Systems tests were investigated under both high priority and low priority conditions.

High Priority Condition Unlimited preferential treatment was given to SSTs to provide the most expeditious service possible. No holding delays in the terminal area were incurred by SST arrivals. Minimal radar vectoring of the SSTs was permitted in the terminal area. Resolution of control problems was accomplished by exercising control over subsonic aircraft. Altitude restrictions to SSTs were permitted only if an SST was in conflict with another SST.

Low Priority Condition Limited preferential treatment was given to SSTs. Resolution of control problems between SSTs and subsonic aircraft was accomplished by exercising control over the SST if necessary; i.e., ladder the SST down in descent, restrict the SST in climb, or radar vector the SST. Terminal holding was permitted with delays not to exceed 20 minutes at the outer fix. Some tests were made in which holding delay was not to exceed 10 minutes.

The FAA Supersonic Transport Economic Ground Rules

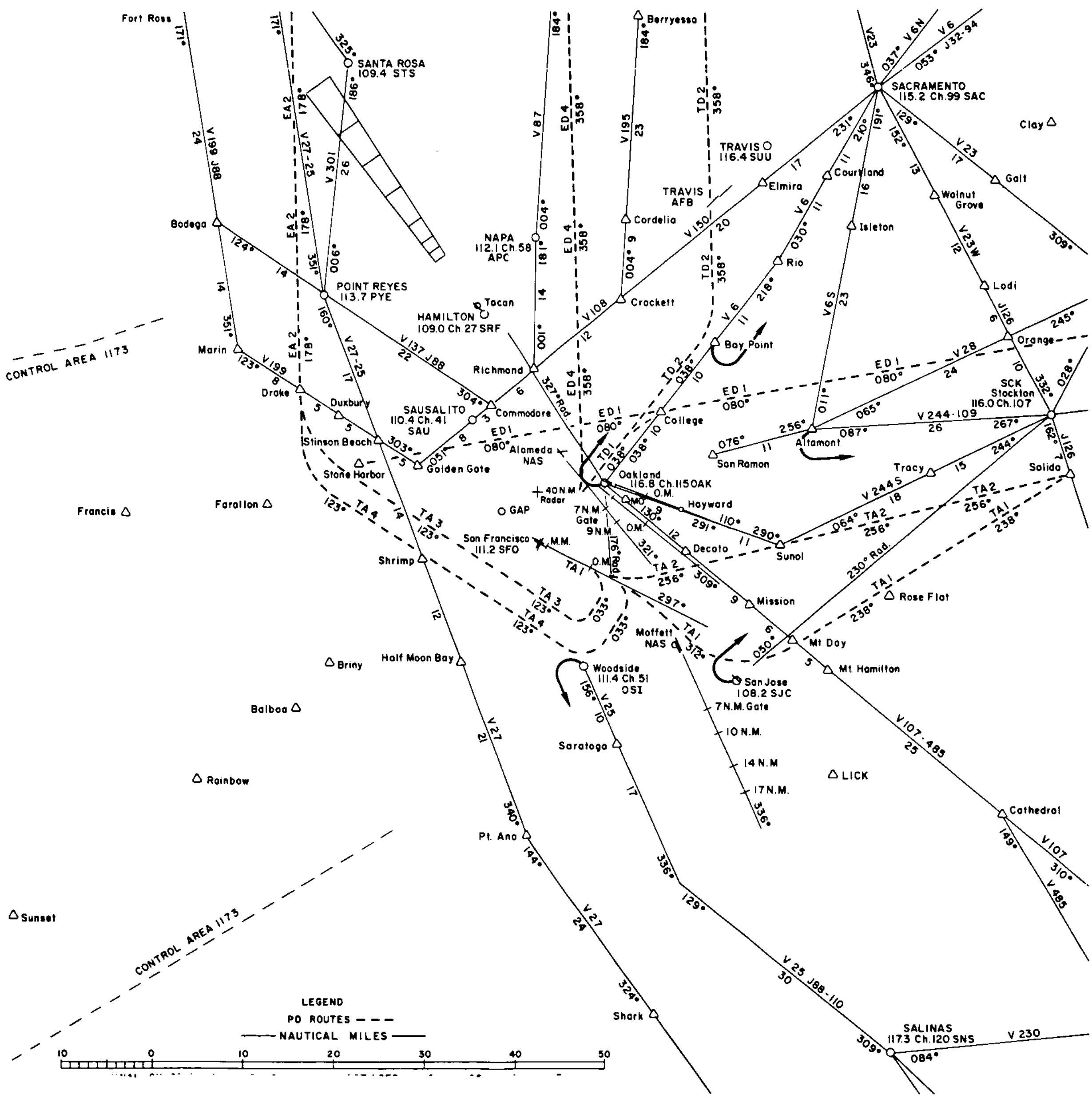


FIG. 20 SFO TERMINAL PICTORIAL DISPLAY ROUTE STRUCTURE

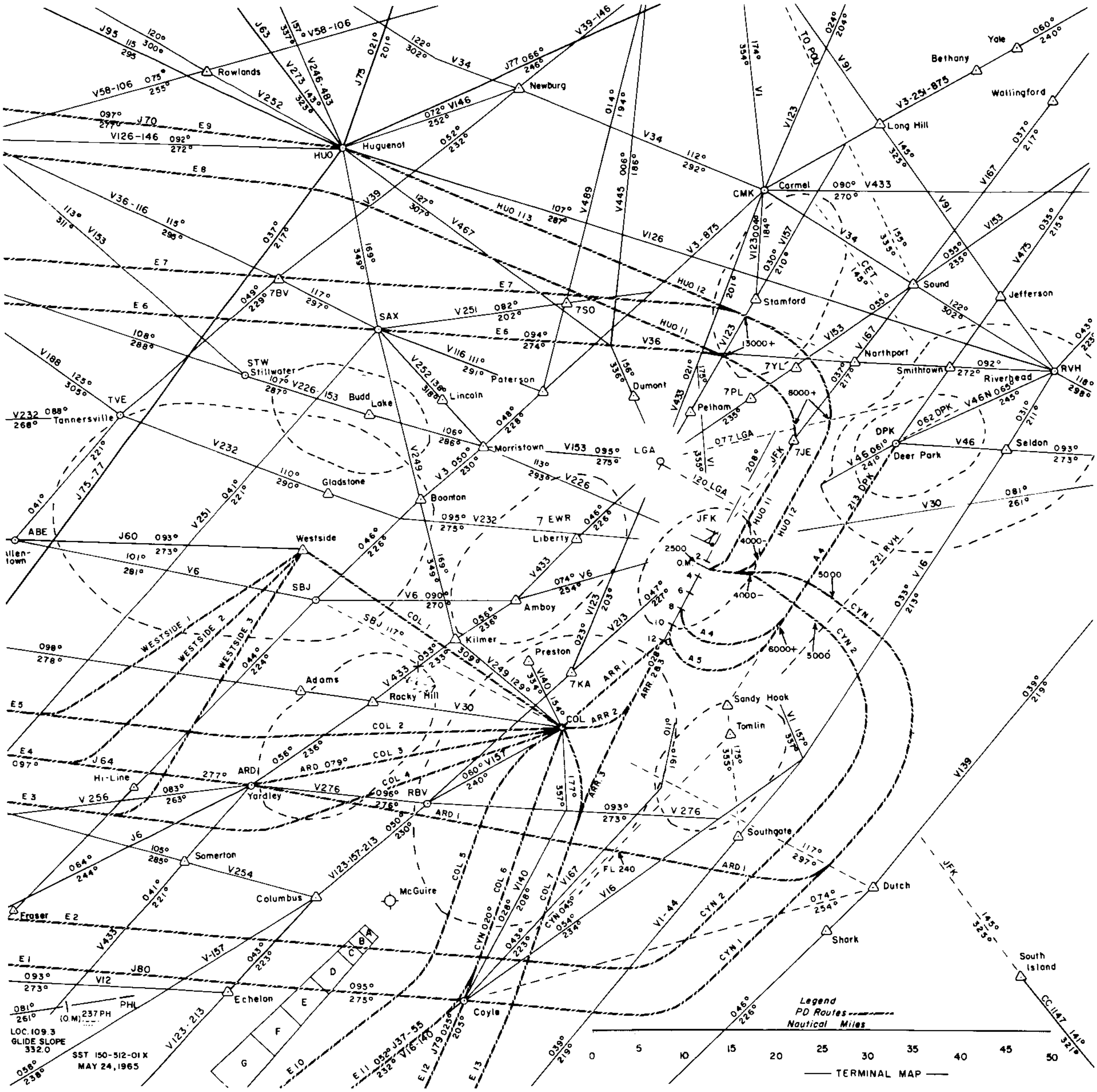


FIG. 21 JFK TERMINAL PICTORIAL DISPLAY ROUTE STRUCTURE

require a holding fuel reserve of 20 minutes at 15,000 feet. These ground rules provide for an additional five minutes of arrival terminal air maneuvering time, with no credit for distance. Four minutes of terminal air maneuvering during departure, with no credit for distance, is also stated in the ground rules.*

Results The results of various items studied in the terminal area are listed by category as follows:

Per cent of Scheduled Arrivals Completed As shown in Table I, the difference due to the variation in priority was not significant (N. S.), while the difference due to separation standards was significant at the .05 level. The findings indicated that the arrival segment of the system was more sensitive to changes in separation standards than to changes in the level of operational priority.

Further tests made between the Present System scores, and the various combinations of the priority and separation variables resulted in reductions in this measure from a high of 71.3% in the Present System, to a low of 51.3% in the High Priority/10 NM Experimental System, all indicating significant differences at the .01 level. The difference cited above was quite strong and indicated a penalty to other traffic if a High Priority/10 NM condition were adopted.

Arrival Operations Per Hour A difference of 11 arrival operations per hour occurred,42.5 in the Present System versus 31.17 in the High Priority/10 NM Experimental System. The analysis of variance (Table I) indicated significant differences attributable to the separation standard variable, with a drop from 37.42 to 33.25 landings per hour when the separation was increased from 5 NM to 10 NM.

The effect of increasing the separation criteria in the terminal area was reflected in the airport arrival operations rates attainable (Table I). In a dense traffic situation the operations rate is a function of the longitudinal separation attained in the approach and/or departure courses. As this separation criteria was increased there were fewer aircraft utilizing the final approach or departure course in

*SST-65-7 (REV) Supersonic Transport Economic Ground Rules, Washington, D.C., Federal Aviation Agency, Office of Supersonic Transport Development, September 1965.

TABLE I

ANALYSIS OF VARIANCE, SYSTEMS EFFICIENCY MEASURES

	Priority			Separation		
Measure	Low	High	Sig.	5 N.M.	10 N.M.	Sig.
Per cent of Scheduled Arrivals Completed	57.9	55.5	N.S.	59.8	53.7	.05
Arrival Operations per Hour	36.42	34.25	N.S.	37.42	33.25	.05
Per Cent of Arrivals Held	51.0	52.0	N.S.	43.0	61.0	.01
Accumulated Arrival Holding Delay (mins.)	335.08	419.01	N.S.	294.95	459.14	.05
Average Duration of Holding Delay per Aircraft Held (mins.)	9.38	12.40	.05	10.39	11.39	N.S.
Number of Altitude Changes Issued to SST Aircraft	15.59	12.25	.01	13.59	14.25	N.S.

a given amount of airspace, resulting in a reduced operations rate. When the airport operations rate is reduced, all aircraft are required to wait longer for a landing or departure. This results in an accumulation of additional delays throughout the operations sequence.

A theoretic example of maximum arrival rates of a single runway is presented below, based on the assumption that:

1. A saturated arrival traffic flow exists, and

2. The average approach speed of these aircraft is 135 Kts.

Using present longitudinal separation standards, the average time interval between landing aircraft could be 80 seconds, thereby permitting a maximum runway acceptance rate of 45 aircraft per hour. Now, utilizing special longitudinal separation for SST aircraft and assuming that six aircraft in an hour's approach sequence are SST types each requiring that the preceding aircraft land not less than five miles ahead of it (as insurance against a possible wave-off for the

SST), and that the next succeeding aircraft be afforded a minimum of three minutes longitudinal separation from the landing SST (to minimize the SST vortices effect), the average time interval between landing aircraft is now increased to 109 seconds. This then reduces the runway acceptance rate to approximately 33.5 aircraft per hour. As these incur delays, then the system is required to contain these aircraft for a longer period, thereby increasing the required controller workload per aircraft handled.

Per cent of Arrivals Held Within the Experimental System data, the two conditions that utilized a five NM separation criteria appeared better than those using 10 NM separation. The per cent of arrivals held (Table I) also showed a significant difference from the separation variables and a nonsignificant difference for the priority variables.

Accumulated Arrival Holding Delay The holding delay incurred in the Present System is only 20.93 minutes, versus 521.52 minutes in the High Priority 10 NM system. Considering $5.00 per minute as the average cost to the aircraft operator for holding delay,* the figures cited represent a cost increase of $2,503 to the total group of users in the system (for an 80-minute period).

Table I shows a significant difference for the separation variable, favorable to five NM versus 10 NM and no significant difference for the priority variable. This again indicates that the system is more sensitive to changes in separation than to changes in priority.

Average Duration of Holding Delay per Aircraft Held While this measure is not considered to be as sensitive to system change as the previous measure, it tends to strengthen suspicion of combination effects from the two variables. Tests showed an increase from 2.72 minutes delay, per arrival aircraft delayed in the Present System, versus between 8.43 and 12.45 minutes in the four conditions of the Experimental System. A significant difference also appears between the levels of the priority variable (Table I).

Number of Altitude Changes Issued to SST Aircraft The change from the five NM to the 10 NM separation standard had no significant effect on the number of SST altitude changes. However, as expected,

*Cost figures based on Digest of Economic Criteria for FAA Expenditures, Memorandum Report; September 1962; FAA, SRDS, Systems Management Division.

the change from the Low Priority condition to the High Priority condition showed a significant reduction from 15.59 to 12.25 (Table I). This is due to the procedures that permitted the controller to issue more altitude restrictions in the Low Priority condition.

Pictorial Display System Subjective opinion indicated that PD routes were advantageous to the ATC system. The following discussion is based solely on this subjective opinion.

PD routes were established within the framework of existing airspace allocations. It was obvious that with prudently designated PD routes, the vectoring area was reduced to a minimum, and maximum utilization was made of the airspace. Parallel routes were also possible without additional navigational aids or complex vectors. When aircraft used the PD, fewer vectors were necessary and there was a decrease in communications workload. It was also possible to establish an arrival sequence and the desired interval long before aircraft reached the final approach course. By positioning aircraft on a given track and adjusting airspeeds of these aircraft to be compatible with each other, it was sometimes only necessary to monitor the traffic all the way to the runway. When SST aircraft were using PD there were no violations of holding pattern airspace, and the controllers' task of monitoring the holding pattern was minimized. The use of PD routes thus decreased controller workload and gave him more time in which to provide better service.

Effects of SST Operating Characteristics The maneuverability of SST aircraft in the terminal area, being comparable to subsonic jet aircraft, posed no special ATC problems. However, the requirement to provide 5,000 feet lead time for an unscheduled level off of SST departures between 4,000 feet and FL400, created an ATC problem. Prior to issuing a clearance to level-off, control personnel queried the pilot for his altitude. The time lost between requesting this information, receiving it from the pilot and issuing a clearance, resulted in altitude overshoots due to the SSTs high rate of climb. Flight simulated tests showed that SSTs can be climbing at rates of 8,000 to 12,000 feet per minute. It is felt, that a Mode C Altitude readout displayed on a controller's radar scope could alleviate the overshoot problem when providing a 5,000 foot lead.

NASA personnel advised that the SST would, from a fuel standpoint, prefer to hold at the lowest available altitude (13,000 feet), except when deviations to an alternate airport are anticipated.

Controller Workload Analysis The positions of operation which dealt primarily with arrival traffic showed a general increase in controller communications workload as the increased separation standards and priority variables were introduced for SSTs. The influence of the SST separation standard variable appeared to govern the amount of arrival controller workload more than the priority variable. Comparing the basic system to the Low Priority/5 NM condition, the arrival controllers communications workload increased by seven per cent in the Low/5 condition. Going from the Low/5 condition to the High/5 condition resulted in a further increase of only one per cent.

Conversely, positions of operation primarily concerned with departure traffic tended to have less workload as these variables were introduced. This was due to the inability to get departures out on schedule. The sectors closest to the terminal were sensitive to interaction of the two variables.

En route Test Procedures

General The en route test program was designed to study SST operations integrated with subsonic traffic, operating under the jurisdiction of an ARTC center. This study was divided into phases wherein three systems, Present, Experimental, and PD were tested. SST operations consisted primarily of traffic originating at, or destined for, the JFK or SFO International Airports with two en route SSTs overflying the test area. SST traffic originating at JFK or SFO was initially controlled by the respective terminal facility and entered the en route areas at appropriate handoff points. Other SST traffic entered the test areas at cruise altitude (FL730 or FL770).

The integration of SST aircraft with subsonic traffic usually occurred at FL390 and below while SST aircraft were climbing to, or descending from, cruise altitude. Subsonic aircraft were controlled throughout the test program in accordance with current ATC procedures. Certain changes to these procedures were made for the control of SST aircraft as discussed on the succeeding pages.

In conjunction with the study of the three systems, two SST scheduling processes were also studied to determine if advantages to the system might be gained by scheduling SST aircraft in closer proximity to each other. The two scheduling processes tested were:

1. SST flights were provided a random distribution within the mix of other traffic.

2. SST flights were scheduled in close proximity (three minutes apart) to each other in groups of three.

General SST operational requirements established by NASA to be compatible with the operating characteristics of SST aircraft, were as follows:

1. A straight route segment 170 NM in length was provided for SST departures to accomplish transonic acceleration to supersonic speed while climbing from FL400 to FL510. Any potential conflict between climbing and descending SST aircraft in this altitude range was resolved by vectoring or applying an altitude restriction to the descending aircraft.

2. Because of the high rate of climb and descent of the SST, ATC was required to notify the pilot at least 5,000 feet prior to level-off, in order to prevent flying through the desired altitude.

3. Maneuverability of SSTs below FL400 was assumed to be the same as current subsonic jets. Above FL400, at supersonic speeds, the radius of turn increased with the increase in Mach number. Supersonic turns were based on a norm of 20° angle of bank with a 25° maximum. SSTs did not accept vectors in excess of 15° from desired course.

4. To provide an optimum descent profile, SST arrivals did not begin descent until the last practical moment. This was usually 175 NM from the outer fix. SSTs were not held above FL450 at supersonic speeds.

Present System In this study, the SST aircraft used current routes, as shown in Figures 1, 2, and 3. No preferential treatment was afforded SSTs and ATC service was the same as that provided subsonic aircraft.

Experimental System In this study, SST aircraft were afforded preferential treatment. In addition, three experimental separation standards, as illustrated in Figure 22, were tested in the control of SST aircraft. Route configurations used are depicted in Figures 1, 2, and 3.

Pictorial Display System In this study, PD routes were used by SST aircraft as the primary means of navigation. PD routes used are depicted in Figures 23 and 24. Use of PD routes was limited to SST aircraft only with other traffic using the existing airway structure. This created a dual airway system which normally segregated the SST from subsonic traffic. These routes were separated laterally by a minimum of 15 NM.

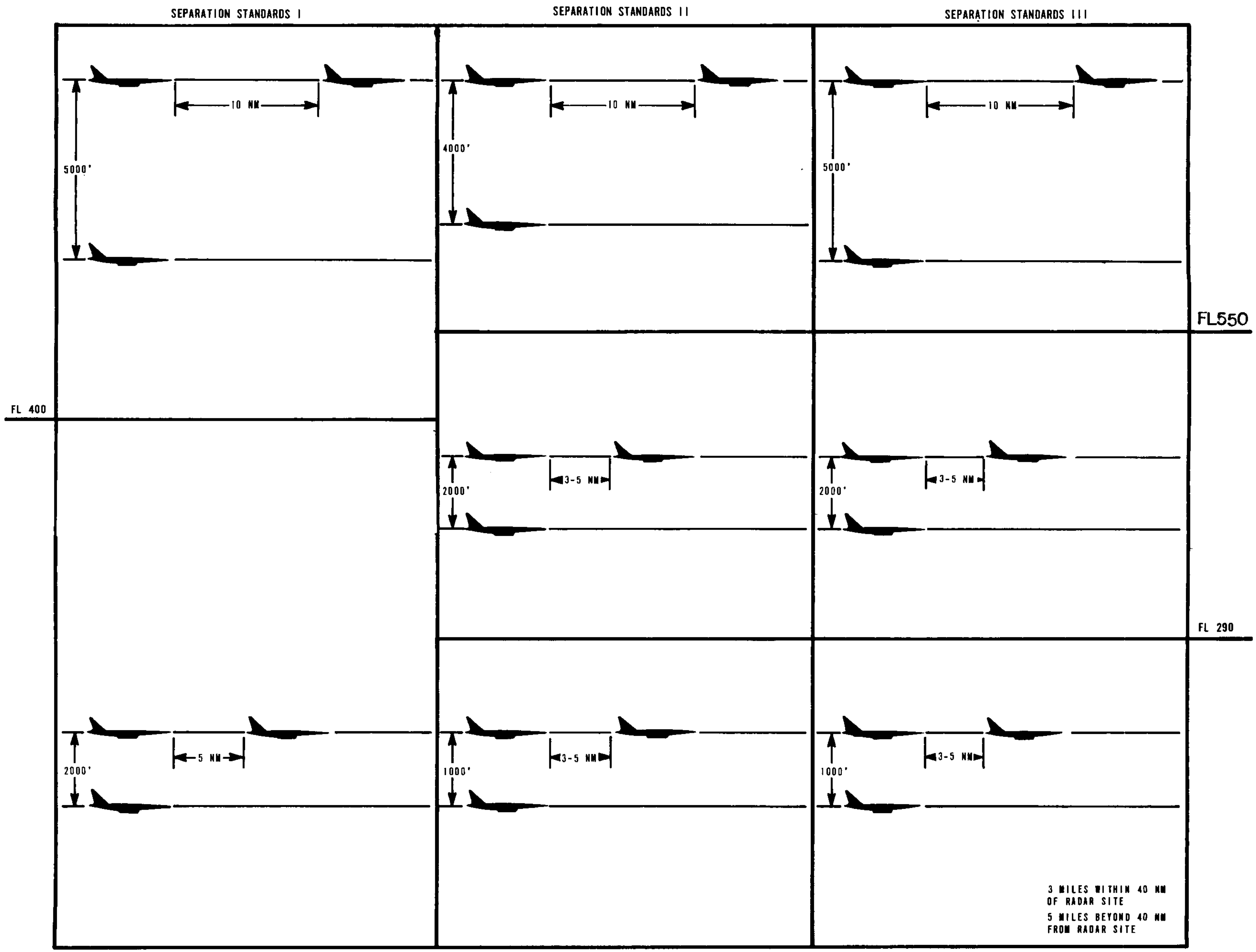


FIG. 22 ENROUTE EXPERIMENTATION SEPARATION STANDARDS

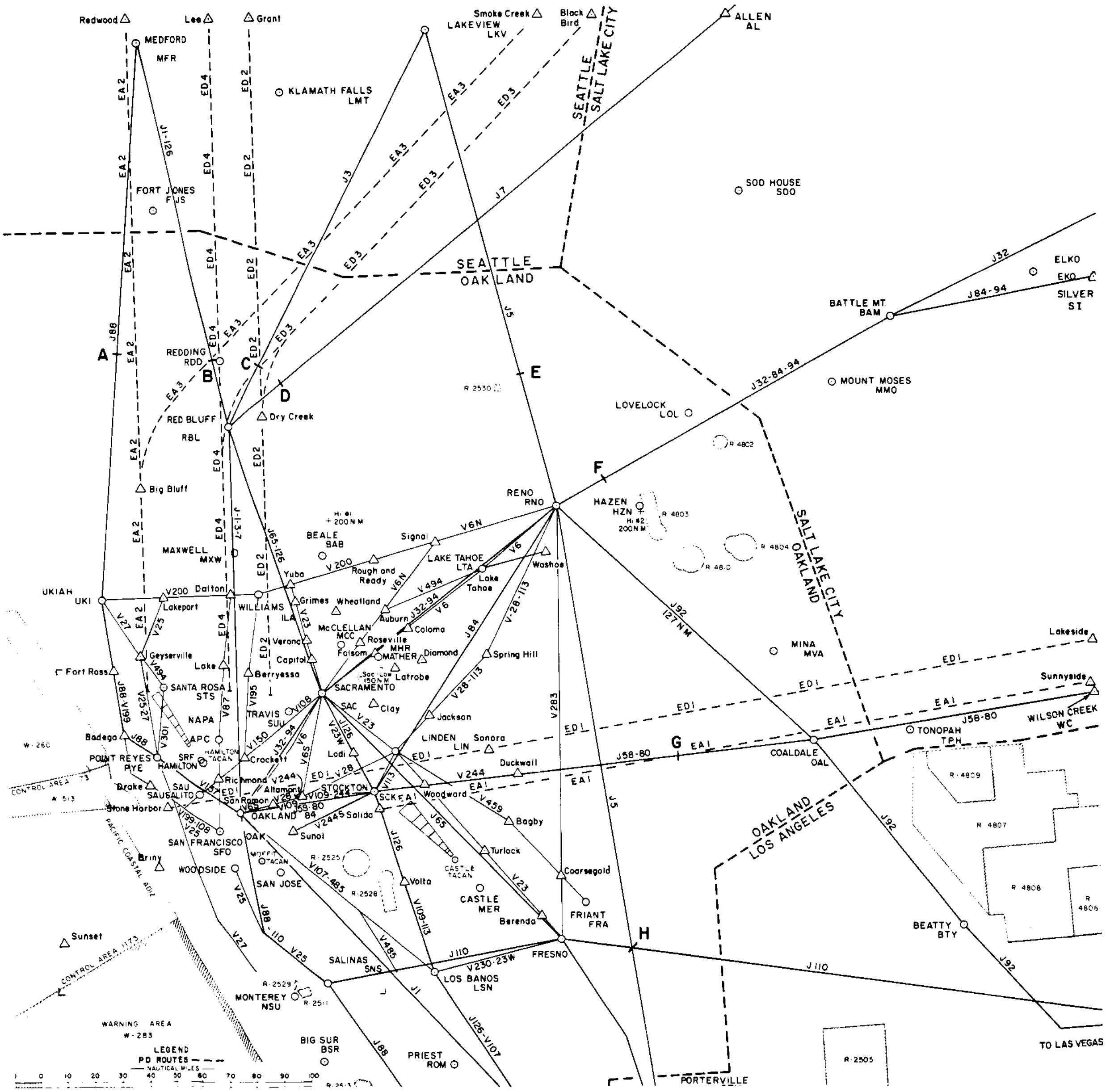


FIG. 23 SFO ENROUTE PICTORIAL DISPLAY ROUTE STRUCTURE

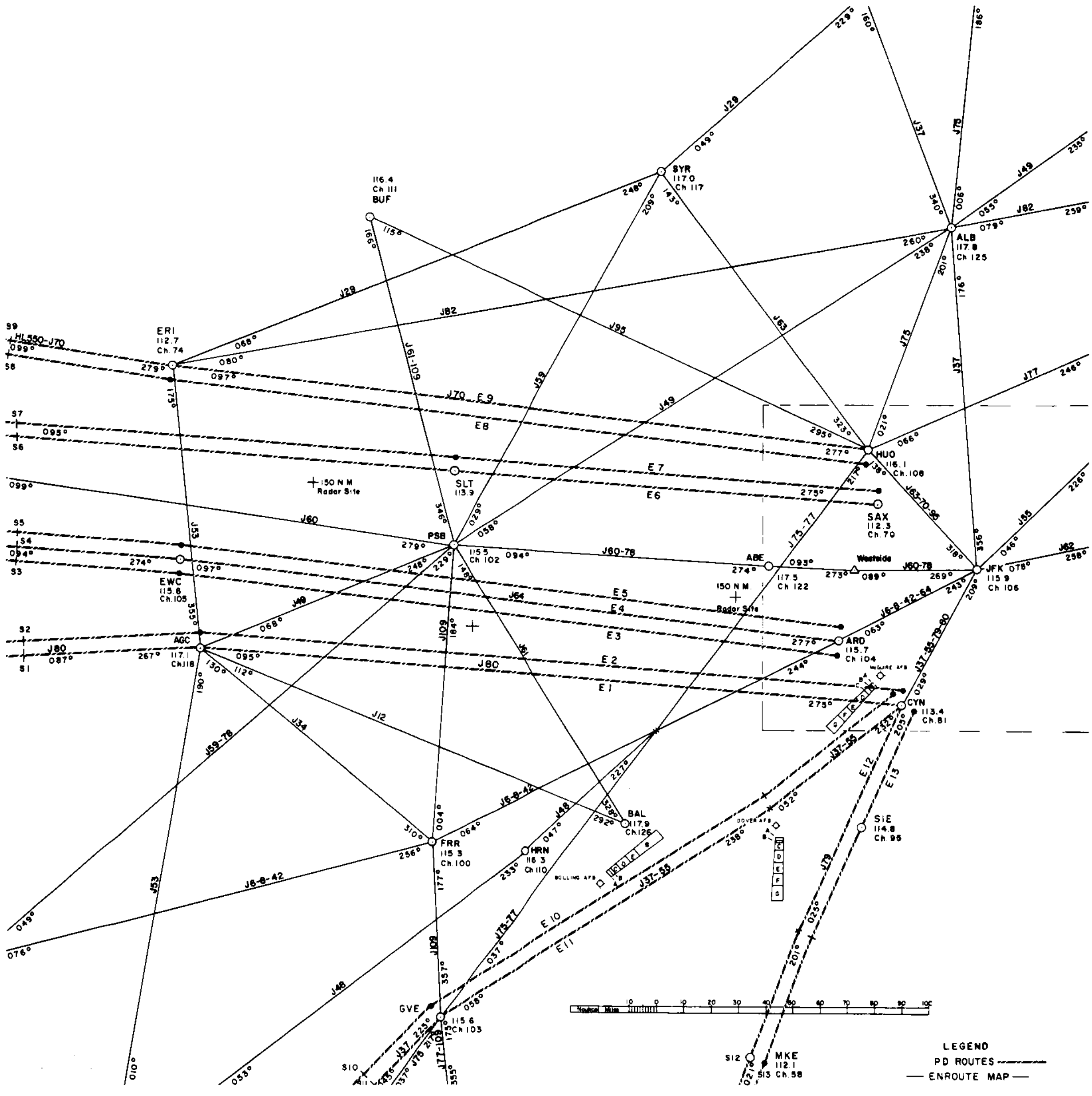


FIG. 24 NEW YORK ENROUTE PICTORIAL DISPLAY ROUTE STRUCTURE

Priority Concepts Experimental System and Pictorial Route System tests were made under both High Priority and Low Priority conditions.

High Priority Condition Preferential treatment was given to SSTs to provide the most expeditious service possible. No en route delays, holding, or excessive course deviations were incurred by SSTs. SST departures were assigned PD routes or vectored via the most direct route to intercept a 170 NM straight route segment to accomplish transonic acceleration to supersonic speed. Turns or altitude restrictions were not issued while on this straight route except in an emergency. A conflict between descending and climbing SSTs was resolved by deviating the descending SST. Resolution of control problems between SST and subsonic aircraft was accomplished by exercising control over subsonic aircraft.

Low Priority Condition Limited preferential treatment was given to SSTs. Resolution of control problems between SSTs and subsonic aircraft was accomplished by exercising control over the subsonic aircraft, or when necessary over the SST with one exception; SST departures in the 170 NM straight route segment were not issued heading changes or given altitude restrictions until above FL510. En route delays were authorized; however, this delay was not to exceed 20 minutes.

Results The results of various items studied in the en route area are discussed by category as follows:

Transonic Acceleration Segment To accomplish acceleration to supersonic speeds, SST departures were provided with a direct steer or route segment 170 NM long. This requirement was provided for climb between FL400 and FL510. No turns or altitude restrictions were permitted during this climb phase. Results of the studies indicated that this route segment should be taken into consideration when planning SST departure routes and be 100 to 170 NM long.

NASA personnel advised, that any turning of SSTs during transonic acceleration will have an adverse effect of intensifying the sonic boom. It was further determined that turns during transonic speeds are undesirable because of loss in climb--acceleration performance at the time of minimum performance capability, in addition to the sonic boom focusing.

Controllers were given a last decision for leveling and/or vectoring an SST by having the pilot report leaving FL310; at this time the controller either leveled the SST at FL370, because of traffic, or

Priority Conditions For the priority variable (high and low) some differences in system efficiency were found between the systems tested, but they were not as pronounced as expected. Neither was there as much significant interaction of the separation and priority variables as had been expected.

When preferential treatment was afforded the SST aircraft, a seven per cent saving in time was realized for these aircraft; however, this resulted in a 13 per cent increase in time for other aircraft in the system. Usable airspace was also lost as this created a sterile area for those aircraft to insure a clear flight path. This imposed penalties to other aircraft as they were often vectored off their intended course, denied their requested altitude or delayed at a fix because of the priority aircraft. Vectors and altitude changes required to move other aircraft away from the path of the aircraft receiving priority increased the controllers communications workload by approximately five per cent.

The greater degree of priority afforded SST aircraft, the more detrimental this became to system efficiency and to controller workload. The Low Priority condition appeared to be the best en route system and the most acceptable compromise between rigid SST priority and the flexibility needed by the ATC system. The High Priority condition was the most detrimental to total system efficiency. When SST aircraft received the same service as all other aircraft, the unique problems in controlling SST aircraft were only those caused by its special operating characteristics.

Pictorial Display System The results of PD in the en route area were obtained subjectively, as in the terminal area, since statistical tests were not made of PD during the SST studies. The use of PD during these tests was limited to SST aircraft only, and was examined to determine if it facilitated the integration of the SST into the ATC system. The advantages of PD over the present system of navigation were the results of a separate project and is the subject of other FAA reports.*

*Dynamic Simulation Studies of Pictorial Navigation Displays as Aids to Air Traffic Control in a High-Density Terminal Area and a Medium-Density Terminal Area, Interim Report, Atlantic City, N.J., FAA, ARDS, November 1961, and Area Coverage Displays and Course Line Computers Experimentation, Final Report No. RD-65-117, Atlantic City, N.J., FAA, SRDS, October 1965.

The use of PD in the en route environment permitted maximum utilization of airspace without requiring additional navigational aids or complex vectors. The direct route segment for transonic acceleration was less difficult to provide with the utilization of PD routes. The assignment of parallel PD routes for SST aircraft also minimized the difficulty of resolving potential head-on conflicts and helped to segregate SST operation from subsonic operations.

Use of PD by SST aircraft reduced the control workload in that ATC was not required to vector these aircraft, but had only to provide monitoring service. This permitted the controller to devote more time to other aircraft in the system.

NASA personnel advised that a preliminary study of tests involving the use of a PD indicated that the pilots could fly specified pictorial routes, with deviations from course of 1-4 NM. The larger deviations occurred in the turns and probably could be reduced by adjusting the pictorial display route turn radii to match the SST performance. The PD was found to be advantageous in performing holding pattern maneuvers in wind conditions, enabling the pilot to fly a smaller, more regularly shaped pattern, and to complete the pattern with less deviation from the expected pattern time. Use of the PD resulted in a reduction in the communication workload for the SST pilots. It appears that a more complete reliance on the PD, than was used in these tests, would further reduce communications; however, use of the PD generally increases the navigation workload, because of including it in the instrument scan task.

Scheduling Processes The results of the two scheduling studies indicate that when preferential treatment is afforded SST aircraft, these aircraft should not be purposely scheduled in close proximity to each other. This was detrimental to the ATC system and was reflected in increased delay and heading changes to other aircraft in the system.

Additional Study

The en route study previously discussed indicated the need for a more detailed investigation of the problems of controlling SST aircraft in the higher altitude en route areas. An additional study was designed to further investigate supersonic operations above FL430. The objectives were to:

1. Determine controller capability to detect potential track conflict between:

   a. Mach 3 vs Mach 3 aircraft

b. Mach 3 vs Mach 2 aircraft
c. Mach 2 vs Mach 2 aircraft
d. Mach 2 vs subsonic aircraft

2. Determine the magnitude of, and point where course deviations should occur to resolve conflictions.

3. Study sectors with larger geographical areas of responsibility.

To accomplish these objectives, a geographical area 400 NM square (FIG. 25) was used. This area was divided into two "High-high" sectors. In some tests it was assumed that Sector I was located in Salt Lake City ARTC Center and Sector II was located in Oakland ARTC Center. In other tests these sectors were assumed to be under the jurisdiction of a single ARTC center. Two 22" horizontal radar scopes, one for each sector, with mosaic radar presentation of two radars were used. The radar scopes covered a radius of approximately 200 NM. Each sector was manned by one controller and one coordinator. The controllers were provided with one radio frequency which was assumed to be discrete and cover the sector area.

Supersonic traffic flow consisted of 15 SSTs all in the state of cruise climb. Routes designed for Mach 3 and Mach 2 operations are shown in Figure 26. These flights were programed to enter the "High-high" sectors at FL500, FL550, FL600, and FL650, climbing to FL730. Climb rate in cruise was approximately 2,000 feet every 100 NM. Turn rate for SSTs at the upper flight levels was 1/2 degree per second with a 20° angle of bank. Three conflicts were programed to occur in each "High-high" sector with each conflict involving two SST aircraft on crossing flight paths. Three variations of control procedures were tested for resolving these conflicts. Each procedure was tested separately as follows:

Procedure I An assumption was made that all aircraft on a crossing or head-on course, with less than 5,000 feet vertical separation, were in conflict with each other. These conflicts were resolved by vectoring one or both aircraft. The vectors were not more than five degrees from desired course and aircraft were to be separated by a minimum of 10 NM. No altitude restrictions were permitted.

Procedure II Same as Procedure I above, with the exception that vectoring was permitted with no restriction on the magnitude of turn.

Procedure III Conflicts were resolved by vectoring and/or

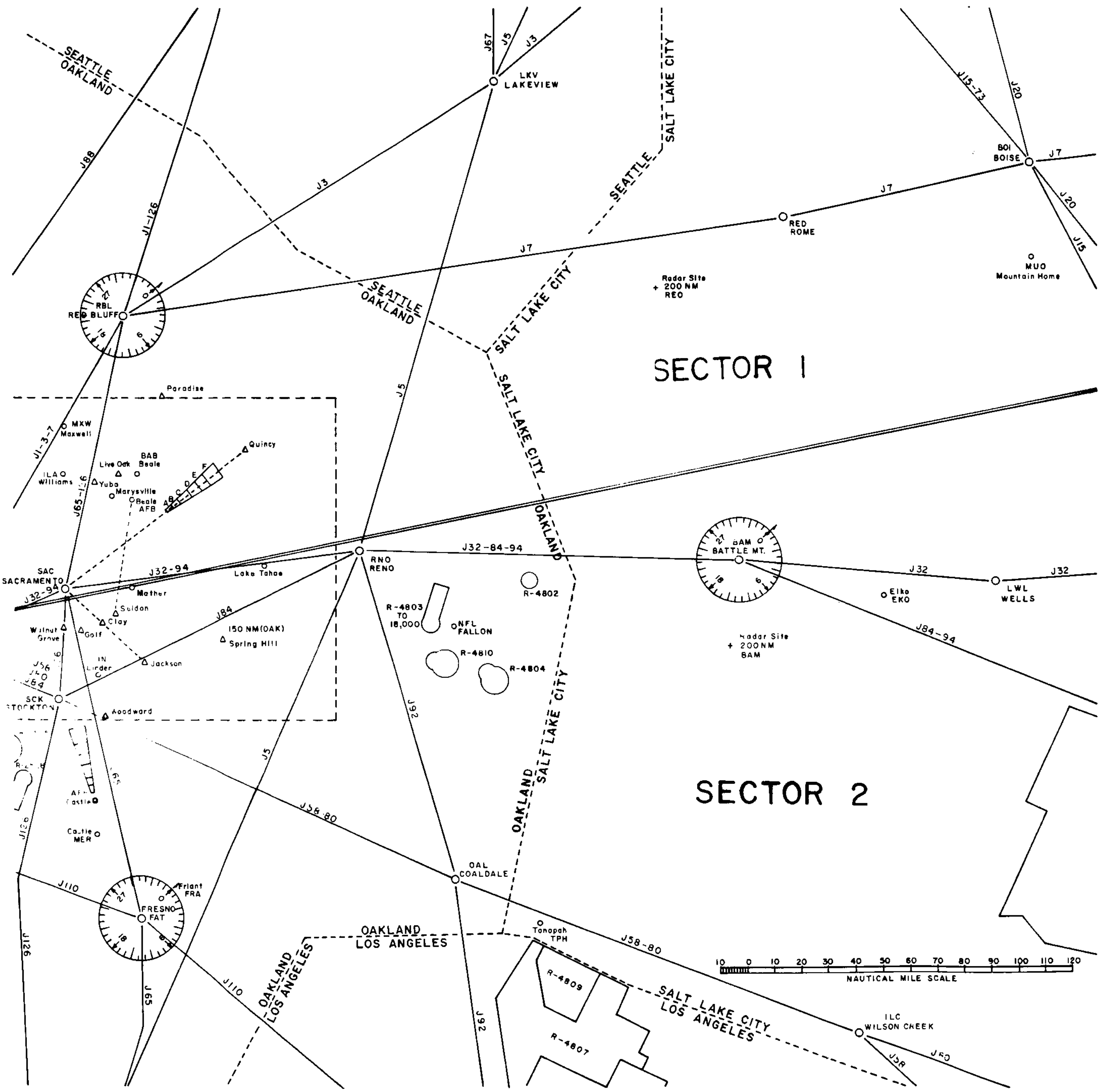


FIG. 25 TEST AREA FOR HIGH ALTITUDE OPERATIONS

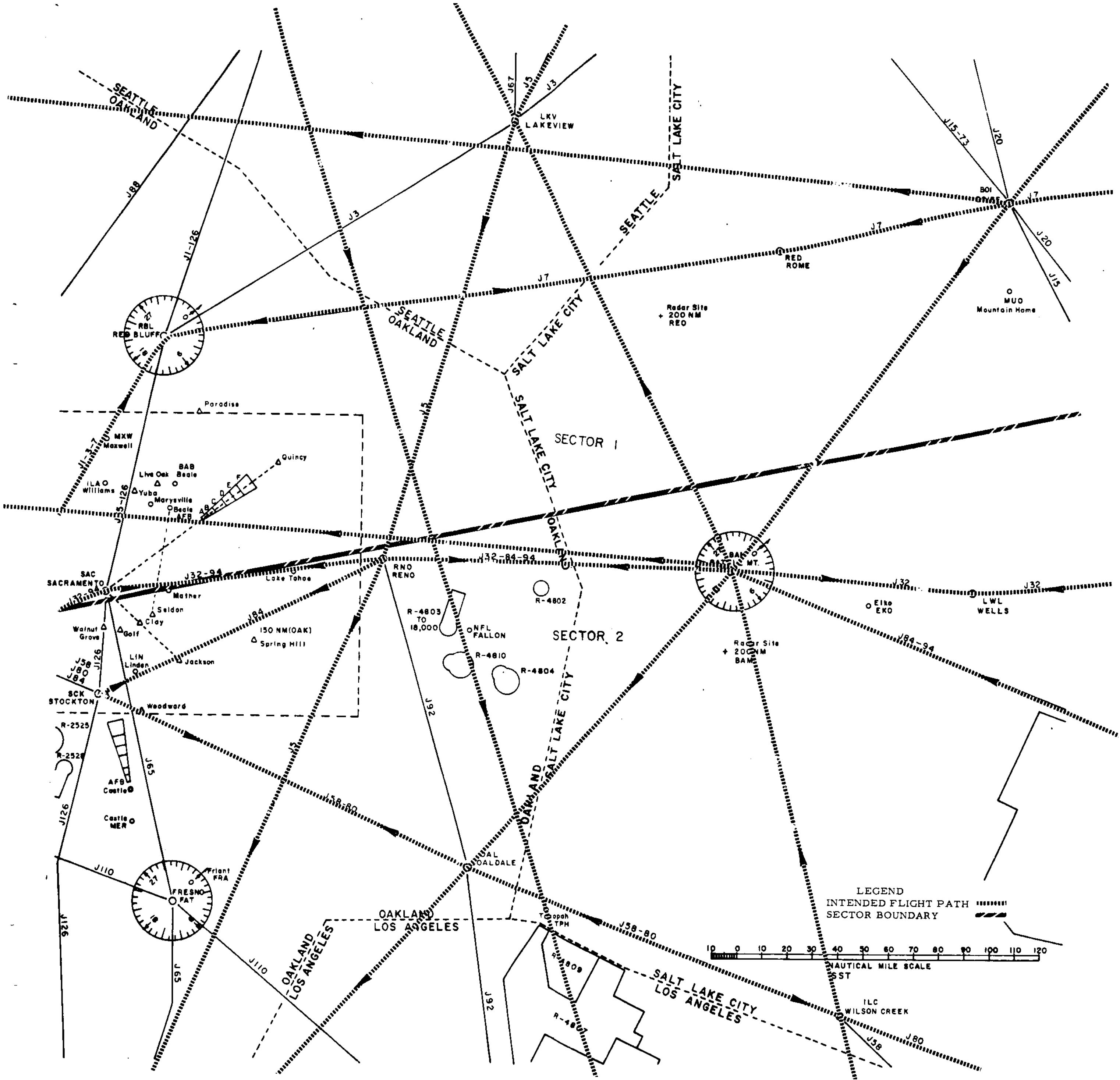


FIG. 26 MACH 3 AND MACH 2 ROUTES

applying altitude restrictions to one or both aircraft. Separation minima of 10 NM radar, or 5,000 feet vertical, were required. Vectoring was permitted with no restriction on the magnitude of turn. En route aircraft in a cruise climb configuration were required to level off or descend to a lower altitude to provide proper vertical separation.

Results The additional study consisted of short exploratory tests which investigated the various items listed under objectives. Results of this study were not subjected to statistical analysis due to the limited number of data runs obtained. However, these results will be used in developing a more detailed test plan which will investigate all of the objectives more thoroughly at a later date. The following results are based on Project Team observation and controller opinion.

Procedure I This procedure was the least desirable method of providing separation. It was effective only in cases of aircraft on opposite courses and the five degree limit on course change required a turn when aircraft were not less than 125 NM apart. With aircraft on crossing or converging courses, the five degree course change was not effective in resolving a potential conflict.

Procedure II This procedure, while it offers wider latitude for control than Procedure I, is still not dependable. It presented the same problems as Procedure I, because of high speeds and the resulting wide radius of turn of the SST aircraft.

Once the SST was vectored off its original course, controllers usually encountered difficulty in re-establishing the aircraft back on course without generating additional conflicts. In many instances, when controllers vectored aircraft to resolve a conflict within the sector, additional conflicts were created within the same sector or in the adjacent sector without either sector controller realizing that this situation would develop.

Although controllers had the option of obtaining altitude information, this information proved to be of little value because the SST was normally cruise climbing. Figure 27 represents typical flight paths of Mach 2 SST aircraft when only vectoring was used to resolve traffic conflictions.

Procedure III This procedure was the best of the three tested, but the consensus of controllers was that it too was not dependable. Separation of traffic using unlimited vectors or temporary altitude assignments were a more realistic approach for providing separation; however, conflicts still occurred.

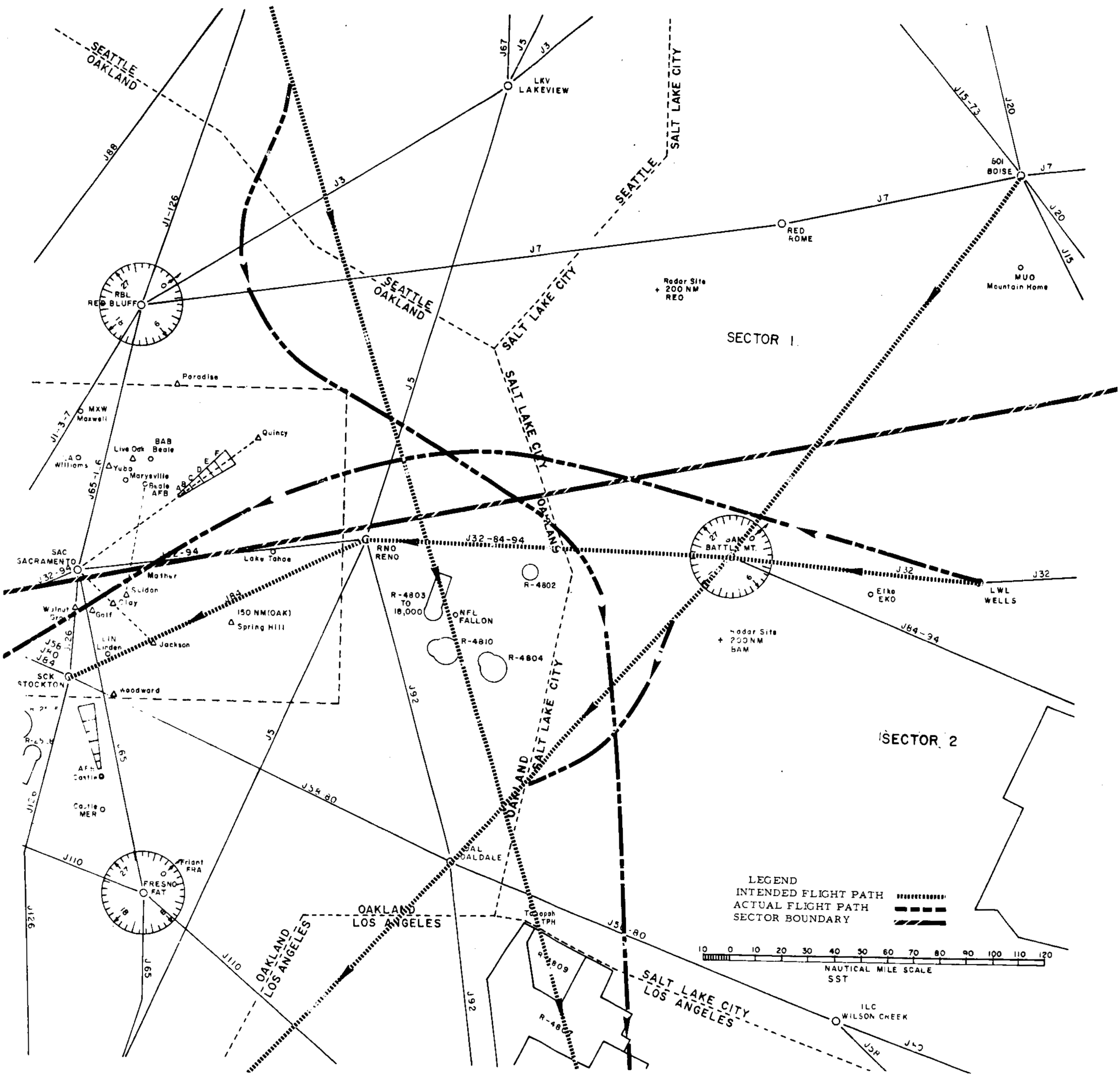


FIG. 27 MACH 2.0 SST FLIGHT PATHS WITH VECTORING ONLY

The SSTs wide radius of turns presented the same problems found in Procedures I and II. Vertical separation of 5,000 feet was difficult to obtain even though the controller was authorized to level or descend en route SSTs that were cruise climbing. The actual altitude of the aircraft could only be obtained by requesting it from the pilot. The descent of the SST was too slow because of the relatively small altitude change per miles traveled. Control instructions for an altitude change had to be given so far in advance of the point of conflict that vertical separation was extremely difficult to apply. Figure 28 represents typical flight paths of Mach 2 SST aircraft when vectoring and vertical separation were used to resolve traffic conflictions.

Sector Size and Routes Sectors of larger geographical areas have merit and were effective for handling the amount of supersonic traffic simulated. When the two sectors were studied as being under the jurisdiction of one ARTC center, one coordinator made the decisions and a smoother operation resulted. Controllers were of the opinion that peripheral radar coverage of adjacent sectors was inadequate and that the display of approximately 100 NM of the adjacent sectors would be highly desirable.

The multi-direction routes, used in these tests, were considered to be very poor during busy periods. One-way routes are considered a necessity.

Course Changes To insure 10 NM lateral separation between two head-on Mach 3 aircraft, it was found that the minimum allowable distance before one had to be turned was 100 NM and the minimum change was 15 degrees. It was also determined that by turning both aircraft 15 degrees to the right of course, the minimum distance between the two aircraft could be reduced to 75 NM.

By substituting Mach 2 aircraft for the Mach 3 aircraft in the same type of head-on situation, the results were basically the same when both aircraft were turned. However, it was found that by turning only one aircraft 30 degrees, 10 NM lateral separation would exist at the time the aircraft passed each other if the turn was started when the distance between aircraft was not less than 50 NM.

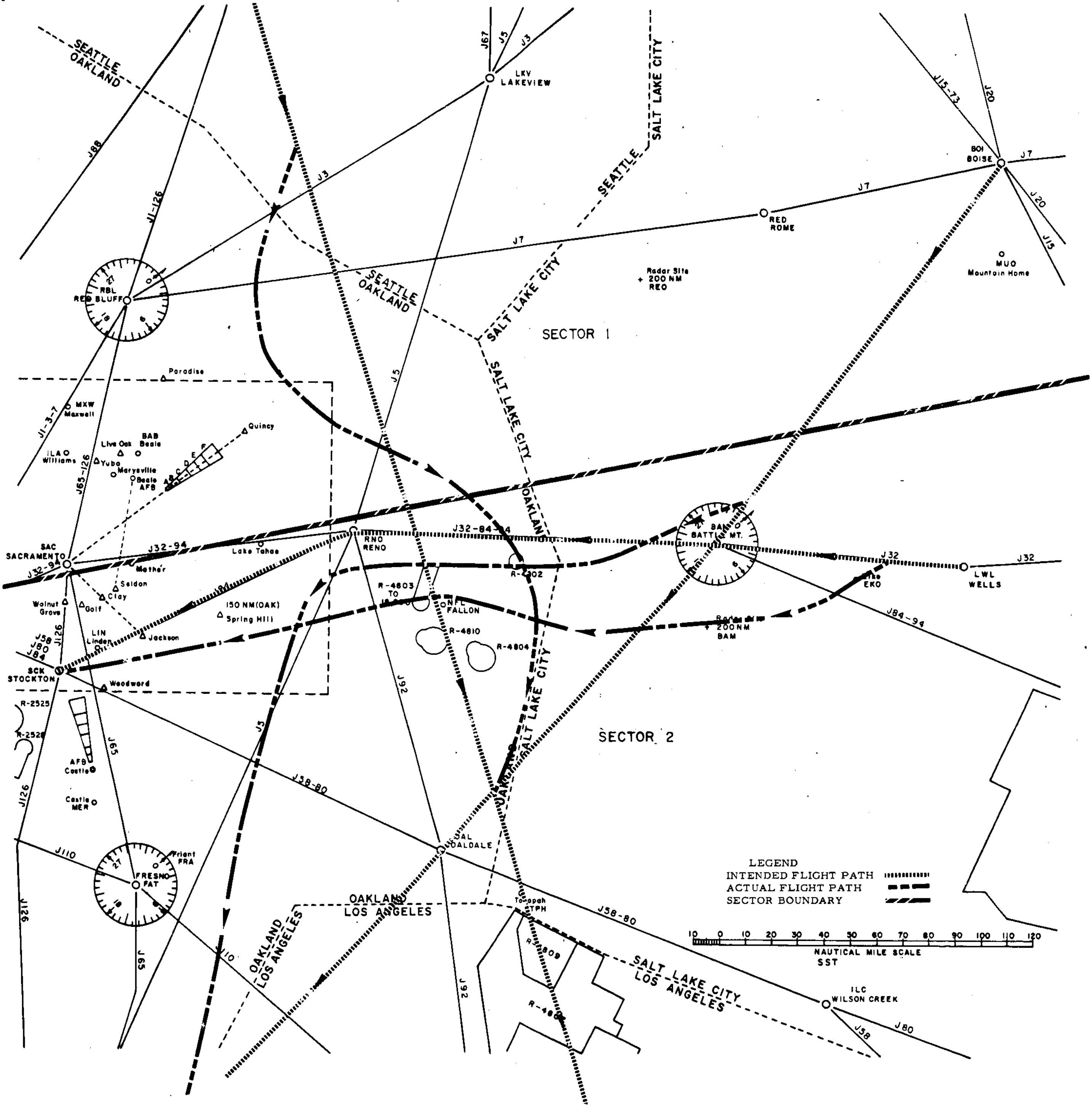


FIG. 28 MACH 2.0 SST FLIGHT PATHS WITH VECTORING AND VERTICAL SEPARATION

CONCLUSIONS

Based on the results of the simulation studies, it is concluded that:

1. The High Priority condition, with separation standards greater than those used today, is the most detrimental to total system efficiency and, if adopted, would result in:

a. Reduced airport acceptance rates, as great as 11 operations per hour at high density terminals.

b. Subsonic traffic incurring long radar vectors, excessive holding, and ground delays. These delays may total as much as 13% greater than Present System delays.

c. An increase in workload for terminal approach controllers, and for en route controllers whose sectors serve the terminal area.

2. The Low Priority condition, with current separation standards, is the most acceptable compromise between rigid SST priority and the flexibility needed by the ATC system.

3. Limited preferential treatment can be provided SST aircraft without major adverse effects on the present ATC system.

4. The assignment of the same route to opposite direction SST traffic is undesirable.

5. More expeditious ATC handling for the SST is possible by the provision of parallel one-way routes.

6. An effective means of providing segregated routing to SST aircraft is through the use of Pictorial Display Equipment.

7. The terminal area is more sensitive to priority handling and increased separation standards than the en route area.

8. The terminal area is more sensitive to increased separation standards than to priority handling.

9. The en route area is more sensitive to the unique performance of the SST than the terminal area.

10. The 170 NM straight route segment, required for SSTs to accomplish transonic acceleration between FL400 and FL510, had no effect on subsonic operations and system efficiency because subsonic aircraft operated below this level. This straight segment was required because:

a. Turns during transonic acceleration were detrimental to SST performance, since the SST excess thrust capability is at a minimum at low supersonic speeds.

b. Turns, when at supersonic speeds, are not only undesirable because of the effect on performance, but in addition create intensified sonic boom overpressures because of the focusing effect of the turn.

11. During ascent, lead time to level an SST at an altitude appears to be in the order of 5,000 feet when below FL400 and above FL510. Between FL400 and FL510 no appreciable lead time is needed. In descent, lead time to level appears to be in the order of 5,000 feet when above FL400, and 3,000 feet when between FL400 and FL200.

12. Current ARTC center high altitude sectors do not encompass areas of sufficient magnitude to effectively control aircraft operating at supersonic speeds.

13. Restricting course deviations to 15° or less proved ineffective in separating supersonic aircraft above FL400 who were within 100 NM of each other.

14. Establishing High-high sectors to control all flights operating at or above FL430 improved the ATC service.

RECOMMENDATIONS

It is recommended that:

1. Preferential treatment for SST aircraft be kept to an absolute minimum.

2. Straight acceleration tracks from 100 to 170 NM long, starting as close as possible to the airport, be provided when planning SST departure routes.

3. Criteria be developed for a route structure (including parallel routes) above FL430 to minimize conflict of opposite direction aircraft.

4. High-high sectors be established which encompass areas of sufficient magnitude (approximately 600 NM in diameter) to control all flights operating at or above FL430 throughout the contiguous United States and adjacent oceanic areas.

5. Pictorial Display Equipment be considered as an aid to navigation to permit maximum utilization of airspace without the addition of ground navigation facilities.

6. Additional studies be made to determine optimum techniques for controlling supersonic operations, especially in the High-high sectors.

7. This report serve as a guide for future studies by the FAA and NASA for Air Traffic Control of Supersonic Transports.

ACKNOWLEDGMENT

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