OPERATING PROBLEMS OF THE SUPERSONIC TRANSPORT IN THE AIR TRAFFIC CONTROL SYSTEM

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INTRODUCTION

In order to study the problems anticipated with the integration of the supersonic transport (SST) into the air traffic control system (ATC), a cooperative research program between the National Aeronautics and Space Administration (NASA) and the Federal Aviation Agency (FAA) has been initiated.

The objectives of the program are (1) to determine the effects of the air traffic control system on the supersonic transport design and equipment requirements and (2) to determine the effects of the supersonic transport on the air traffic control system requirements.

In this paper, results are presented of studies of navigational and operational problems in terminal-area operations for two SST design configurations operating in the present-day airways system under current ATC procedures. Results from a preliminary study of the use of a pictorial navigation display in connection with pictorial navigation routes are also given.

EQUIPMENT

A block diagram of the facilities involved in the program is shown in figure 1. The blocks on the left represent the equipment at NASA Langley Research Center and those on the right represent the equipment at the National Aviation Facilities Experimental Center (NAFEC) in Atlantic City, New Jersey. Supersonic transport simulation at NASA's Langley Research Center is accomplished by the use of a fixed-base SST simulator and an analog computer facility. An interior

L-4693

view of the SST simulator's flight compartment is shown in figure 2. Seating is provided similar to that of current jet transport aircraft, with the instrument ranges modified for the higher altitude and Mach number operation of the SST. Figure 3 shows the analog computers which are programed to solve the six-degree-of-freedom equations of motion for an aircraft having the design characteristics of the SST under study.

Air traffic control simulation at NAFEC is accomplished by the use of air traffic controllers and an air traffic sample. Figure 4 shows the air traffic controller's facility simulator. Approximately 30 experienced controllers are used and are equipped with a modern TV-type radar display. An air traffic sample is simulated by the use of radar target generators, as shown in figure 5. By turning knobs and manipulating levers, the operator can maneuver the simulated aircraft along the airway routes according to a predetermined schedule and instructions from ATC. A mixture of supersonic transports and piston- and turbine-powered subsonic transports are simulated.

As indicated in figure 1, radar position information (and when requested, beacon transponder aircraft identity) from NASA's SST simulator is transmitted to NAFEC over leased telephone lines. This position information from NASA's SST simulator appears as a blip on the controller's radar scope along with signals from the target generators. Simulated VHF communications between the SST simulator pilots and the air traffic controllers are also carried over leased telephone lines. A dual channel tape recorder is provided for recording all air-to-ground and ground-to-air communications.

For the latest series of tests, a pictorial navigation display was included as an operational cockpit instrument. A view of the pictorial display can be seen in figure 6. This is a moving-map display with the aircraft symbol fixed in position in the center of the screen. The airplane symbol and attached cursor rotate as the airplane initiates a heading change, and heading cursor information is depicted at the edge of the screen. The map remains north-oriented at all times. Physical size of the display projection screen is 5 inches by 7 inches. The pictorial display provided for selection of en route (10 n. mi. per inch) and terminal (5 n. mi. per inch) maps which depicted only basic airway, navigation, and ATC information.

TEST PROGRAM

The tests consisted of simulated arrivals and departures under instrument flight rule (IFR) conditions in the New York terminal area during present-day peak-traffic conditions. Oceanic and domestic departure and arrival routes flown in the tests are shown in figures 7, 8, and 9. Routes used in the tests with the pictorial display were designed to lay over and parallel to the established domestic departure and arrival jet routes. The simulation was conducted in real-time utilizing a mixed-traffic sample including SST aircraft, one of which was the SST simulator. All traffic was under positive control of the New York Air Route Traffic Control Center, adjacent centers, and Kennedy departure, arrival, and tower facilities. Two SST aircraft design configurations were simulated. Configuration A was a variable-sweep wing design and configuration B was a fixed delta-wing design. These are generalized SST configurations and do not necessarily represent the characteristics of SST configurations in the national program.

Climb and Descent Profiles

The climb and descent profiles, as well as some operational limitations for configuration A are shown in figure 10. The engine and structural limitations define a corridor through which the SST must operate. After take-off and initial acceleration, the SST climbs at an airspeed of 360 knots until the sonic boom boundary of 2.0 pounds-per-square-foot is reached. When 570 knots is attained, ascent is then continued at this airspeed until cruise conditions are reached. For descent, deceleration begins at cruise altitude until an indicated airspeed of 340 knots is reached and is held constant down to 50,000 feet where level off is initiated. At a Mach number of 0.9, altitude again decreases as descent is made at this Mach number until an indicated airspeed of about 340 knots is reached again which is held constant until terminal approach speeds are necessary. The climb and descent profiles for configuration B are shown in figure 11 and are seen to be similar to configuration A except that indicated airspeeds of 325 knots and 500 knots are held constant on the ascent. The descent profile differs from configuration A in that an indicated airspeed of 300 knots was followed and there was no level off at 50,000 feet altitude.

RESULTS

Vertical Flight Path Control

In following the sonic boom boundary region of the climb profile, figures 10 and 11, the pilots experienced difficulty in remaining close to the scheduled profile. This is because in this region altitude, Mach number, indicated airspeed, and rate of climb are all varying so that the pilot has no constant instrument indication to monitor. To reduce the deviations from the scheduled profile and to ease the pilot's task considerably, a flight director was programed for the pilots to use along this section of the profile. Figure 12 shows that the magnitude of the deviations from the desired path without a flight director are of the order of 1,000 feet. However, with the flight director the deviations were reduced to about ±300 feet.

SST Navigation

The results of the tests along the oceanic departure and arrival routes, figures 7 and 8, indicated that routes for the SST should be designed to avoid turns at supersonic speeds. For example, oceanic arrivals to JFK required a supersonic turn at Nantucket Island. In figure 13, the airway structure at Nantucket is shown. For the arrival from South Bangor, a 45° heading change at a speed of $M = 2$ resulted in a large overshoot of the desired course when the turn was not initiated until over Nantucket. This large overshoot occurs because the radius of turn at a given bank angle increases as the square of the speed. The turn radius at $M = 2$ is about six times greater than that of subsonic jet transport at cruise speed. The excursion past the intersection interferes with departing SST traffic, thus creating a need for increased separation. To avoid these overshoots, the pilots were given lead distance information which enabled them to initiate their supersonic turns at a given lead (DME) distance from the station. The lead distance information was based on the method given in reference 1. An example of a lead turn at Nantucket is shown in figure 13. When lead information is used, a smooth transition from one course to the next is made. However, any turn at supersonic speeds has the adverse effect of intensifying the sonic boom. Amplification factors of from 2 to 4 have been recorded in tests using fighter-type aircraft (ref. 2). It was determined from the oceanic departure routes that turns at transonic speeds are also undesirable because of loss in climb-accelerate performance at the time of minimum performance capability, in addition to sonic boom focusing. The requirement for turns at supersonic speeds can be eliminated by allowing area navigation of the SST at altitudes above about 40,000 feet where the SST is supersonic. Below about 40,000 feet, at subsonic speeds, the SST could operate in the present airway system. Experience gained from these oceanic departure routes proved it would be advantageous, when planning future departure routes, to provide straight acceleration tracks from 100 to 170 n. mi. long starting as close as possible to the airport.

It was determined from initial test runs along the domestic departure routes (fig. 9) that the SST would be at transonic speeds at the turn by Coyle (CYN) on the standard instrument departure. Two experimental routes shown south of the standard route were then developed to aline the SST with straight portions of routes beyond Coyle as soon as possible for acceleration to supersonic speeds. The SST was throttled back to remain subsonic until alined. This procedure eliminated the turns at supersonic speeds and thus prevented loss in climb-accelerate capability. This procedure would also prevent sonic boom focusing under actual flight conditions.

Maneuver Time

The maneuver time required for departures and arrivals for a number of test runs is shown in figure 14 in bar graph form. The ordinate, maneuver time, is defined as the time difference between a straight unrestricted climbout and a climbout in which the SST operates in the ATC system and (a) follows airways, (b) is radar vectored by ATC, and (c) obeys ATC altitude restrictions. The dotted line represents the SST design ground rule specified in the National supersonic transport development program which provides for 5 minutes operation at 250 knots and 5,000 feet altitude as maneuver time allowance. For an aircraft of the weight of the SST, the Air Transport Association (ATA) method of determining direct operating costs for a subsonic jet would provide 10 minutes maneuver time, and is shown by the solid line. The ranges from minimum to maximum values for the tests are represented by the area of shading. Due to insufficient data, no bar graph appears for the oceanic experimental departure route.

It can be seen that the maneuver times along the domestic departure routes are considerably greater than for the oceanic routes. This is mainly due to the fact that, for a domestic departure, a considerable amount of eastward flying is required before westward headings can be flown. From the figure it can also be seen that, for the majority of the domestic departures, the maneuver time used exceeded the SST ground rule. For the experimental routes, the average maneuver time is somewhat higher than the average for the runs made on the present-day routes. This result shows the penalty incurred by remaining subsonic until turns could be completed onto straight-line portions of airway routes for the transonic acceleration phase.

Comparison of the arrival maneuver times indicates that the times were greater for the domestic routes than for the oceanic routes. One main factor governing this result is the runways used and the radar vectoring received in final approach to these runways. On occasion, holds were required at Colts Neck and Deer Park with holding times up to 14 minutes. These holding times are not included in the maneuver times.

Maneuver Fuel

Figure 15 shows maneuver fuel used as a percent of mission fuel for the same tests. Maneuver fuel is defined as the additional fuel used by the SST in operating in the ATC system compared with an unrestricted climbout. For the domestic and oceanic present-day departure routes, the average maneuver fuel used was about the same, with the majority of the runs exceeding the maneuver fuel specified by the SST design ground rule. The average maneuver fuel used was about 1 percent higher than that specified by the ground rule. Fuel used on all of the experimental departure route test runs exceeded the amount specified by the SST design ground rule due to the added time spent at subsonic speeds. In this case, the average maneuver fuel used was more than 2 percent higher than that specified by the ground rule.

For the arrivals, a greater percent of mission fuel was used on the average on the domestic routes compared to the oceanic routes. This result would be expected due to the greater maneuver time for domestic arrivals as shown in figure 14. Since there is no specified allowance for maneuver fuel during arrivals, this would necessitate including this maneuver fuel in the reserve fuel.

Communications-Navigation Workload

Figure 16 gives a comparison of the communication-navigation workload between the SST and a subsonic jet during an arrival. The ordinate of the bar graph represents number of operations prior to touchdown, separated into 10-minute time intervals as shown. A breakdown listing the type of operations included in the workload analysis is displayed above the bar graph. In the time periods 30-to-20 and 20-to-10 minutes prior to touchdown, the SST workload, defined by the number of operations in a given period, is considerably higher than a subsonic jet. This is due to the greater altitude range which the SST passes through in the same time period. For the time period 10 minutes prior to touchdown, the SST and the subsonic jet are operating at essentially the same speed and over the same range, thus the workload is comparable. During a departure, the communication-navigation workload for the SST and a subsonic jet was about the same.

Pictorial Display

In figure 17, the advantages of using a pictorial display for holding in a strong wind are shown. The holds were made at about 11,000 feet with a north wind of 70 knots. Without the pictorial display, the first leg of the pattern was about a minute longer than a no-wind pattern because the pilot failed to compensate for the effect of the wind. The effect of the wind is also evident in the irregularity of the pattern. With the pictorial display, the pilot was able to compensate for the wind by adjusting the time for the downward leg and was able to complete a more regularly shaped pattern. The time used in completing the pattern without pictorial display was about 2 minutes longer than a no-wind pattern, while the time used for the pattern with pictorial display was about the same as a no-wind pattern.

In figure 18, the southerly pictorial display departure routes through Coyle and test runs flown along them are shown. All pictorial display routes were arbitrarily spaced at a distance of 5 n. mi. apart. There was some difficulty in the initial alinement of the SST with the pictorial display routes because of the high performance of the SST and the large heading change required after take-off. The deviations from course along the straight portions of the pictorial display routes were in the order of 1-2 n. mi. However, there was an increased difficulty in holding course in the turns, especially at the higher speeds, with deviations of 3-4 n. mi. experienced.

In figure 19, the northerly pictorial display departure routes through Huguenot (HUO) and Sparta (SAX) and test runs flown along them are shown. As before, the pilots experienced some difficulty in alining the SST with the entrance to the pictorial display routes. A problem was again experienced in remaining on course through the turns. The large deviations from course shown with two of these runs could be labeled as gross blunders on the part of the pilots. It is believed that the difficulty in holding course in the turns noted in figures 18 and 19 can be reduced by adjusting the pictorial display route turn radii to match the SST's performance.

It should be mentioned that the deviations from course are the result of piloting error since the errors associated with a navigational system were not represented in the inputs to the pictorial display. Thus, the deviations from course shown are less than those that would have occurred in actual practice.

The communication workload between the SST pilots and the air traffic controllers was reduced when the pictorial display was used since this eliminated the need for radar vectors. It was apparent that a further reduction in pilot-controller communications could be effected by eliminating the requirement for clearances to climb when clear of altitude restricted areas. In addition, with complete reliance on the pictorial display, there would be a reduction in the navigation workload by eliminating the navigation frequency changes presently required in position checks at airway intersections and radials defining altitude restrictions.

CONCLUDING REMARKS

In the initial simulation studies of the operating problems of two SST design configurations (variable-sweep and fixed-delta wing), the following results have been indicated for terminal area operation in the present air traffic control system:

A reduction in altitude errors in following the sonic boom boundary of the climb profile, as well as a reduction in the pilot's task was accomplished by the use of a flight director programed for vertical flight-path control.

Overshooting at airway intersections while turning at supersonic speeds was prevented by using lead distance information which enabled the pilots to initiate lead-type turns prior to the airway intersection.

Maneuver time and fuel for climbouts of the SST are consistently greater than that provided for in the SST design allowance, as determined from operations in the present-day New York air traffic control system. Provisions for unrestricted climbout routes for the SST would alleviate this situation.

For early portions of the descent, the SST communication-navigation workload was found to be considerably higher than that for a subsonic jet.

A preliminary study of tests involving the use of a pictorial navigation display indicated that the pilots could fly specified pictorial display routes, with deviations from course of 1-4 n. mi. The larger deviations occurred in the turns and probably could be reduced by adjusting the pictorial display route turn radii to match the SST's performance. The pictorial display 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 pictorial display resulted in a reduction in the communication workload for the SST pilots, and it appears that a more complete reliance on the pictorial display than was used in these tests would further reduce communications and also reduce the navigational workload.

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2. Maglieri, Domenic J.; and Lansing, Donald L.: Sonic Booms From Aircraft in Maneuvers. NASA TN D-2370, 1964.

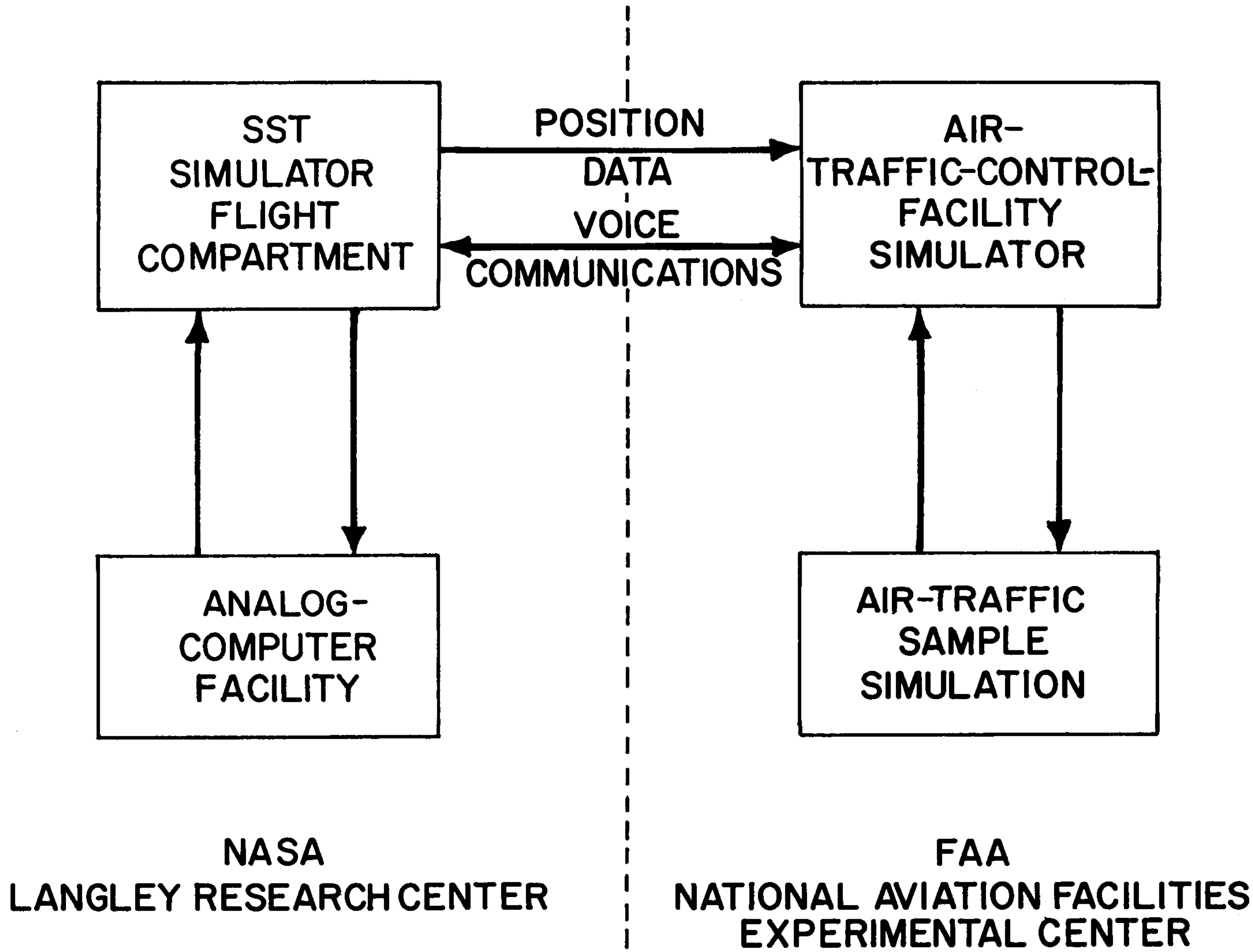

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Figure 1.- SST-ATC simulation method.

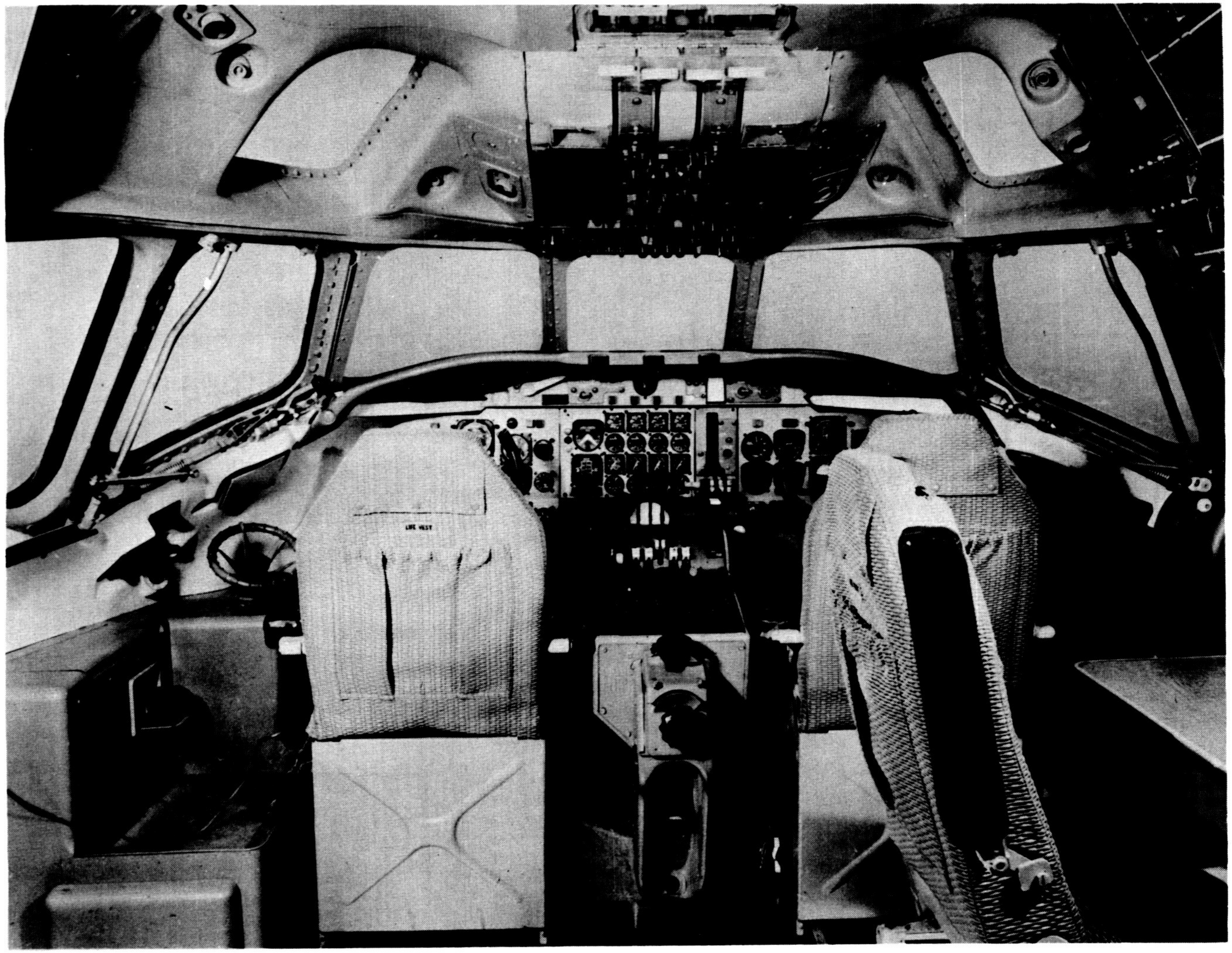

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Figure 2.- Langley fixed-base SST simulator cockpit.

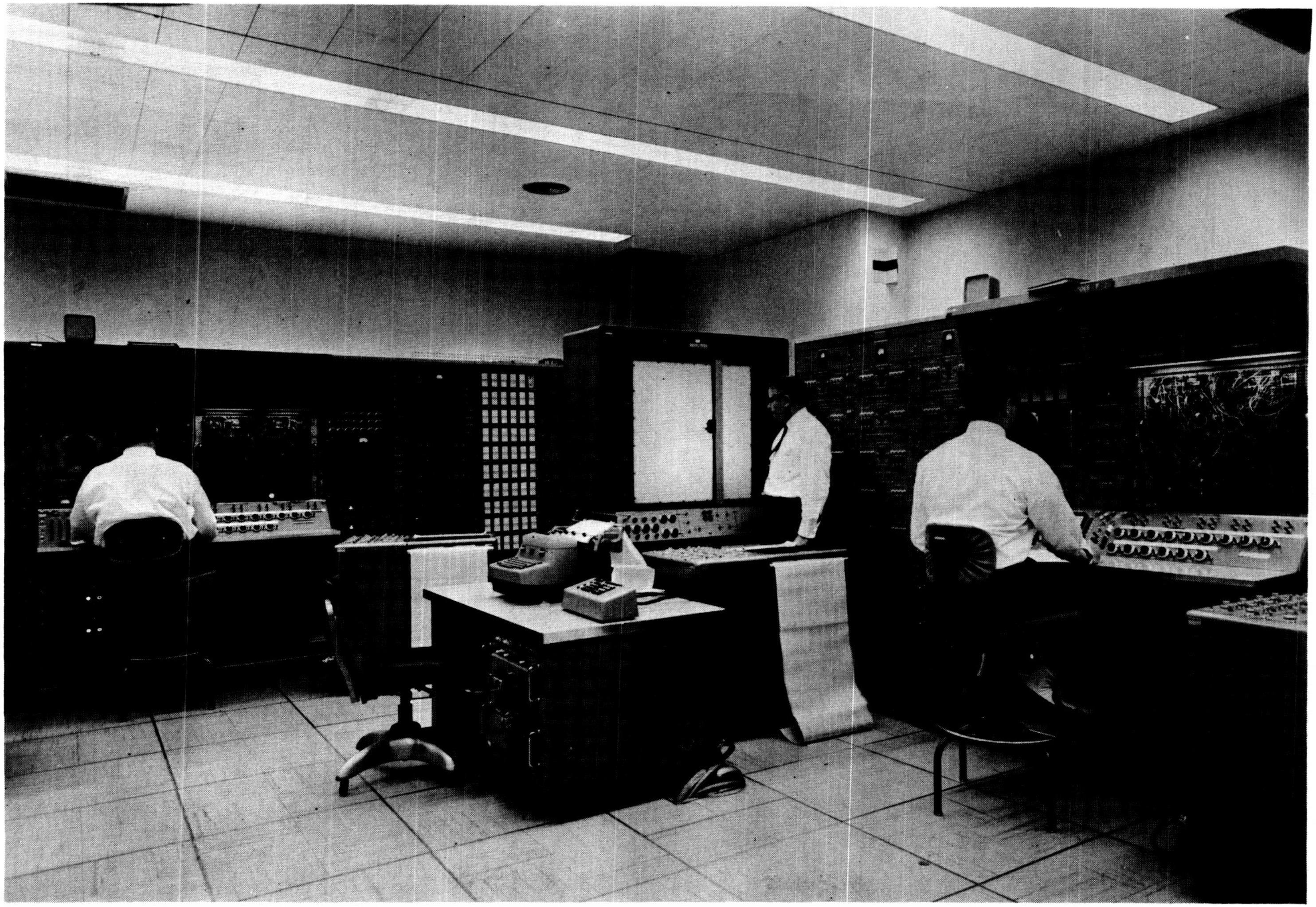

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Figure 3.- Analog computer.

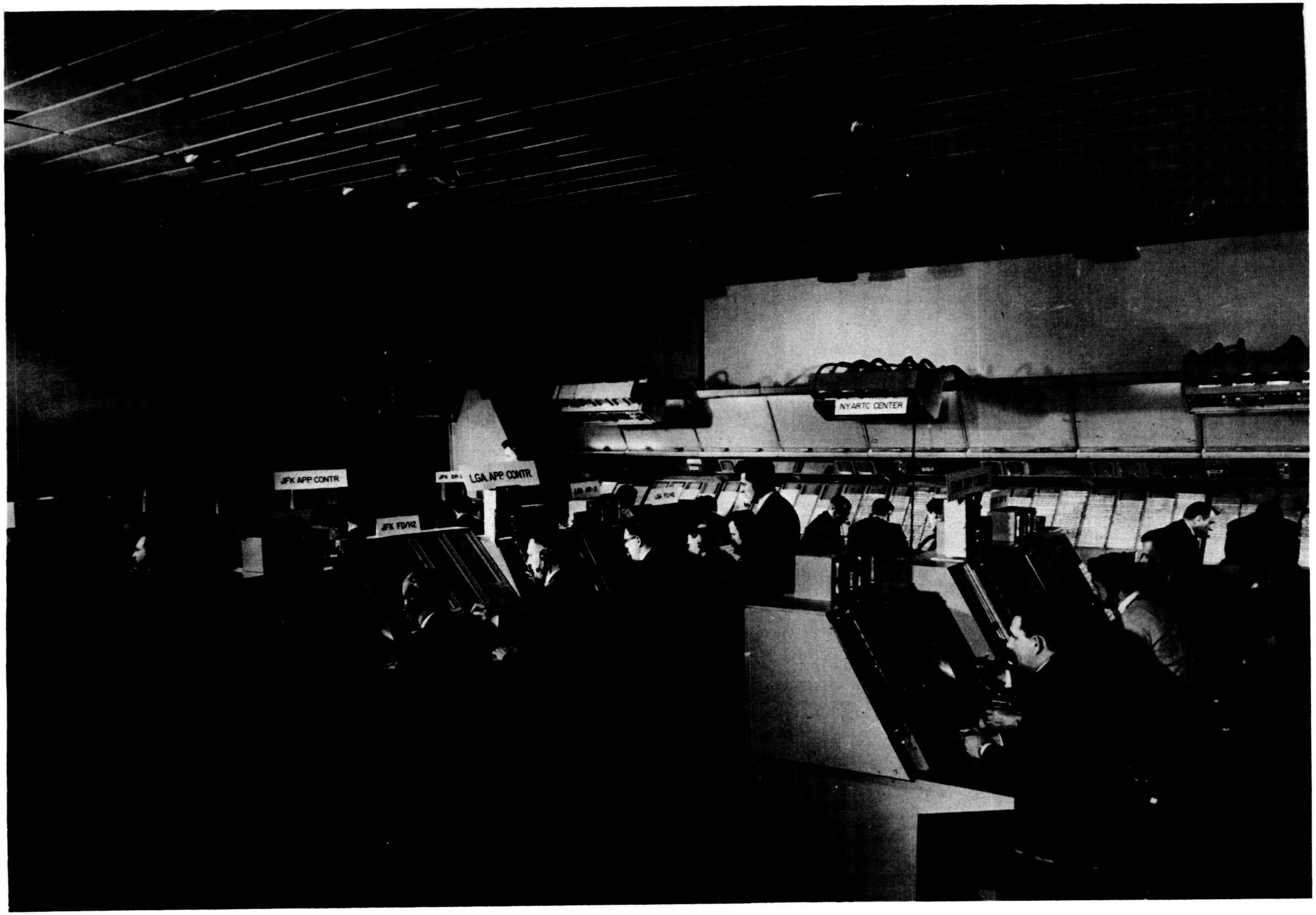

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Figure 4.- ATC facility simulator.

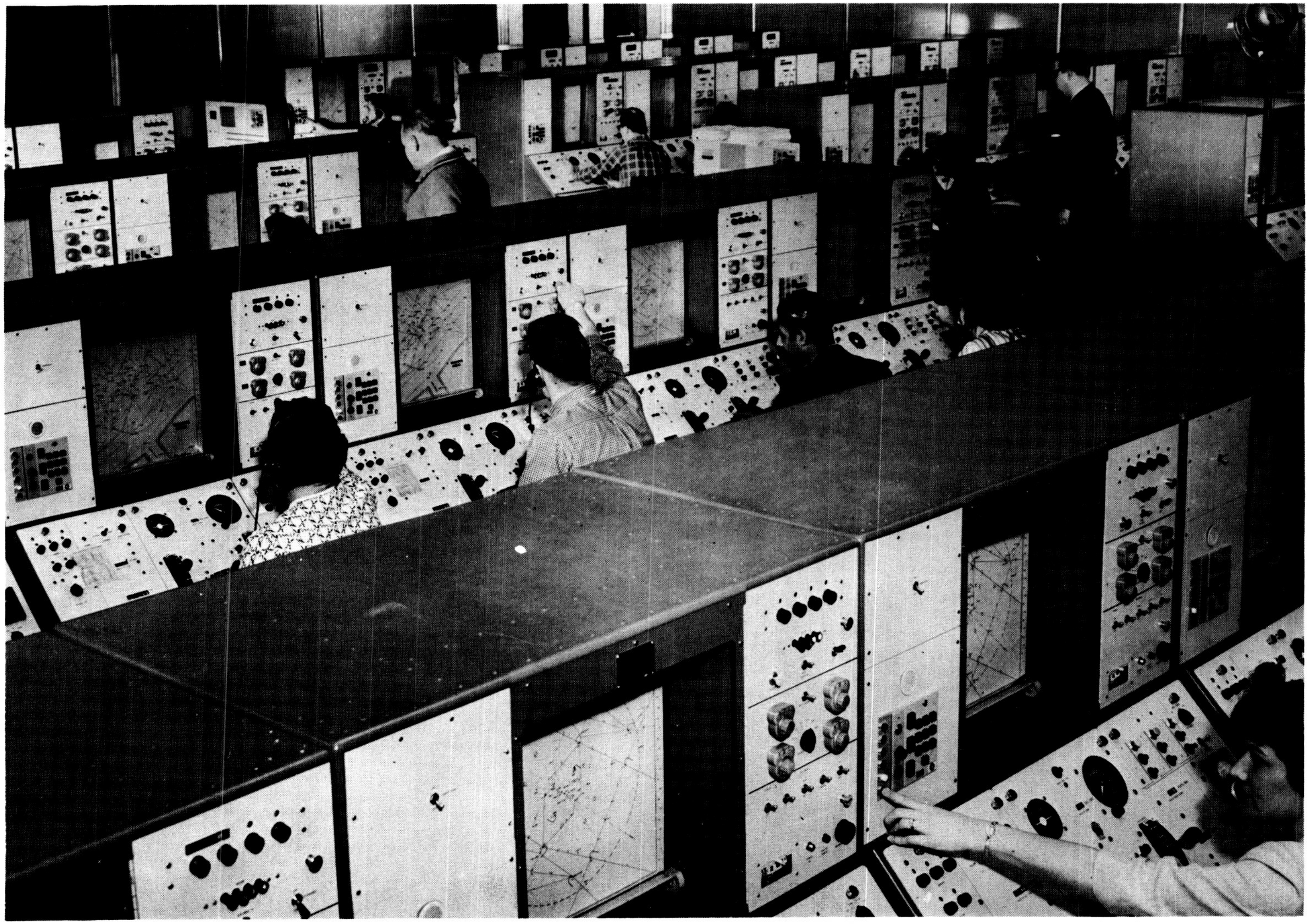

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Figure 5.- Radar target generators.

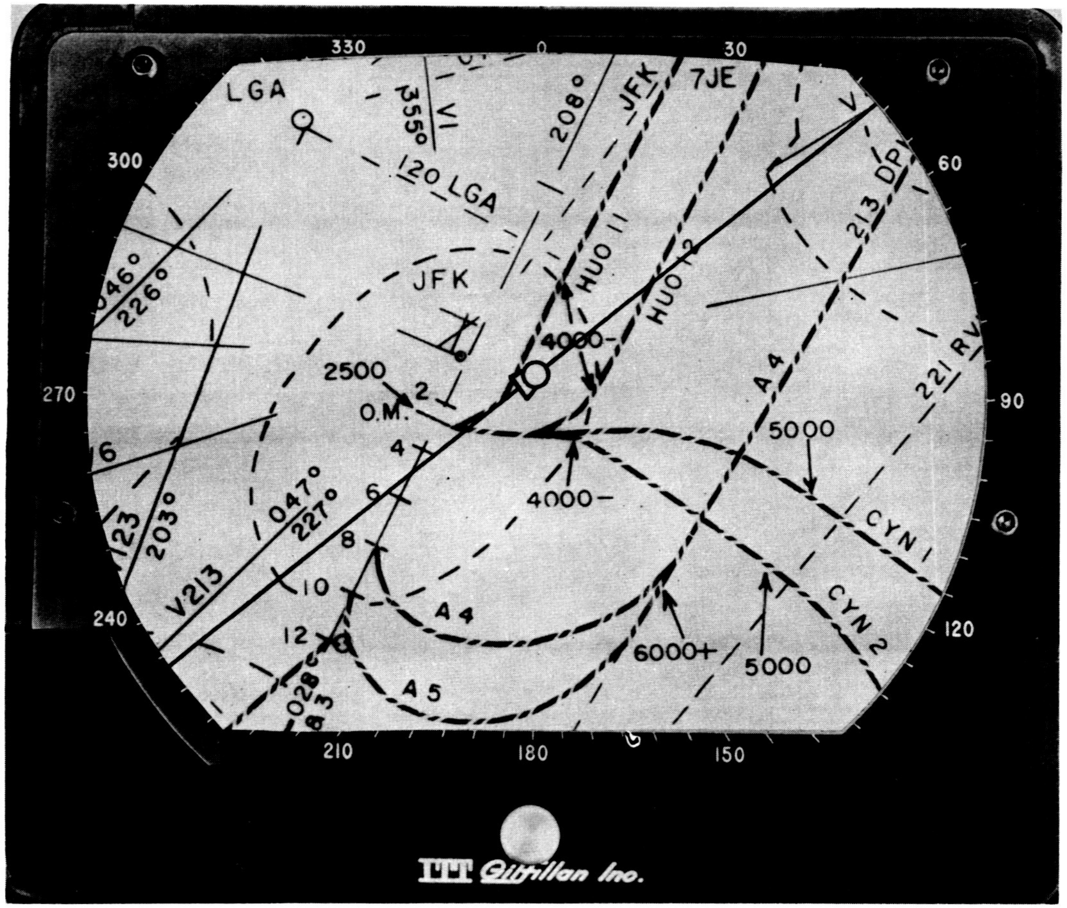

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Figure 6.- Pictorial navigation display. (Approx. 2/3 full scale.)

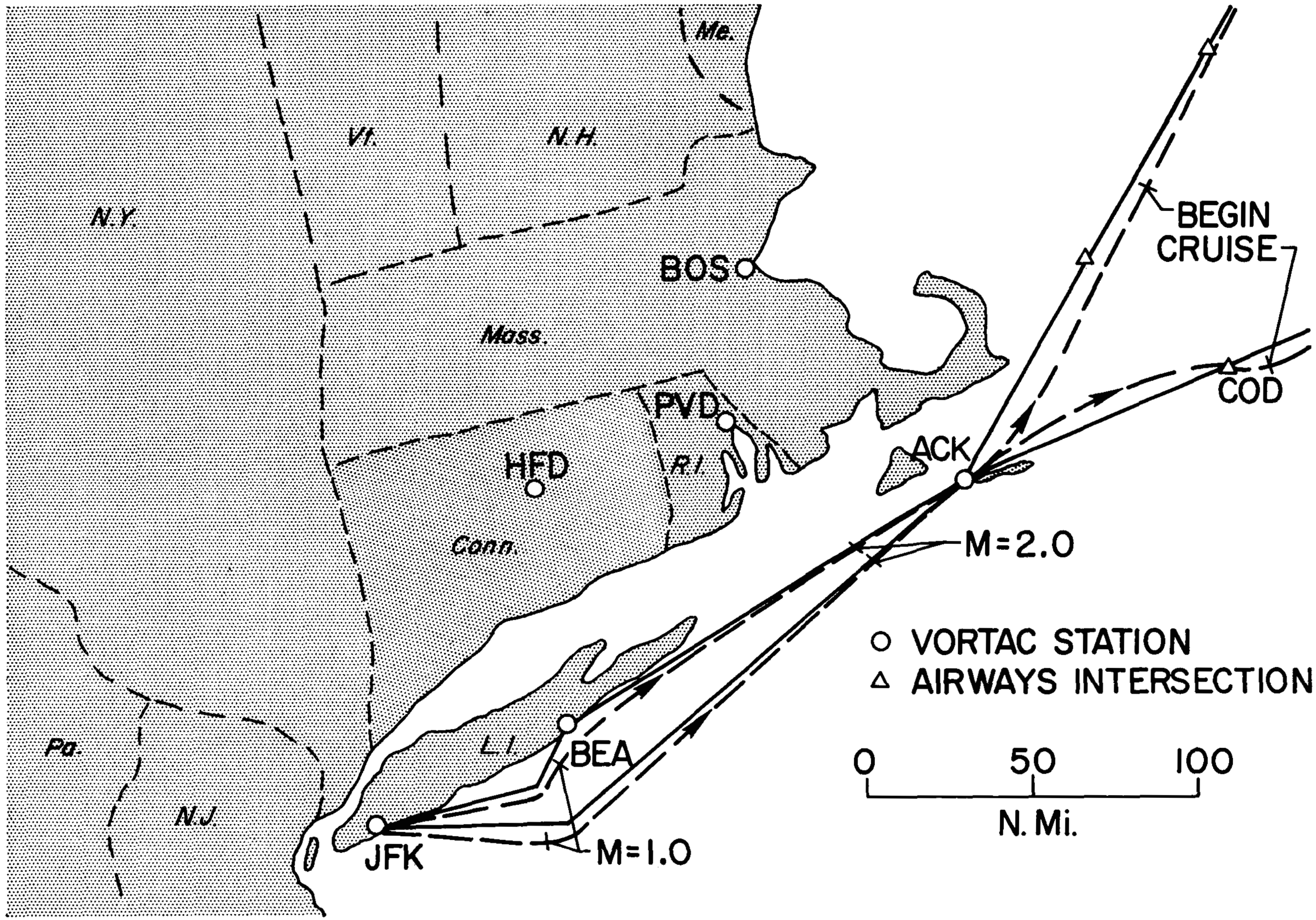

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Figure 7.- Oceanic departure routes.

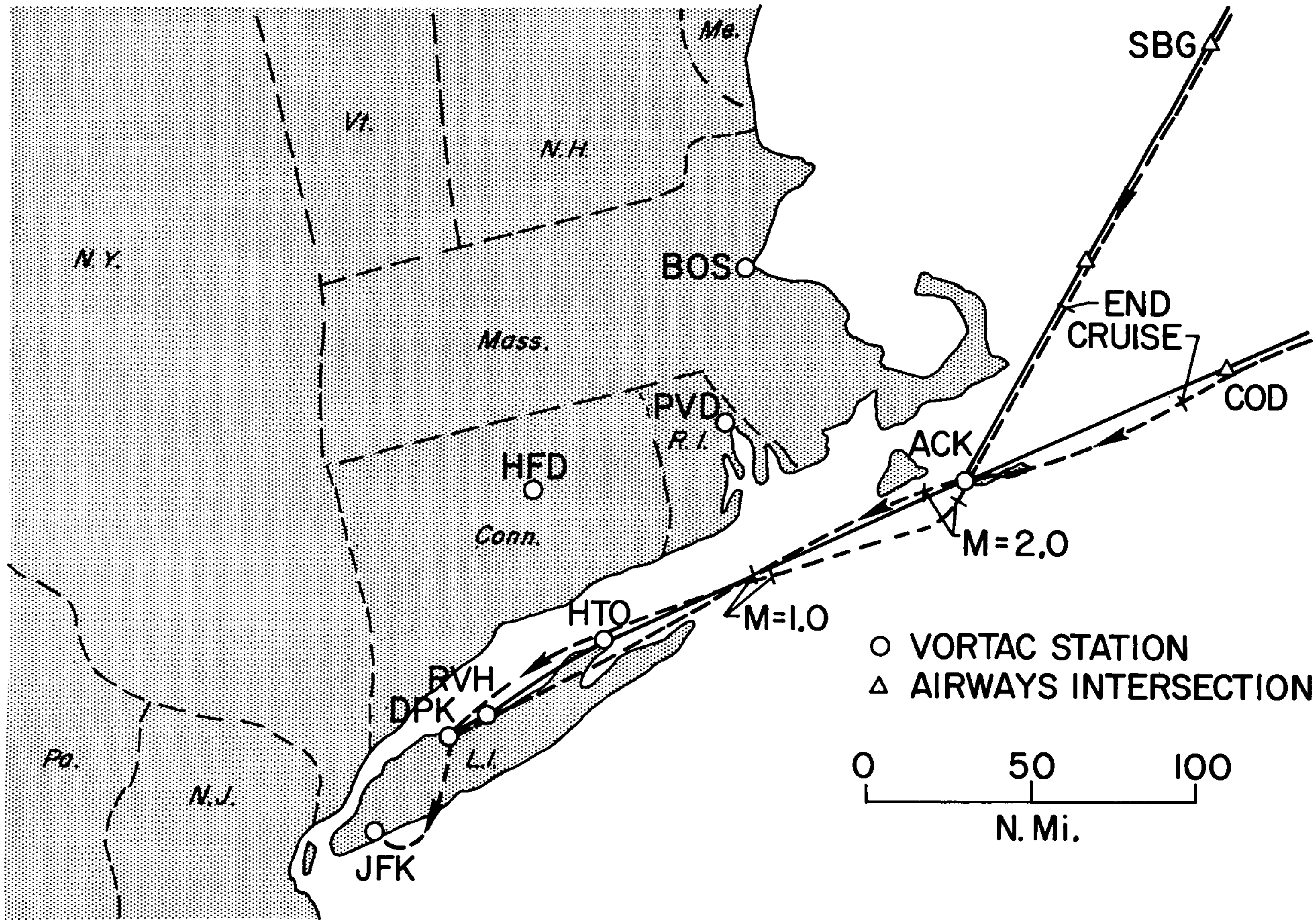

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Figure 8.- Oceanic arrival routes.

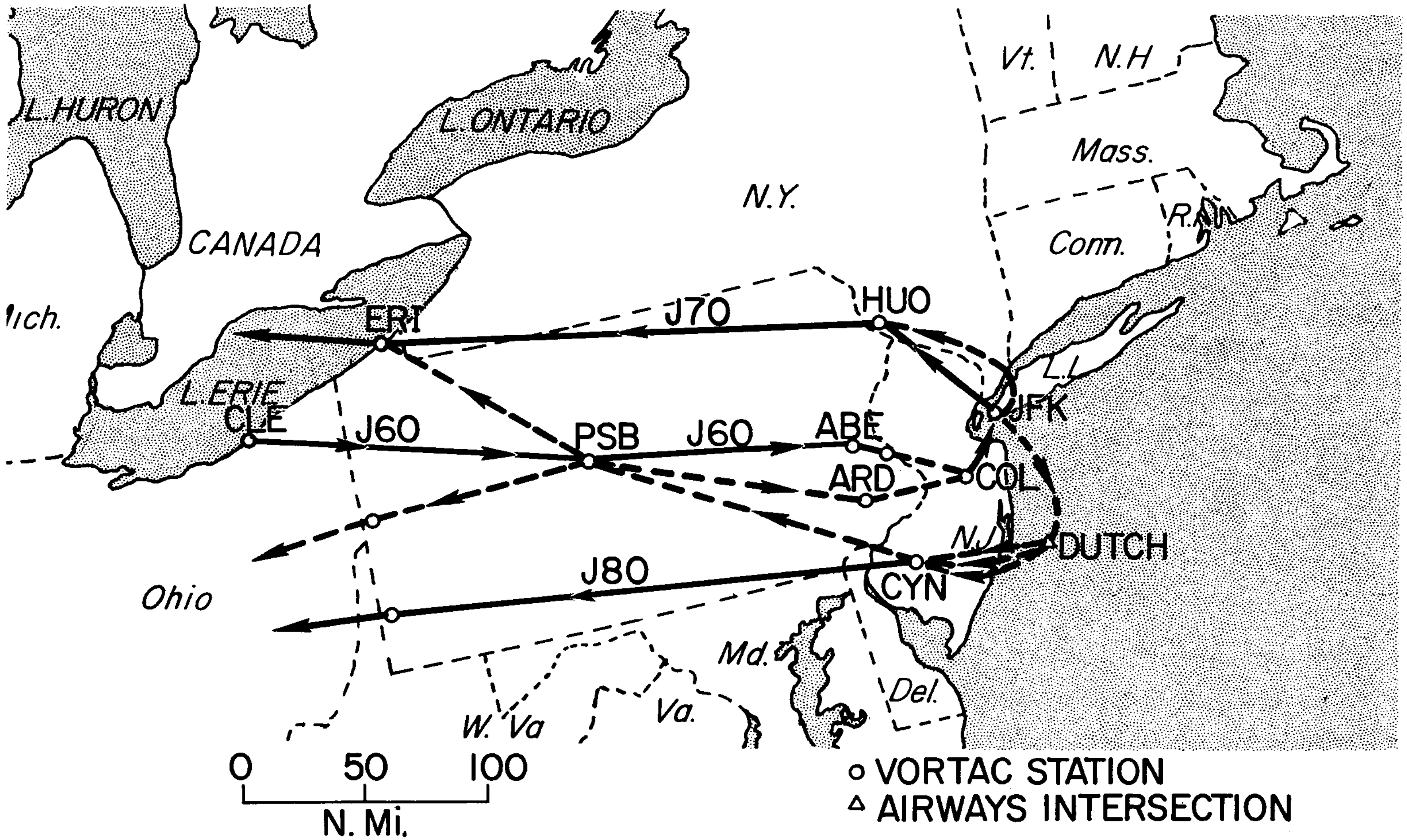

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Figure 9.- Domestic departure and arrival routes.

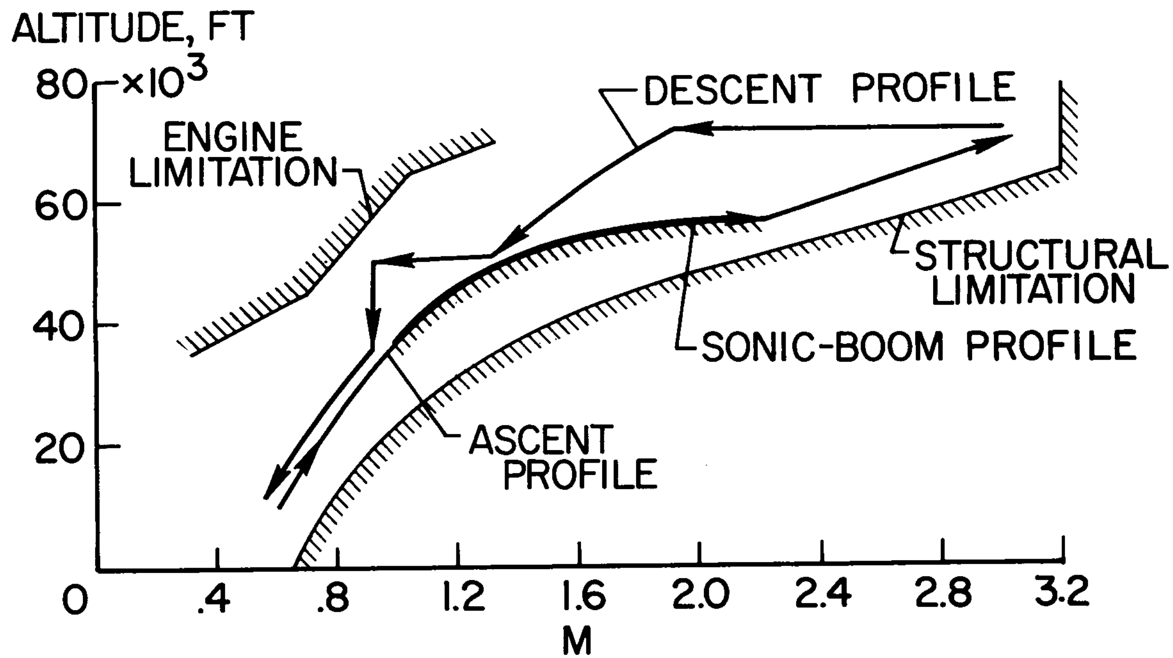

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Figure 10.- Profiles and limitations.

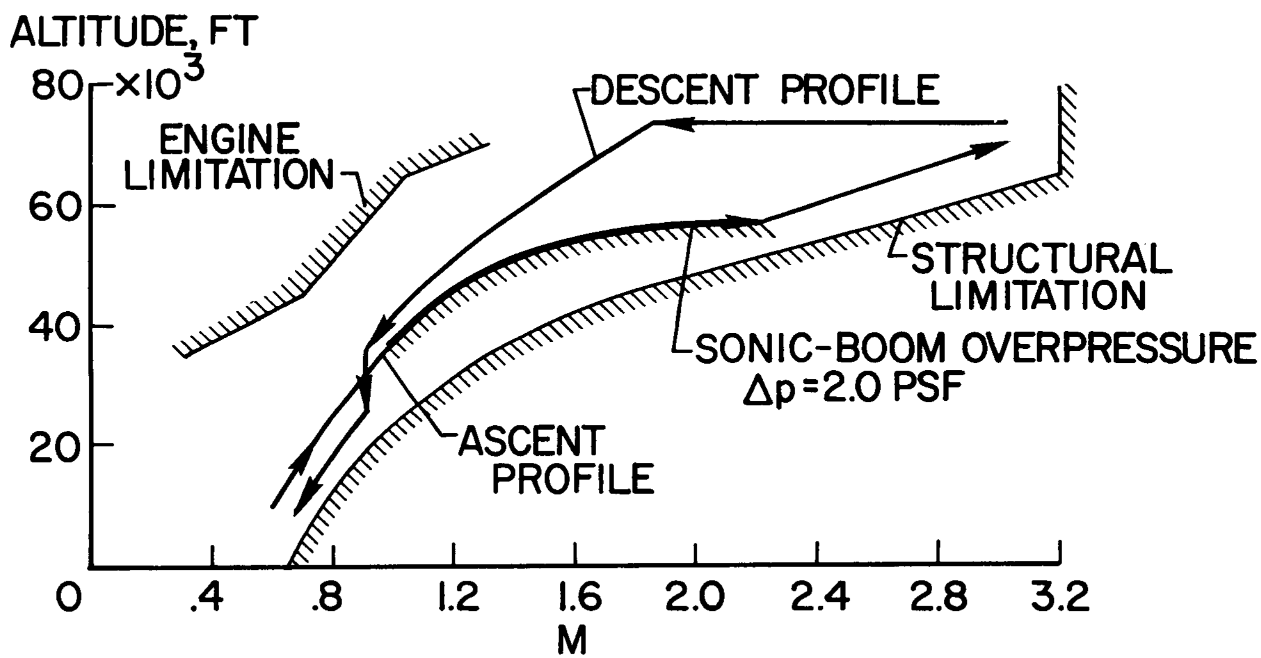

Figure 11.- Profiles and limitations.

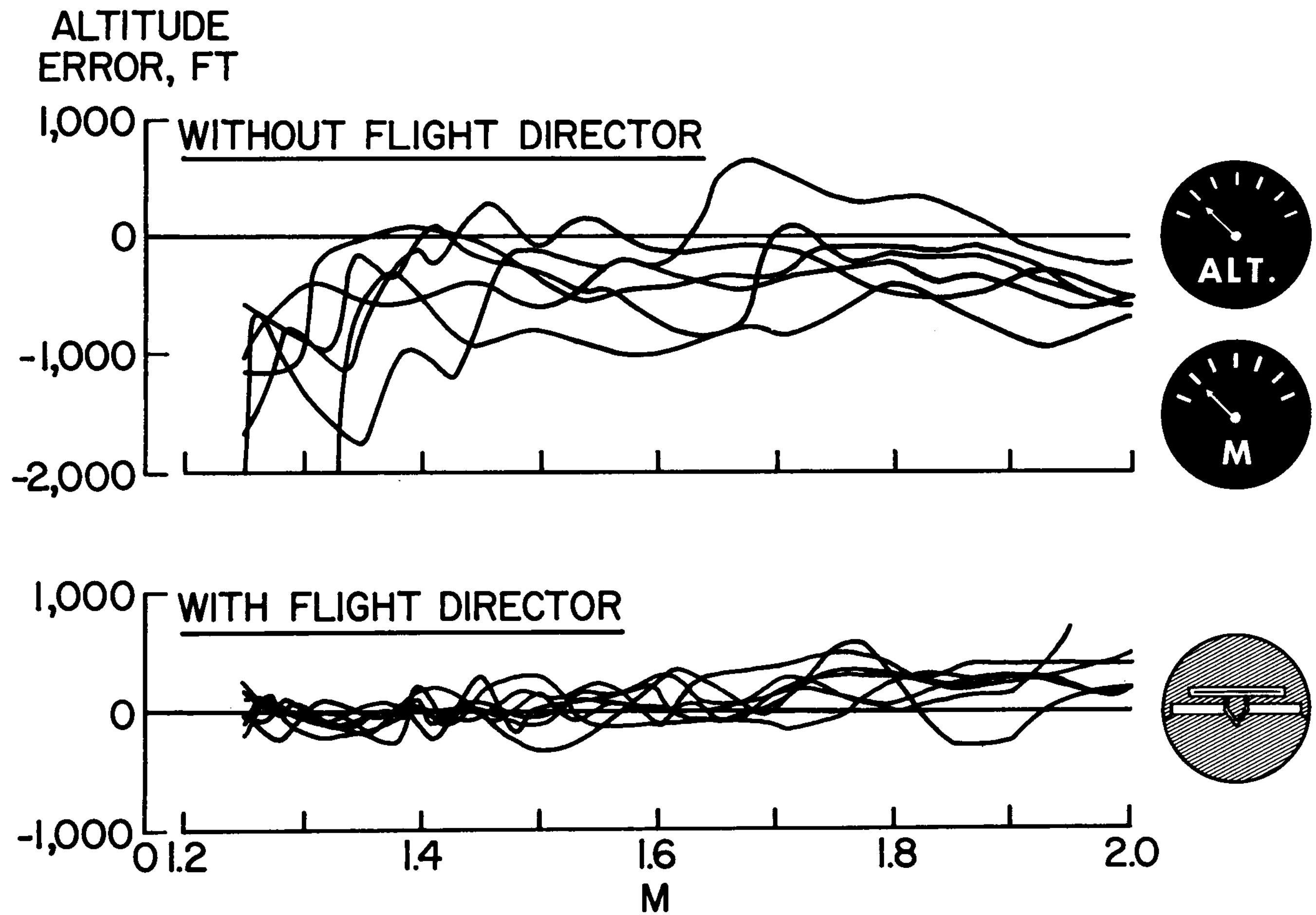

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Figure 12.- Altitude error in following sonic-boom profile.

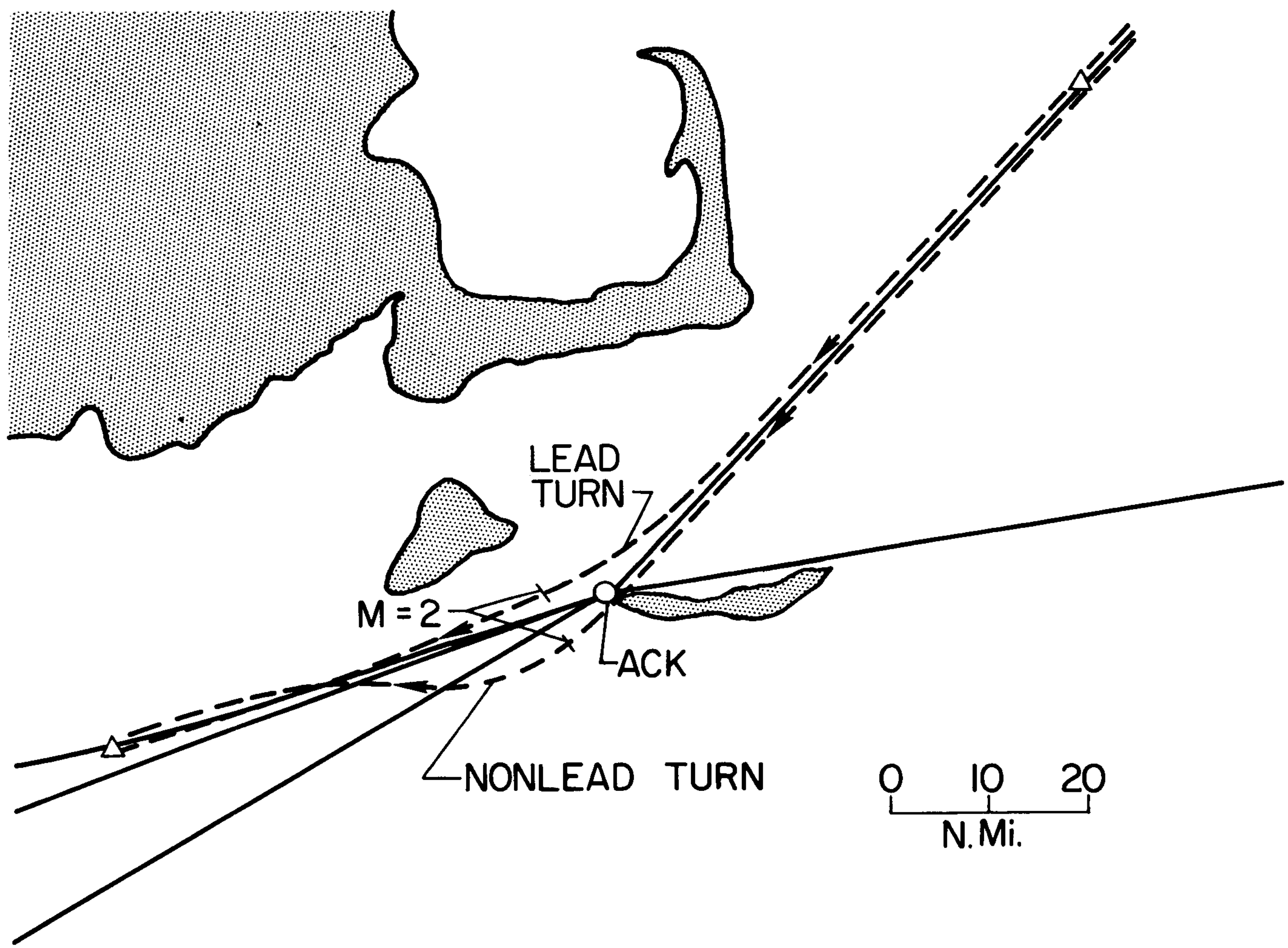

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Figure 13.- Supersonic turns.

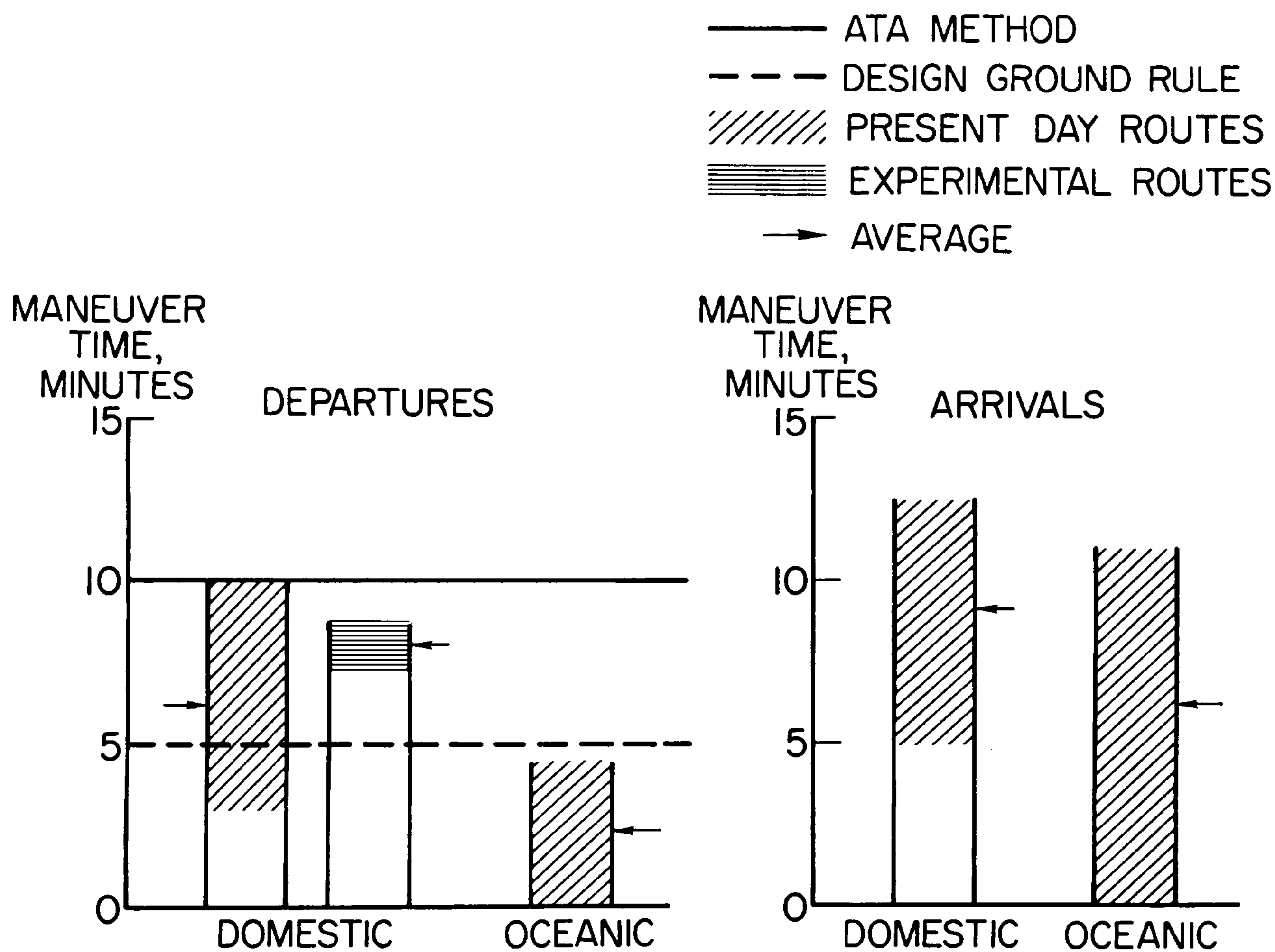

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Figure 14.- Effect of ATC on time.

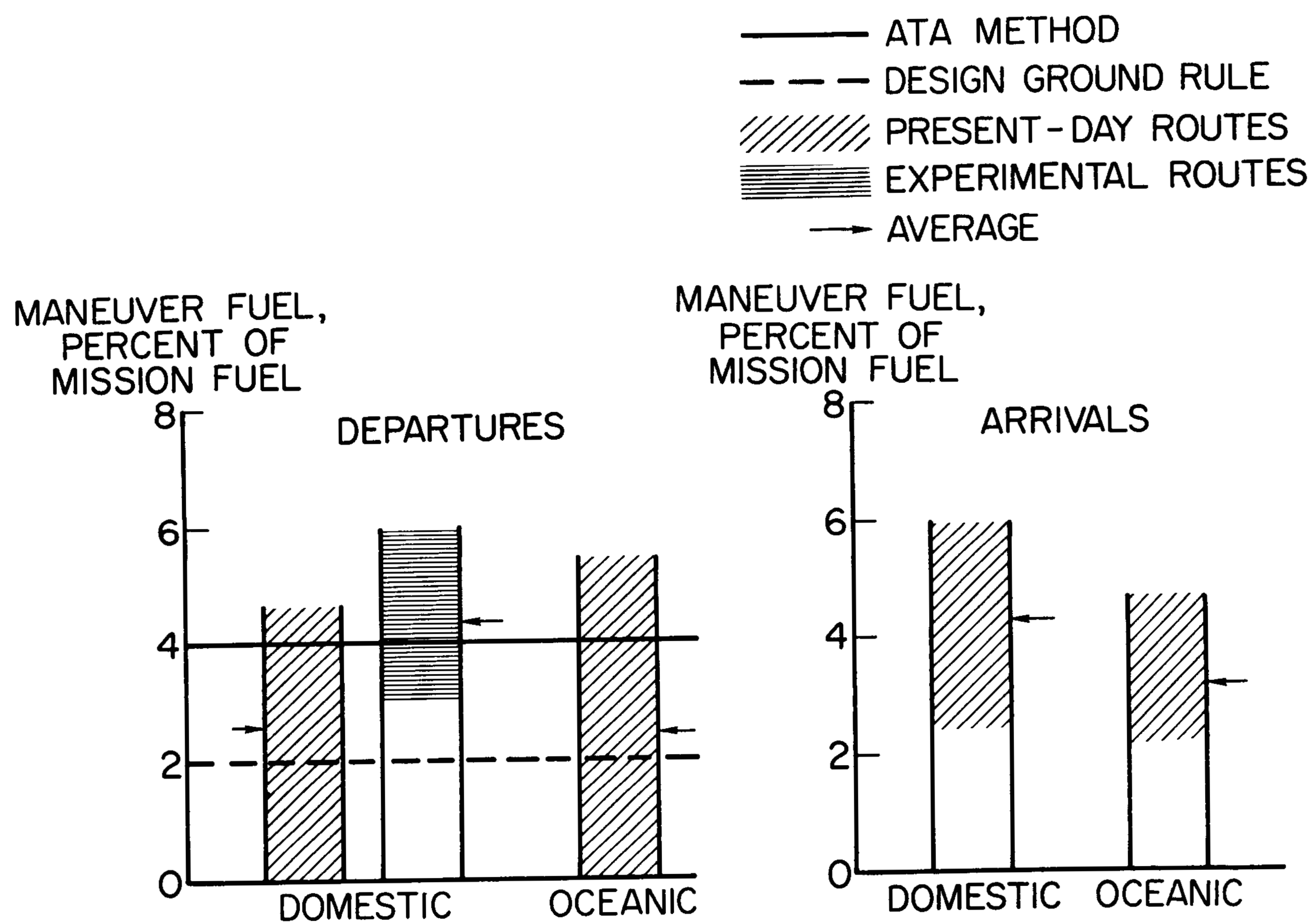

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Figure 15.- Effect of ATC on fuel.

OPERATIONS

- NAVIGATION FREQUENCY CHANGES
- COMMUNICATIONS FREQUENCY CHANGES
- COMMUNICATION MESSAGE
- TRANSPONDER SQUAWK CODE

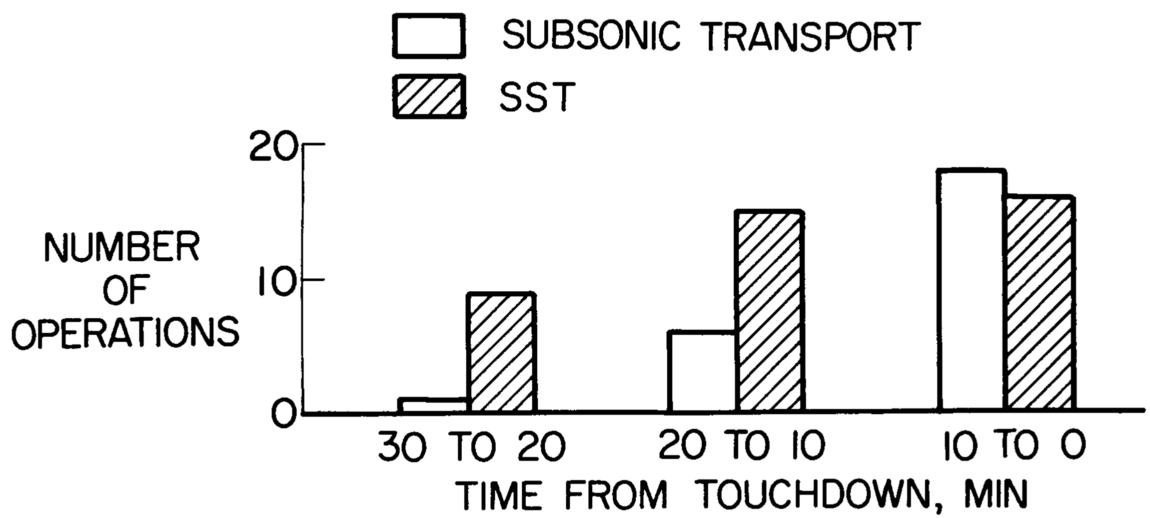

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Figure 16.- Communications-navigation workload arrival.

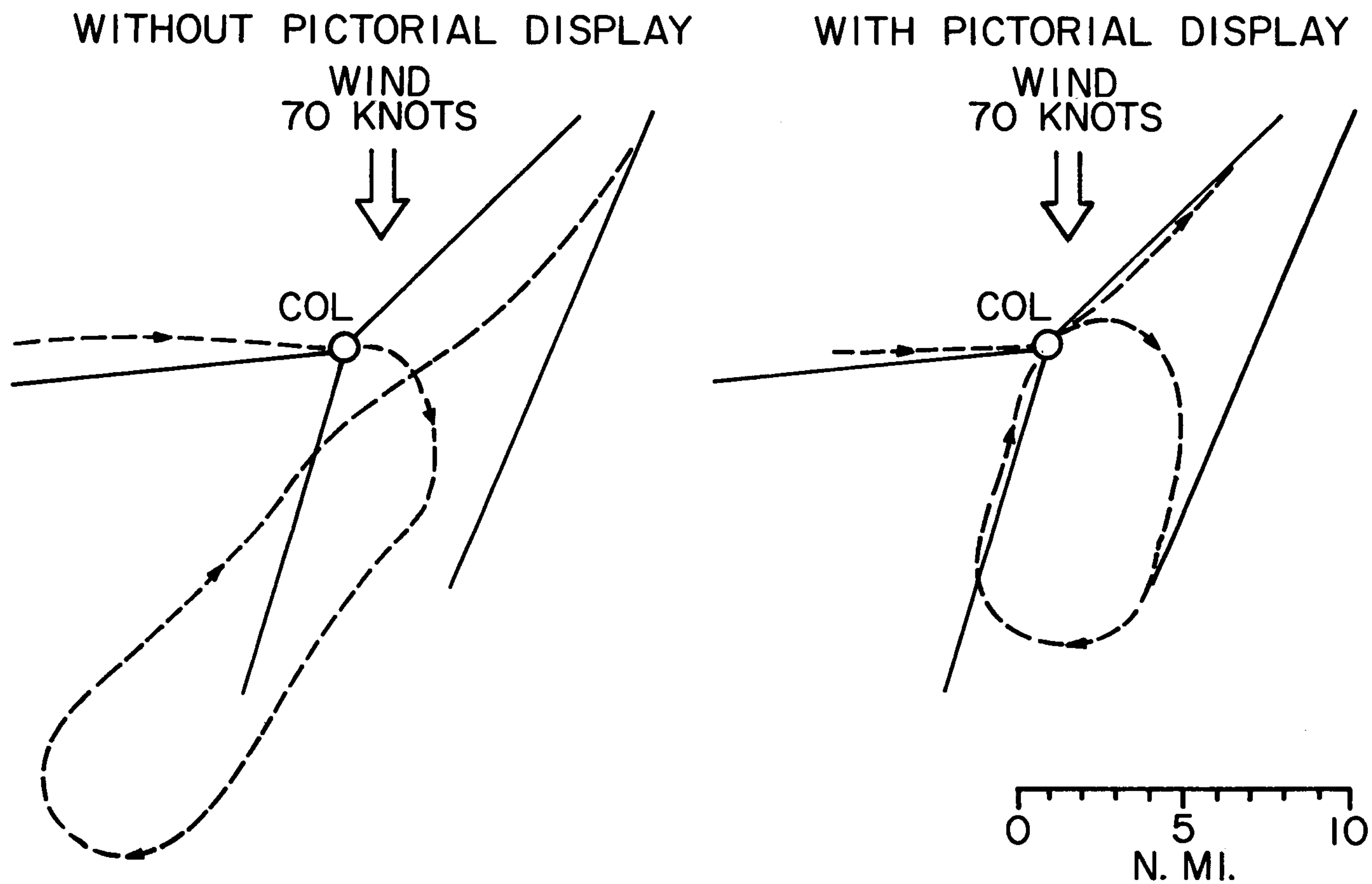

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Figure 17.- Advantages in holding with pictorial display.

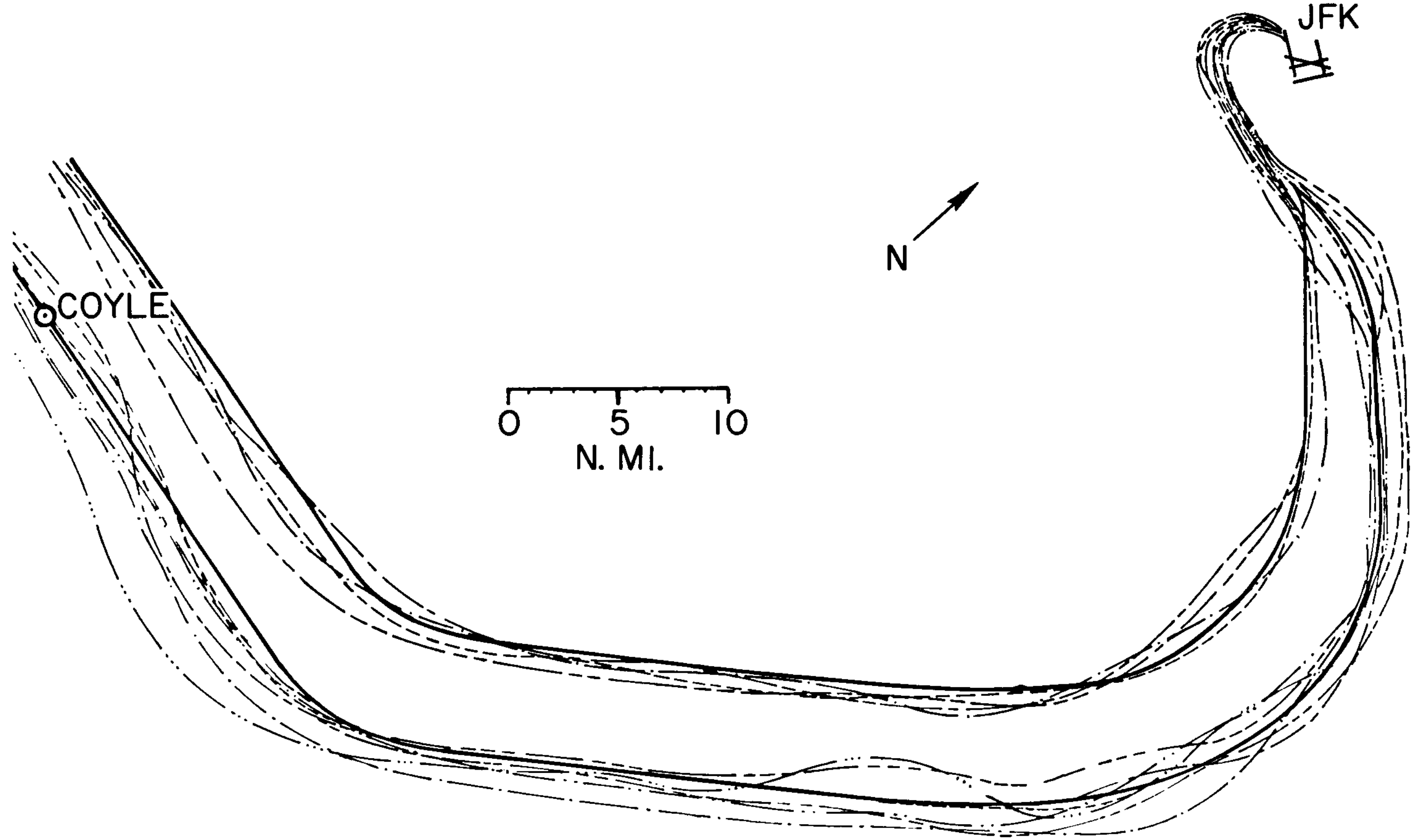

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Figure 18.- Coyle departure pictorial display routes.

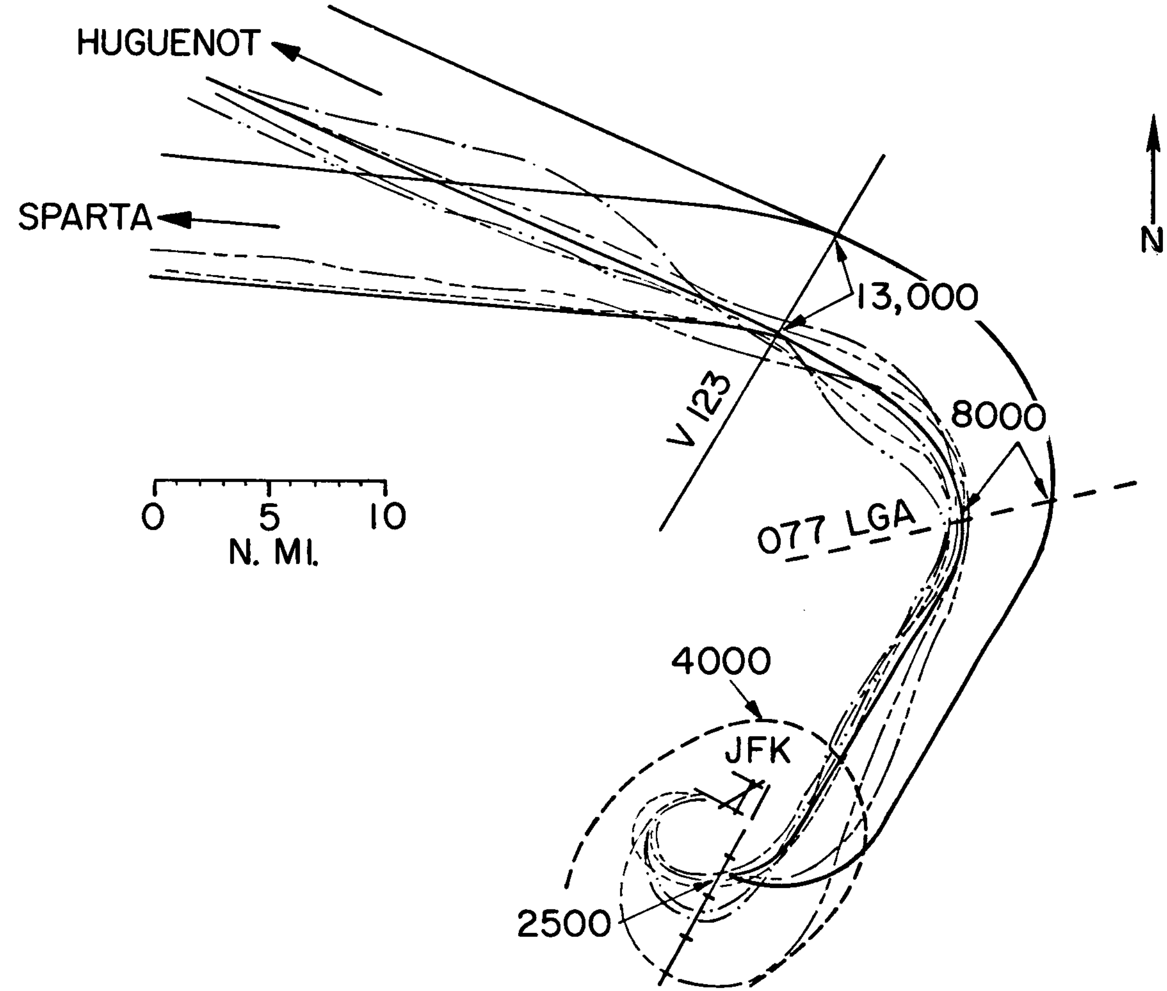

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Figure 19.- Huguenot/Sparta departure pictorial display routes.

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