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OCEANIC AREA SYSTEM IMPROVEMENT STUDY (OASIS)

Volume VI: North Atlantic, Central East Pacific, and Caribbean Regions Navigation Systems Description

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FINAL REPORT

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16. Abstract

The Oceanic (and selected Non-Oceanic) Area System Improvement Study (OASIS), conducted by SRI International under contract with the Federal Aviation Administration (FAA), was part of a broad oceanic aeronautical system improvement study program coordinated by the "Committee to Review the Application of Satellite and Other Techniques to Civil Aviation" (also called the Aviation Review Committee or the ARC). The OASIS Project, with inputs from the international aviation community, examined current and potential future oceanic air traffic control (ATC) systems in the North Atlantic (NAT), Central East Pacific (CEP), and Caribbean (CAR) regions. This phase of the Aviation Review Committee program began in late-1978 and was completed in mid-1981.

The thrust of the Aviation Review Committee program, which OASIS broadly supported, was to analyze the present ATC systems; examine future system requirements; identify areas where the present systems might be improved; and develop and analyze potential system improvement options. The time frame of this study is the period 1979 to 2005.

This report describes the navigation systems in use in the NAT, CEP and CAR.

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Oceanic Area System Improvement Study (OASIS)

Final Report

This report is one of a set of companion documents which includes the following volumes:

Volume I
Executive Summary and Improvement Alternatives Development and Analysis

Volume II
North Atlantic Region Air Traffic Services System Description

Volume III
Central East Pacific Region Air Traffic Services System Description

Volume IV
Caribbean Region Air Traffic Services System Description

Volume V
North Atlantic, Central East Pacific, and Caribbean Regions Communication Systems Description

Volume VI
North Atlantic, Central East Pacific, and Caribbean Regions Navigation Systems Description

Volume VII
North Atlantic Region Flight Cost Model Results

Volume VIII
Central East Pacific Region Flight Cost Model Results

Volume IX
Flight Cost Model Description

Volume X
North Atlantic, Central East Pacific, and Caribbean Regions Aviation Traffic Forecasts

PREFACE

The Oceanic Area System Improvement Study (OASIS) was conducted in coordination with the "Committee to Review the Application of Satellite and Other Techniques to Civil Aviation (also called the Aviation Review Committee or the ARC)." This study examined the operational, technological, and economic aspects of the current and proposed future oceanic air traffic systems in the North Atlantic (NAT), Caribbean (CAR), and Central East Pacific (CEP) regions and assessed the relative merits of alternative improvement options. A key requirement of this study was to develop a detailed description of the present air traffic system. In support of this requirement, and in cooperation with working groups of the Committee, questionnaires were distributed to the providers and users of the oceanic air traffic systems. Responses to these questionnaires, special reports prepared by system provider organizations, other publications, and field observations made by the OASIS staff were the basis for the systems descriptions presented in this report. The descriptions also were based on information obtained during Working Group A and B meetings and workshops sponsored by Working Group A. The information given in this report documents the state of the oceanic air traffic system in mid 1979.

In the course of the work valuable contributions, advice, data, and opinions were received from a number of sources both in the United States and outside it. Valuable information and guidance were received and utilized from the International Civil Aviaiton Organization (ICAO), the North Atlantic Systems Planning Group (NAT/SPG), the North Atlantic Traffic Forecast Group (NAT/TFG), several administrations, the International Air Transport Association (IATA), the airlines, the International Federation of Airline Pilots Association (IFALPA), other aviation associated organizations, and especially from the "Committee to Review the Application of Satellite and Other Techniques to Civil Aviation."

It is understood of course, and should be noted, that participation in this work or contribution to it does not imply either endorsement or agreement to the findings by any contributors or policy agreement by any administration which graciously chose to contribute.

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EXECUTIVE SUMMARY

The state of oceanic navigatin technology (along with human factors and ATC technology) is a primary determinant of how efficiently aircraft can utilize oceanic airspace while maintaining acceptable levels of safety. This technology encompasses position determining equipment such as inertial navigation systems, Omega, automatic direction finding receivers, and altimeter devices. It also encompasses attitude and airspeed measurement systems.

To make the movement of many aircraft in the same airspace manageable, most aircraft in the North Atlantic (NAT), Central East Pacific (CEP), and Caribbean (CAR) are flown on tracks. In the case of the NAT and CEP there are a number of parallel east-west tracks designed to handle the bulk of traffic. In the CAR, many tracks are along routes defined by ground based nondirectional beacons and Very High Frequency Omniranges (VOR).

Based on a combination of historical experience and analysis of sample aircraft navigation errors, aircraft flying the same geographic area at or above 29000 must be separated by either 2,000 ft vertically or by 15 to 20 min (depending on operation mode) in crossing over common fixes. Alternatively aircraft tracks can be separated laterally by 100 to 120 nmi (depending on the oceanic area). Composite separations of 1000 feet and 100 nmi are used between some parallel tracks.

Major oceanic routes are often entered under direct radar surveillance. While aircraft are on their oceanic routes there is only indirect surveillance of the aircraft, accomplished by radio relay of position reports to air traffic control centers.

To determine when horizontal separation minima can safely be reduced, providers of air traffic services in the NAT monitor the lateral and longitudinal navigation performance of aircraft. Recently, the lateral separation minimum in the organized track system of the NAT was reduced from 120 to 60 nmi; and shortly, the longitudinal separation minimum on these tracks will be reduced from 15 to 10 min.

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We are highly appreciative of the guidance and support provided by the "Committee to Review the Application of Satellite and Other Techniques to Civil Aviation," particularly the support provided by Working Group B of the Committee and the Working Group's rapporteur, Mr. J. O. Clark. Special thanks are given to Mr. V. E. Foose, FAA Program Manager, for his assistance.

This research was conducted by SRI International under the leadership of Dr. George J. Couluris. This system description was developed by Dr. Bjorn Conrad with the assistance of Ms. Marika E. Garskis. Ms. Geri Childs prepared this report. The project was conducted under the administrative supervision of Dr. Robert S. Ratner and Mr. Joel R. Norman.

GLOSSARY OF ACRONYMS

ADF	Automatic direction finding
AFTN	Aeronautical Fixed Telecommunications Network
ATC	Air traffic control
CAR	Caribbean
CEP	Central East Pacific
CDU	Control display unit
DME	Distance measuring equipment
ETA	Estimated Time of Arrival
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FIR	Flight Information Region
GPS	Global Positioning System
HF	High Frequency
ICAO	International Civil Aviation Organization
INS	Inertial navigaton system
Loran	LOng RAnge Navigation system
min	Minute
MNPS	Minimum Navigation Performance Specification
MTBF	Mean time between failure
NAT	North Atlantic
NAT/SPG	NAT Systems Planning Group
NAV	Navigation
NDB	Nondirectional Beacon
Omega	Low frequency global navigation system
OTS	Organized Track System
SAR	Search and rescue
SD	Standard Deviation
UK	United Kingdom
US	United States
VLF	Very low frequency
VOR	Very-high frequency omnirange

1. INTRODUCTION

This document contains a brief description of navigation systems specific to the oceanic areas covered in this study. These areas include the North Atlantic (NAT), Central East Pacific (CEP), and portions of the Caribbean (CAR) regions. The primary purpose of the report is to provide the reader with an understanding of the role of navigation technology in shaping oceanic operations. Emphasis is placed on identifying navigation systems in use and describing the capabilities of those systems as they influence such factors as separation minima and operating policy.

Navigation technology has evolved at a rapid pace in the last two decades, spearheaded by the introduction of inertial navigation systems (INS) to the commercial aircraft fleet in the 1960's. Section 2 is an overview of navigation and control concepts utilized to maintain the flow of traffic using this technology in oceanic areas. Sections 3, 4, and 5 present details particular to operations in the NAT, CEP, and CAR, respectively.

2. AIRCRAFT NAVIGATION (AND CONTROL)

2.1 Background

When flying under instrument flight rules, aircraft plying the NAT, CEP, and CAR regions are required to obey the "Rules of the Air," specified in Annex 2 to the Convention of International Civil Aviation published by ICAO (Ref. 1, Sec.5.1.1). Annex 2 specifies that: "aircraft shall be equipped with suitable instruments and with navigational equipment appropriate to the route to be flown." The countries in which aircraft are registered have the responsibility of assuring that aircraft are properly equipped, and that training, operating procedures, maintenance etc. meet specified standards.

Annex 6 of ICAO (Ref. 2) goes a little further in Sections 7.2.2 and 7.3 by specifying that navigation and communication must be redundant.

Within most high density domestic airspace, aircraft equipment requirements often require certain types of specific equipment such as navigation receivers and indicators that can be used to navigate using specified radionavigation aid signals. The accuracy of components of both airborne and ground based equipments are sometimes specifically defined. In the oceanic areas studied in this program, the navigation equipments are seldom stated explicitly, (unless states of registry choose to specify them). Instead a general specification is used delineating the overall accuracy of aircraft operation. Indeed, various oceanic navigation systems that may be used to cross the subject areas in the CEP, NAT, and CAR. States of registry have the responsibility of assuring compliance with requirements in existence for various oceanic FIRs.

2.1.1 Aircraft Control Concepts

Aircraft navigation (and control) can be accomplished in two ways. The first is by continual ground instructions from controllers such as that often used in terminal areas. The instructions can consist of headings, airspeeds, altitudes, climb rates, and the like, that an aircraft should maintain. The instructions can also consist of short segments of routes to be flown. This type of control will be called "tactical" aircraft control, and is most often used where both controllers and pilots are continuously in direct contact and both know, within a small percentage of error, where the aircraft is. A controller must know instantly where all nearby aircraft are, what their intentions are, and there must exist procedures for aircraft to continue their flights with reasonable safety in the event of various systems failures such as loss of controller/pilot voice contact or radar failure.

The second way to navigate (and control) aircraft is by issuance of detailed preplanned clearances issued to aircraft prior to entry into a particular area; the clearances typically are approvals or suggested modifications of flight plans filed by pilots. Controllers issuing clearances must use procedures that ensure reasonable safety and preclude the occurrence of aircraft conflicts between aircraft using a certain region or aircraft assigned particular tracks or routes. This second method will be called "strategic" control and tends to be used wherever radar and/or communications services to aircraft are limited or unavailable. Strategic clearance procedures must be designed so that normal inflight vagaries associated with crew or equipment performance will not degrade system safety. (NOTE: The terms "strategic" and "tactical" control as used in this document should not be confused with similar terminology (i.e., strategic and tactical planning) commonly used by NAT ATS personnel with reference to clearance limits.)

In practice, most airspace is controlled with a combination of strategic and tactical control. Sometimes one dimension is controlled strategically while another is controlled tactically. For example, over the oceans, controllers may monitor aircraft speed by observing aircraft reporting point arrival times and issuing instructions requesting change of Mach when necessary.

Since aircraft under strategic control may cross each other's paths and follow each other under conditions where see and avoid concepts are infeasible, the concept of "time" is important in navigation. That is, an aircraft's flight crew should be able to predict when they will pass by certain points so other aircraft approaching those points can cross them without excessive delay (i.e., without excessively large separation minimums). The concept of time prediction clearly involves speed control of aircraft. Time prediction accuracy of navigation is an important factor in determining how much communication is required between aircraft and/or aircraft and ground-based controllers and how well existing airspace can be utilized. The ability of a flight crew to accurately predict the progress in time of their flight can reduce the need to report positions to controllers who must maintain separations between nearby aircraft.

In the oceanic areas there is a preponderance of strategic control. Unlike highly developed domestic areas, the oceanic areas have almost no radar coverage except at some entry and exit points and no direct pilot/controller communications. There is, however, indirect aeronautical mobile radio coverage, which is used to follow aircraft and monitor separations via radio reports. This mechanism is used to deal with unpredictable situations that occur in flight (such as failures of equipment). It is also used to handle requests by aircraft to make maneuvers (such as climbs or route deviations).

2.1.2 Factors Affecting Controllability of Aircraft

The tracks or routes that an aircraft uses to transit oceanic airspace are defined by center lines, which are segments of great circles connecting specific points (defined by latitudes and longitudes) and pressure altitude. The accuracy with which an aircraft can stay on its track can be described by:

Altitude accuracy--the ability to measure and maintain barometric altitude within a specified number of feet.

Cross-track accuracy--the ability to measure and stay within a specified distance of the route centerline.

Along-track accuracy--the ability to estimate and control within a specified accuracy how far along the route an aircraft has gone.

Time (or velocity) accuracy--the ability to estimate within a specified accuracy in minutes the time at which an aircraft will arrive at an along-track point.

Altitude is determined by barometric pressure; cross track position and along track position are determined by radio type devices and/or self-contained devices such as INS. Ground speed can be derived from several sources. Some devices such as INS or Doppler can determine ground speed directly with good accuracy. Ground speed can also be estimated by differencing position fixes or using estimated winds, airspeed, and heading to calculate ground speed. Airspeed is determined by suitably processed pitot static system data.

Maintaining separations between aircraft requires that "relative" positions between aircraft be correct. For example, if following aircraft indicate the same airspeed, which is seldom equal to ground speed, they will not catch up to each other, presuming that they experience the same atmospheric conditions. A similar statement can be made about altitude. Hence, for separation purposes, aircraft can sometimes operate with navigation devices that are consistent from aircraft to aircraft but do not provide absolute measures of position relative to earth-fixed coordinates.

The primary source of navigation and control error in the airspace considered in this study is thought to be human error rather than equipment error. Human error (by pilots, controllers, communications, etc.) includes misuse of equipment, operation without proper equipment, errors in reading or copying clearances, and so on. In the domestic environment the human error is heavily mitigated by independent radar surveillance of aircraft movement wherever there is heavy airspace utilization. In the oceanic environment, safety is maintained by requiring aircraft to operate at large separation distances and maintaining dependent surveillance of aircraft with radio position reports from pilot to ground.

2.2 Navigation (and Control) Technology

Existing and future separation minima and operating procedures are heavily dependent on the technology used to determine and control aircraft position and velocity. This technology consists of equipment that directly affects navigation accuracy, and equipment that allows independent checking of that accuracy, including communications devices, surveillance equipment, collision avoidance systems, and so on.

2.2.1 Primary Oceanic Navigation Equipment

For the purposes of this study we group navigation devices

(1) Altimetry equipment
(2) Horizontal position measurement equipment
(3) Airspeed measurement equipment.

2.2.1.1 Altitude Determination

Transport aircraft generally cruise at specific flight levels where a specified constant atmospheric pressure is maintained. The height above mean sea-level at which an aircraft actually flies is thus a function of how the atmosphere varies from a defined mean at any given time. All nearby aircraft experience similar atmospheric deviations. Hence, though the atmospheric pressure versus altitude may cause aircraft to fly up and down relative to mean sea level, nearby aircraft flying assigned barometric pressures would maintain their relative separations.

"Pressure altitude," or flight level, is measured from pitot-static systems on an aircraft. The static system pressure transducer is generally fed into an air data computer that can compensate for various known static system errors.

In two older Arinc Specifications (e.g., Arinc 549 and Arinc 565, Refs. 3 and 4) the 95% accuracies for altimeter equipment at 30,000 ft are given as +/-75 ft and +/-40 ft, respectively; at 50,000 ft they are given as +/-125 ft and +/-80 ft, respectively.

Current vertical separations for jet-aircraft cruising altitudes above 29,000 ft is 2,000 feet. That is, a block of +/-1,000 ft from an aircraft's nominal flight path is assumed to provide adequate protection. Actual vertical separations between aircraft operating in the same airspace are difficult to measure even in domestic areas where there is radar coverage. Primary radar systems cannot determine aircraft altitude, only aircraft locations in range and azimuth relative to its position. Secondary surveillance radars utilize a transmitted digital reading from an aircraft's own altimeter system to obtain the

aircraft's pressure altitude. Radar data from secondary surveillance systems (where available) tend to identify pilot or autopilot errors in achieving or maintaining clearance pressure altitudes, within the accuracy tolerances of the individual airborne alternator systems.

Aircraft in low altitude airspace (where see-and-avoid concepts can be used) operate with vertical separations as small as 500 ft. Aircraft up to Flight Level 290 in US domestic airspace can operate with Instrument Flight Rules (IFR) traffic assigned to altitudes that are multiples of 1,000 feet, and Visual Flight Rules (VFR) traffic can use these altitudes offset by 500 ft (see Federal Aviation Regulations 91.109 and 91.121). If pilot, control error, actual instrument and other errors could be accurately analyzed, it might be possible to reduce vertical separations above Flight Level 290.

2.2.1.2 Horizontal (Lateral and Longitudinal) Position on

In the horizontal plane, aircraft must be able to identify their current position either as at (1) a particular latitude and longitude or (2) some direction and distance from a known reference or (3) some other arbitrary coordinates. Aircraft must also be able to follow a specified radial from a ground device or fly over a fixed great circle segment defined by two points. Table 1 briefly summarizes the methods used for horizontal navigation.

The accuracy of lateral (cross track) navigation is important in determining the minimal allowable separations that can be assigned to parallel flight paths. Currently, the ICAO specification for aircraft operating in NAT tracks require that aircraft be capable of navigating with a 1 standard deviation of 6.2 nmi of their assigned route. That specification also specifies more important parameters such as limits on the percentage of time systems might operate out of preset tolerances. The specification is called the Minimum Navigation Performance Specification (MNPS), and is outlined in ICAO Document TN 13/5N, "Guidance and Information Material Concerning Air Navigation in the NAT Region."

Longitudinal aircraft navigation accuracies determine how close aircraft can follow each other in-trail and how far apart aircraft should be when they cross paths. This involves speed measurement because there is a predictive element (discussed in the following section) in determining an aircraft's crossing of specified reporting points.

Lateral and longitudinal navigation accuracies are roughly similar when aircraft use such systems as Omega or INS to determine position. Their accuracies tend to vary, however, as a function of time (in the case of INS) and geographic position and other vagaries (in the case of Omega). When aircraft fly using medium or short range ground-based aids such as non-directional beacons (NDBs) or very high frequency omnidirectional ranges (VORs) the situation is complicated because omnidirectional ground-based aids generally provide better navigation accuracy when aircraft are in close proximity to the ground stations.

TABLE 1

BRIEF DESCRIPTIONS OF COMMONLY USED
HORIZONTAL NAVIGATION TECHNIQUES

(1) Dead reckoning. Starting from a known position and using airspeed and estimated wind and compass heading, estimate a future position.

(2) VOR navigation. Fixed ground stations radiate an omnidirectional VHF signal on a published VHF channel. The signal is modulated so that an aircraft instrument can sense the radial relative to any VOR station to which its receiver is tuned. It can conveniently intercept and fly inbound or outbound on any specified radial, all of which are referenced to magnetic North. Much domestic airspace is navigated this way.

(3) ADF navigation. Fixed ground stations radiate an omnidirectional signal in the 200-1750 KHz band, acting as nondirectional beacons (NDB). Automatic direction finding equipment (ADF) can find the bearing of the station (relative to the direction of the nose of the aircraft). By using the compass to determine aircraft heading, it is possible to calculate the radial on which the aircraft is flying to or from the NDB and to intercept and track inbound or outbound on a radial. This requires some subtle wind compensation since the heading held by the aircraft is not the same as the heaing of the ground track that the aircraft follows.

(4) DME. Fixed ground transponder generally co-located with VORs. Airborne equipment gives slant distance to the station. With both VOR/DME or several DMEs an aircraft can calculate its latitude and longitude.

(5) INS. Self-contained inertial instruments on board the aircraft sense horizontal and rotational accelerations. Starting from a known position and velocity, i.e., a ramp at an airport where the aircraft is parked, the system is aligned (usually by sensing the earth's rotation) and thence it integrates (using a computer) accelerometer data to get velocity relative to the earth and also to get position relative to the earth. These systems are self-contained. At or near the poles it may be impossible to align the systems due to the fact that the earth's rotation vector is straight up relative to the INS, but operation over the poles with an aligned system poses no problems.

TABLE 1 (Concluded)

(6) Omega Systems. Using a worldwide network of eight special low frequency ground-based radio stations an on-board aircraft unit can select several signals and calculate, using a digital computer, latitude and longitude. Such systems operate best if aircraft velocity data, measured by an independent system such as doppler radar, is also programmed into the computer to permit independent compensation of signal changes due to aircraft motion. For accurate navigation, corrections for propagation anomalies are also made by the computer.

(7) Loran C. This is functionally similar to Omega above but primarily for coastal navigation. It is more accurate than Omega but coverage is not global. The onboard equipment is radically different from the Omega system. It cannot provide broad ocean coverage and requires many stations for complete coastal coverage.

(8) Doppler. This is an airborne unit that utilizes a radar signal reflected from the earth's surface beneath the aircraft. The doppler shift of the return is used to estimate velocity. This velocity is combined with aircraft attitude systems in a computer, and the result is numerically integrated from a known initial fix (such as an airport) to determine position. The return signal can be lost for significant periods of time due to poor reflection, during which time navigation continuity is provided by the computer memory. These systems are relatively inaccurate and will have errors that grow significantly unless frequent position fixes are used to correct drifts. Hence, doppler is primarily used to provide auxiliary data to other systems.

2.2.1.3 Airspeed Measurement

Longitudinal navigation of aircraft generally requires control of airspeed (expressed in terms of Mach number in cruise conditions), as opposed to ground speed. Mach number is a function of the atmosphere through which aircraft fly. Aircraft flying approximately the same paths generally experience atmospheric conditions that are similar. Hence, if two aircraft fly behind each other at known Mach numbers it is generally possible to predict how their spatial separations will vary with time.

Mach number accuracy from air data computers such as those meeting Arinc Specification 565 (Ref. 4), are specified to be:

+/- .005 at mach 0.5
+/- .005 at mach 0.95
+/- .01 at mach 1.00

At nominal flight levels of 350 (35,000 ft) Mach 1 flight corresponds to a true airspeed of 578 knots. Typical cruising speeds are around Mach 0.8 which is 462 knots (at 35,000 ft). In one hour, an aircraft could vary in its estimate of future position by about .005 x 462 = 2.3 nmi due to Mach error. In fact, wind and other factors may increase position prediction error, but in the practical case all aircraft in the same environment will be similarly affected.

Many jet transports used for longer oceanic flights carry systems that measure ground speed directly. Such aircraft still must rely on predictions of winds when estimating their arrival time at a point in the future, but, in general, they can make better estimates of ETAs at along track position fixes than aircraft that do not carry such equipment.

Current operating procedures for most airlines involve (1) in the majority of cases choosing a Mach number at which to operate or (2) accepting a Mach number from controllers. That speed is then maintained by manual adjustment of throttles or by using a flight management system that automatically controls airspeed. Experience on the North Atlantic has indicated consistent longitudinal separation of commercial aircraft flying common tracks, and based on this experience, longitudinal separation has been decreased to present limits over the past decade.

2.3 Navigation Procedures

The typical sequence for oceanic navigation is as follows:

(1) An aircraft crew at an airport sets its INS, Omega, etc., into an initialization mode by inserting appropriate information into the navigation computer. It may also program the waypoints along which it will fly (if known). The latter can be changed in flight. Figures 1 and 2 show typical INS and Omega computer/display units used to input data. (Systems

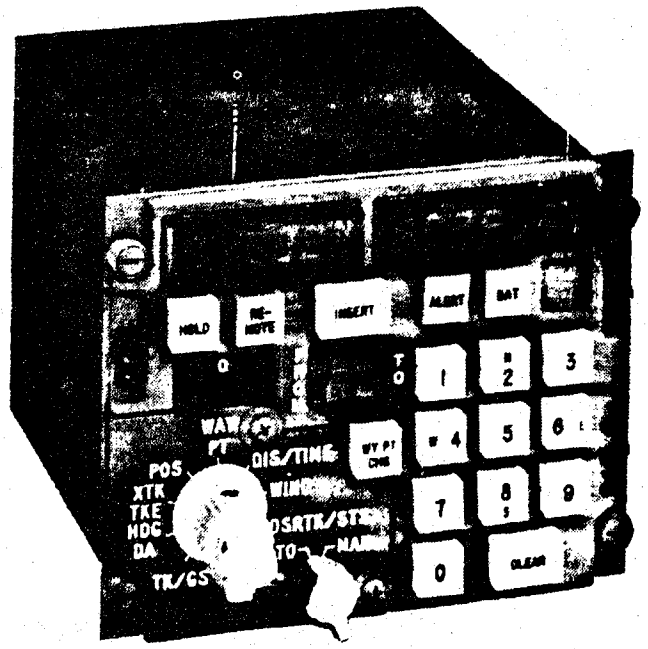

FIGURE 1 A TYPICAL CONTROL/DISPLAY UNIT (CDU) FOR INERTIAL NAVIGATION SYSTEM

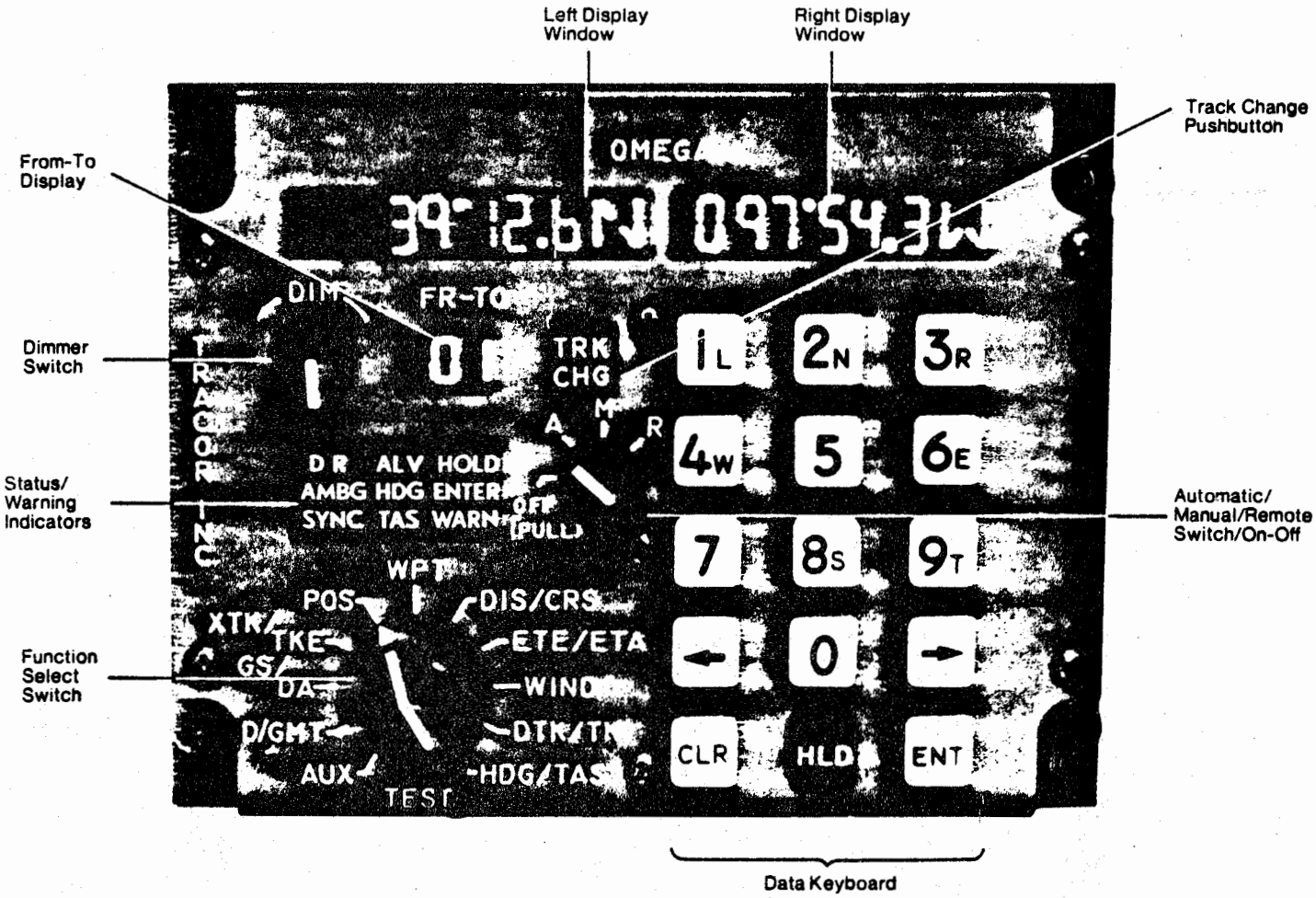

FIGURE 2 A TYPICAL CONTROL/DISPLAY UNIT (CDU) FOR OMEGA NAVIGATION SYSTEM

with extensive memory, such as tape cassettes, are used in some aircraft. Some of these systems can program the system, call up prestored waypoints, and do other functions once the pilot has defined a route.)

(2) The crew also selects the appropriate frequencies on navigation receivers (VORs and ADFs) to be used on departure. Appropriate new frequencies are selected as aircraft move from one navigation aid to the next in domestic airspace. Since DMEs are usually colocated with VORs, they are normally channel paired in a unique way so that selecting a VOR frequency automatically selects the frequency at an associated DME.

(3) The aircraft departs the runway. If in radar-controlled domestic airspace, the crew is frequently given radar vectors that vary from its plan but allow it to return to the plan in case of radar or communications failure. Aircraft taking off from an airport near an oceanic boundary may receive an oceanic clearance while on the ground. Other aircraft receive their oceanic clearances while in flight. The clearance can specify the earliest time at which the entry point to the ocean should be crossed.

(4) Assuming no radar vectors, the aircraft navigates to an oceanic entry point using a speed that will bring it to that point at the proper time. It determines its progress along the planned flight path by proper application at available short range radio navigation.

(5) When beyond the shorter-range navigational aids, the aircraft proceeds to follow its planned flight path using INS, Omega, or other suitable navigation references. The INS can provide display of latitude and longitude at pilot request and displays the arrival at a waypoint (generally a reporting point). Typical INS and Omega units also estimate the time of arrival at the next waypoint on the basis of current ground-speed projections.

(6) The crew flies on its route at its cleared or flight planned Mach number, depending on whether or not special Mach separation rules are in effect on the aircraft's track. At specified waypoints (often every 10 degrees of longitude) the crew reports time of crossing and expected times of next crossing via radio.

(7) The crew, during its flight, can request altitude changes via radio. Under certain circumstances it may request more complicated routing changes. If conditions require aircraft deviation from a clearance for safe flight, there are published special preferential maneuvers and radio reports must be issued to concerned controllers regarding the deviation.

(8) On arriving within range of shorter range navigation aids, the aircraft crew may use them to update long range navigation equipment, or they may revert to short range navigation techniques.

The number and serviceability of radionavigation devices to be carried by civil aircraft on international flights are specified by the competent civil aviation authority in accordance with the provisions, as a minimum, of ICAO Annex 6. In the case of some systems, the installations provide for automatic comparisons of redundant systems to detect discrepancies and to isolate malfunction in equipment. In any case, it is necessary for flight crews to monitor and crosscheck various equipment for indications of malfunctions. The entire issue of error in navigation is extremely complex and is discussed further in the following section.

The flight crews can generally elect to manually steer aircraft or directly connect navigation outputs to the aircraft autopilot, with the latter mode predominating in long range cruise flight. In the first generation of jet transports such as the Boeing 707, interfaces between autopilots, displays, etc., were generally via analog signals. Modern equipment utilizes digital interfaces between navigation equipments and widespread use is being made of small digital computers and digital displays in navigation and control subsystems.

2.4 Navigation Limitations

There are broad classes of error that must be considered when determining how accurately aircraft can navigate. These are:

* Crew error or ground personnel error in using systems
* Basic equipment accuracy limits
* Equipment failures.

These classifications are not simple to make because there are regions of overlap in catagorizing them. For example, a navigation system may fail, but a crew member may not notice a failure indication signal or the discrepancy between several devices. As another example, it may be difficult to make the distinction between what constitutes a failed system and what constitutes an inaccuracy. Equipment failures may or may not be detectable by an aircraft crew.

In practice, human error is thought to be a large element in aircraft navigation error. Human error occurs in a number of ways, but good operating procedures can contain them within acceptable limits. Particularly with highly automated systems, it is important that equipment design be such that the improper insertions of data or program is highly unlikely, and that good cross-checking procedures be instituted to minimize the possibility of improper insertions.

In the NAT extensive surveys (Ref. 5) continue to be conducted of lateral navigation errors of aircraft arriving within radar coverage after crossing the ocean through MNPS airspace. Preliminary data from that study lumped normal navigation errors and equipment failures. In 33,000 flights, 23 were detected as having lateral errors of 30 nmi or more from their expected arrival track. Of these, 9 deviations were attributed to normal accuracy or failures (2 of which were reported to ATC while aircraft were flying), while the other fourteen errors appear to be human errors. All extremely large errors (those that violated current separation standards fell into the human error category; these included airspace use by improperly equipped aircraft and improper insertion of navigation data into navigation systems (such as the use of erroneous waypoints due to ATC or flight crew error).

Available analyses of navigation system errors did not answer several questions of general importance when considering future oceanic system improvements. Some of these are:

(1) What portion of errors (if any) are assumed due to hard failures that should be detected and corrected by human intervention?

(2) How should the redundancy provided in systems be used to minimize navigation errors?

(3) What are the failure characteristics of individual navigation units?

Answers to questions (1) and (2) would help directly in determining to what extent oceanic system analysis can treat failures as special cases (such as turnbacks in the track systems) in computing separation standards. Question 3 is important because an answer to it is necessary before questions on the benefits of redundancy can be answered.

Answers to questions such as the above would strongly affect an assessment of the long-term capability of strategically controlled aircraft and the desirability or necessity of providing refinements and improvements to the present system.

Oceanic separation minima are now so large that occasional failures in navigation and control mechanisms will have little effect on safety. In the case of a known failure of an aircraft's long range navigation

system, pilots or controllers can maintain separation of an aircraft, if necessary, from others via altitude changes. Wide lane widths and long distances between aircraft make occasional letdown or climbs possible without risk of a collision.

2.5 Some Trends in Navigation Equipment

In the last 10 years the cost of INS appears to have dropped (in real dollars), and Omega now offers an even less expensive navigation system for some applications. Commercial INS prototypes using laser gyros have already been flown successfully. Laser inertial systems have been specified for the next generation of Boeing transports to provide primary attitude stabilization data as well as navigation outputs. Lasers eliminate much of the mechanical reliability limitations inherent in conventional gyros. It also appears that existing manufacturers are making more accurate equipment. Even intermediate-range radio devices such as ADFs used in the Caribbean and in some other offshore areas have become more accurate, utilizing nonmechanical devices to track signal direction.

Altitude and Mach measurement equipment has improved. The use of digital air data computers permits more convenient and accurate calibration of data presented to the flight crew.

Data from various devices are being combined digitally to permit blending of various navigation systems. This can enhance accuracy, make possible automatic calculations of such parameters as winds, and permit some automated cross-checking of various sensors or subsystems. Some commercially available navigation systems, for example, can utilize VOR/DME and INS signals to cross-check self-contained navigation devices and adjust estimates of position based on interpolation of the data when the aircraft is within range of ground-based navigation aids.

The United States Air Force has launched prototype orbiting satellites in support of testing a concept that would provide global navigation coverage using relatively inexpensive navigation receivers. Signals from this system may become available to civilian users. These signals can have accuracies that are better than those available from conventional domestic VOR/DME signals. The system is called the Navstar Global Positioning System (GPS).

Another development, closely related to navigation, involves efforts associated with collision avoidance system concepts. Separation minima are constrained by the need to prevent collisions in the rare instance when an aircraft deviates from assigned track or speed. Collision avoidance systems might provide a measure of warning against conflict situations in a way that is not entirely dissimilar to that provided by radar.

3 NAT NAVIGATION

3.1 Routes

NAT traffic is dominated by the 300 or so aircraft per day flying between Europe and North America. This traffic is almost all easterly in the early part of the day (0000-0900 Greenwich Mean Time) and westerly later in the day. Merging with this traffic is traffic that follows polar routes between the western part of the U.S., Canada, and Europe. This polar traffic must merge with or cross the mainstream of traffic mentioned above. Also, a flow of traffic between southern Europe, the Caribbean, and other southern points may merge with or cross the mainstream of the European/North American traffic.

The main traffic flow is handled on an organized track system (OTS)--a set of tracks defined once per day for easterly traffic and once per day for westerly traffic. The tracks have predominantly one-way traffic; at most, only a few tracks are dedicated for counter flow. Details of organized tracks are made known to users via traditional aeronautical information distribution sources.

Aircraft flying in OTS request the track they want. These tracks are designed to optimize aircraft performance by considering upper air circulation, but some tracks are more desirable than others; these are awarded on a first-come/first-served basis. Aircraft flying counter to the OTS main-traffic direction, or flying so as to merge or cross the OTS, file random tracks. Aircraft that fly counter to track traffic or random tracks can often fly well north or south of the tracks because they want to avoid the wind conditions that are most desirable for the majority of traffic. Organized tracks may be provided for counter-flow traffic, if necessary.

3.2 Overview of Navigation and Control Characteristics of NAT OTS Traffic

Most aircraft enter and depart the end points of the organized tracks under radar control and/or over a fix defined by a short-range VOR/DME or NDB. Other aircraft fly randomly filed tracks that may merge with an organized track (under certain conditions). Furthermore, when OTS tracks are northerly, some aircraft operate for a short time under radar coverage of Iceland and can be guided directly by ground controllers for altitude and other changes. Figures 3 and 4 show NAT track entry and exit areas, and Figure 5 shows estimated radar coverage areas at 30,000 ft at entry and exit areas.

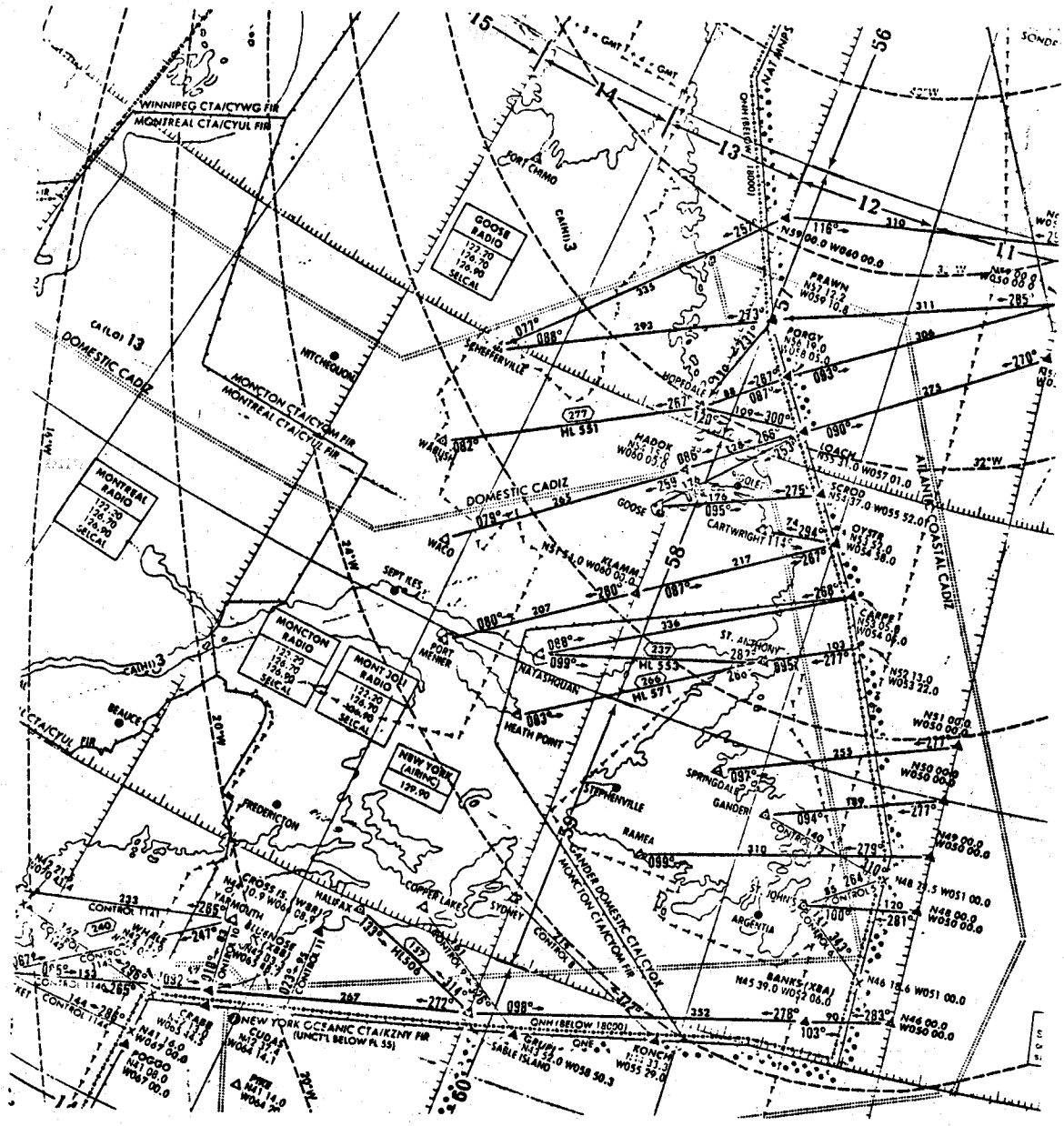

FIGURE 3

LAND-BASED NAVIGATION AIDS AVAILABLE FOR NAT TRACK ENTRY AND EXIT AT WEST END

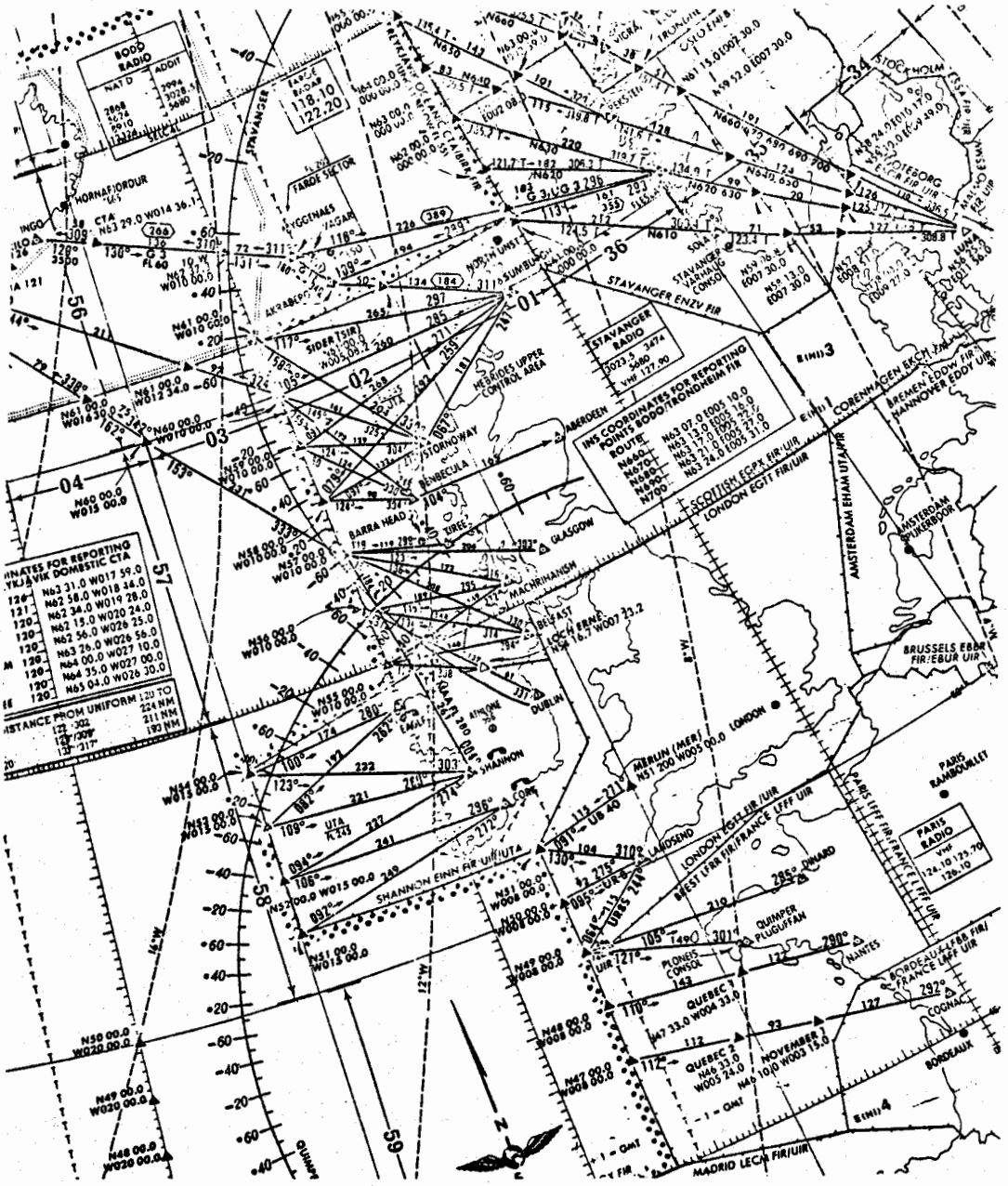

FIGURE 4
LAND-BASED NAVIGATION AIDS AVAILABLE FOR NAT TRACK ENTRY AND EXIT AT EAST END

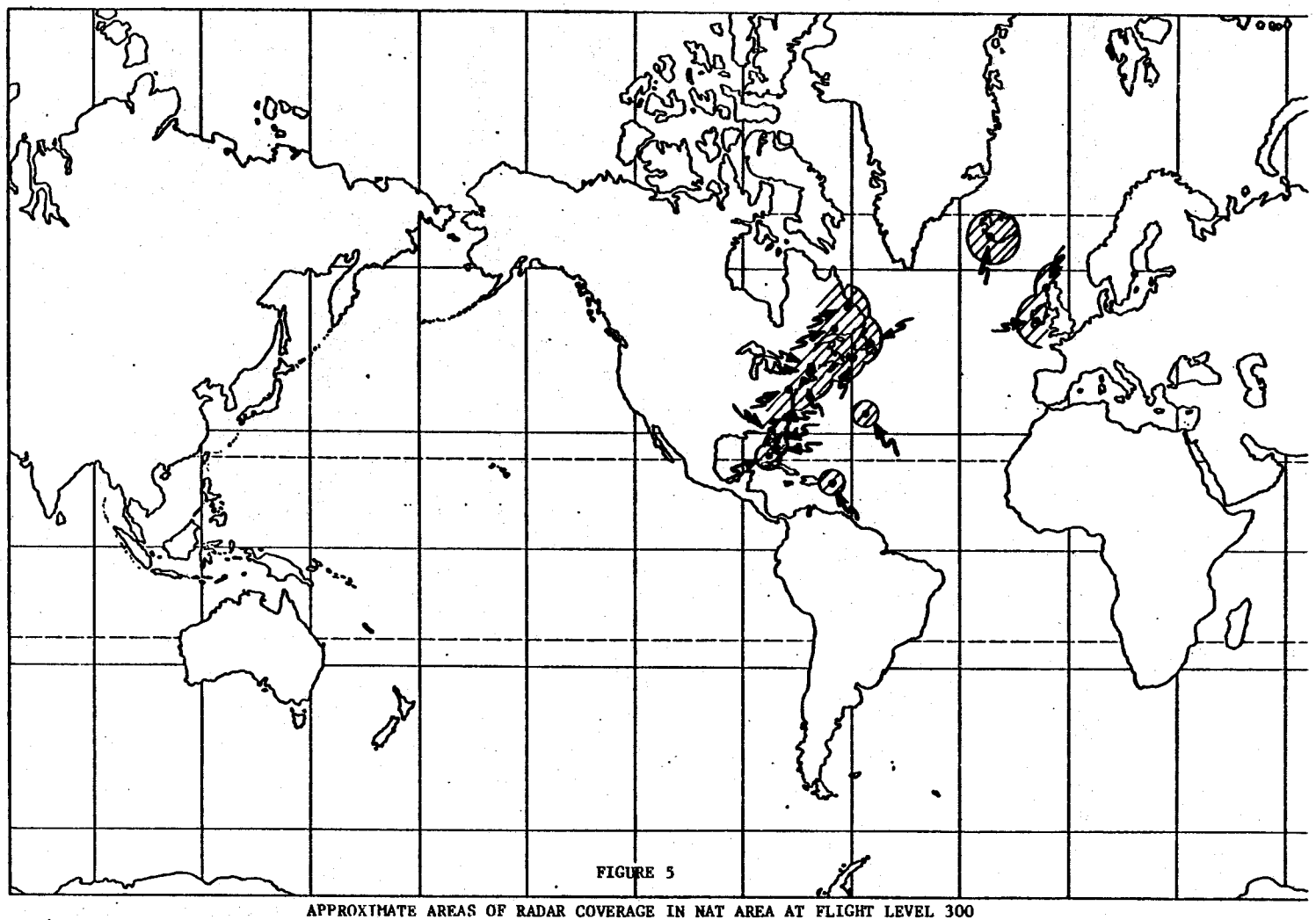

FIGURE 5

APPROXIMATE AREAS OF RADAR COVERAGE IN NAT AREA AT FLIGHT LEVEL 300

Tables 2 and 3 show samples of organized track listings for the NAT. Most tracks are defined by integral latitude and longitude points. Some tracks had composite separation through 1980, meaning that aircraft at the same flight level were separated laterally by 120 nmi, and aircraft operating at 1000 ft above and below were separated laterally by 60 nmi from aircraft on the first-mentioned track. Figure 6 shows how aircraft were actually separated in a particular westbound flow period. Figures 7 and 8 plot the westbound organized tracks as they occurred on July 6, 1981.

Organized NAT track information is generally available to air carriers at least 8 hours before an OTS goes into effect. Waypoints can be entered on the ground prior to takeoff (if a clearance is already available), or in the air when a track clearance is issued. Each waypoint latitude and longitude to be used is keyed into a pilot's CDU (control and display unit) of the INS or Omega navigation system; so that it may be checked visually for accuracy before being entered into the computer.

3.2.1 OTS Traffic

Currently, all aircraft using specified portions of the NAT airspace must meet minimum navigation performance specifications (MNPS) that specify how accurately aircraft must be able to fly assigned tracks over the ocean. The MNPS requirements were developed by various bodies including the ICAO 9th Air Navigation Conference, the Limited ICAO NAT RAN meeting (1976), and the NAT Systems Planning Group (NAT/SPG). Basic requirements are contained in ICAO document 7030, Regional Supplementary Procedures, and are elaborated in the ICAO document. "Guidance and Information Material Concerning Air Navigation in the NAT Region", T 13/5N, July 1978. A sample MNPS advisory circular specifying MNPS requirements as issued by the US FAA is given in Appendix A. Currently, only aircraft with some combination of redundant INS and/or Omega systems are capable of meeting MNPS standards. Aircraft unable to meet MNPS standards cannot fly in the area blocked out by 27 degrees North and 67 degrees North, the eastern boundaries of the Santa Maria Oceanic, Shanwick Oceanic and Reykjavik FIRs, the western boundaries of Reykjavik and Gander Oceanic and New York Oceanic FIRs east of 60 degrees West and flight levels 275 and 400.

Radar at each end of the OTS is used to monitor compliance with MNPS standards by making sure aircraft have stayed within acceptable bounds of their assigned route. Tables 4 and 5 (excerpted from ref. 5) are sample summaries of how far off course aircraft have been observed when arriving at their end points. These data are further discussed in a later subsection. The most recent data was not available at the time of this writing.

TABLE 2

ORGANIZED TRACK LISTING FOR WESTBOUND FLOW ON JULY 6, 1978

HAL076 060120
DD CYZZAA KNZZNT MUHACUOW PHNLXANT MKJPJMOW MYNNZG
060115 EGGXZQ
NAT TRACKS FLS 310/370 INCLUSIVE JULY 06/1100Z TO 06/2200Z
PART ONE OF TWO PARTS

A 59/10 62/20 62/30 61/40 59/50 PRAWN CYKL
WEST LVLS 310 330 350
EAST LVLS NIL
EUR RTS WEST 2
EUR RTS EAST NIL
NAR NA150 NA194 NA196 NA197

B 57/10 60/20 60/30 59/40 57/50 LOACH HADOK CYKK
WEST LVLS 310 330 350 370
EAST LVLS NIL
EUR RTS WEST 2
EUR RTS EAST NIL
NAR NA140 NA186

C 56/10 58/20 58/30 57/40 55/50 OYSTR KLAMM CYPN
WEST LVLS 310 330 350 370
EAST LVLS NIL
EUR RTS WEST 2
EUR RTS EAST NIL
NAR NA134 NA179

D 55/10 57/20 57/30 56/40 54/50 CARPE CYNA
WEST LVLS 320 340 360
EAST LVLS NIL
EUR RTS WEST 2
EUR RTS EAST NIL
NAR NA128 NA175

E EGL 56/20 56/30 55/40 53/50 CYAY
WEST LVLS 310 330 350 370
EAST LVLS NIL
EUR RTS WEST 2
EUR RTS EAST NIL
NAR NA125 NA171

END OF PART ONE OF TWO PARTS

TABLE 2 (Concluded)
ORGANIZED TRACK LISTING FOR WESTBOUND FLOW ON JULY 6, 1978

HAL081 060131
DD CYZZAA KNZZNT MUHACUOW PHNLXANT MKJPJMOW NYNNZG
060126 EGGXZQ
NAT TRACKS FLS 310/370 INCLUSIVE JULY 06/1100Z TO 06/2200Z
PART TWO OF TWO PARTS

F 53/15 54/20 54/30 53/40 51/50 CYSG
WEST LVLS 310 330 350 370
EAST LVLS NIL
EUR RTS WEST 2 VIA SNN
EUR RTS EAST NIL
NAR NA122 NA168

G 52/15 53/20 53/30 52/40 50/50 CYQX
WEST LVLS NIL
EAST LVLS 320 340 360
EUR RTS WEST NIL
EUR RTS EAST CRK
NAR NA12 NA67 NA68

H 50/08 50/20 50/30 50/40 49/50 CYRZ
WEST LVLS 310 350
EAST LVLS 330 370
EUR RTS WEST 2
EUR RTS EAST LND
NAR NA7 NA63 NA64 NA112 NA161

J 48/08 48/20 48/30 48/40 47/50 COLOR
WEST LVLS 330 350 370
EAST LVLS NIL
EUR RTS WEST QPR
EUR RTS EAST NIL
NAR NA131 NA159

K 4430/13 46/20 46/30 46/40 46/50 COLOR
WEST LVLS 310
EAST LVLS NIL
EUR RTS WEST STG
EUR RTS EAST NIL
NAR NA131 NA159

L 4030/15 42/20 43/30 43/40 43/50 42/60 POGGO
WEST LVLS 310 350
EAST LVLS NIL
EUR RTS WEST BUGIO
EUR RTS EAST NIL
NAR NA100

WESTBOUND TRAFFIC ON TRACK KILO CONTACT SHANWICK OAC FOR CLEARANCE

TABLE 3

ORGANIZED TRACK LISTING FOR EASTBOUND FLOW ON JULY 6, 1978

CYZZAA KNZZNT MUHACUOW MKJPJMOW PHNLXANT MYNNZG MKPPZR
051159 CYQXZQ
NAT TRACKS FL310/370 INCLUSIVE
JULY 06 0000Z – 0900Z

U CYAY 53/50 53/40 55/30 55/20 55/10 BEL
FL EASTBOUND 330, 350, 370
FL WESTBOUND NIL
NARS NA21 NA22 NA81

V CYSG 51/50 52/40 54/30 54/20 54/15 EGL
FL EASTBOUND 320, 340, 360
FL WESTBOUND NIL
NARS NA17 NA18 NA72

W CYQX 50/50 51/40 53/30 53/20 53/15 SNN
FL EASTBOUND 310, 330, 350, 370
FL WESTBOUND NIL
NARS NA13 NA14 NA67 NA68

X CYRZ 49/50 50/40 52/30 52/20 52/15 CRK
FL EASTBOUND 320, 340, 360
FL WESTBOUND NIL
NARS NA7 NA63 NA64

Y CYYT 48/50 49/40 51/30 51/20 50/08 LND
FL EASTBOUND 310, 330, 350, 370
FL WESTBOUND NIL
NARS NA5 NA59 NA60

Z CYSA 46/50 47/40 49/30 49/20 48/08 QPR
FL EASTBOUND 330, 350, 370
FL WESTBOUND NIL
NARS NA1 NA51 NA52

ANK021 051206

Flight Level	Route A	B	C	D	E	F	G	H	J, K (converge)	L
370	X	W	W		W	W		E	W(J)	X
360				W			E			
350	W	W	W		W	W		W	W(J)	W
340				W			E			
330	W	W	W		W	W		E	W(J)	X
320				W			E			
310	W	W	W		W	W		W	W(K)	W
300										
290										

120 NM

2000'

60 NM

1000'

W = West
E = East
X = Unassigned

FIGURE 6
COMPOSITE SEPARATION OF TRACKS ON TABLE 2

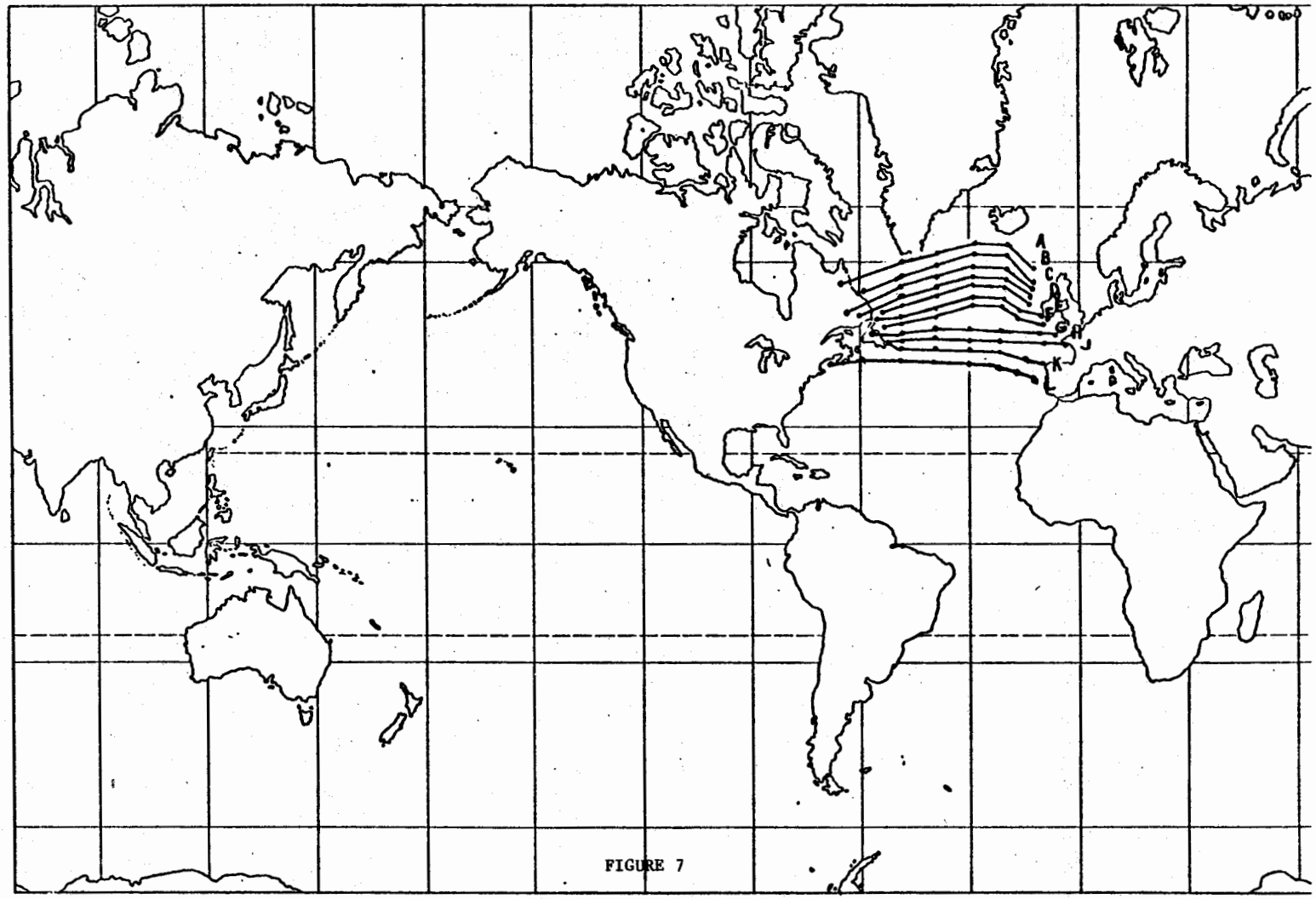

FIGURE 7

GROUND TRACKS FOR OTS SHOWN IN TABLE 2 (JULY 6, 1978; 1100Z-2200Z)

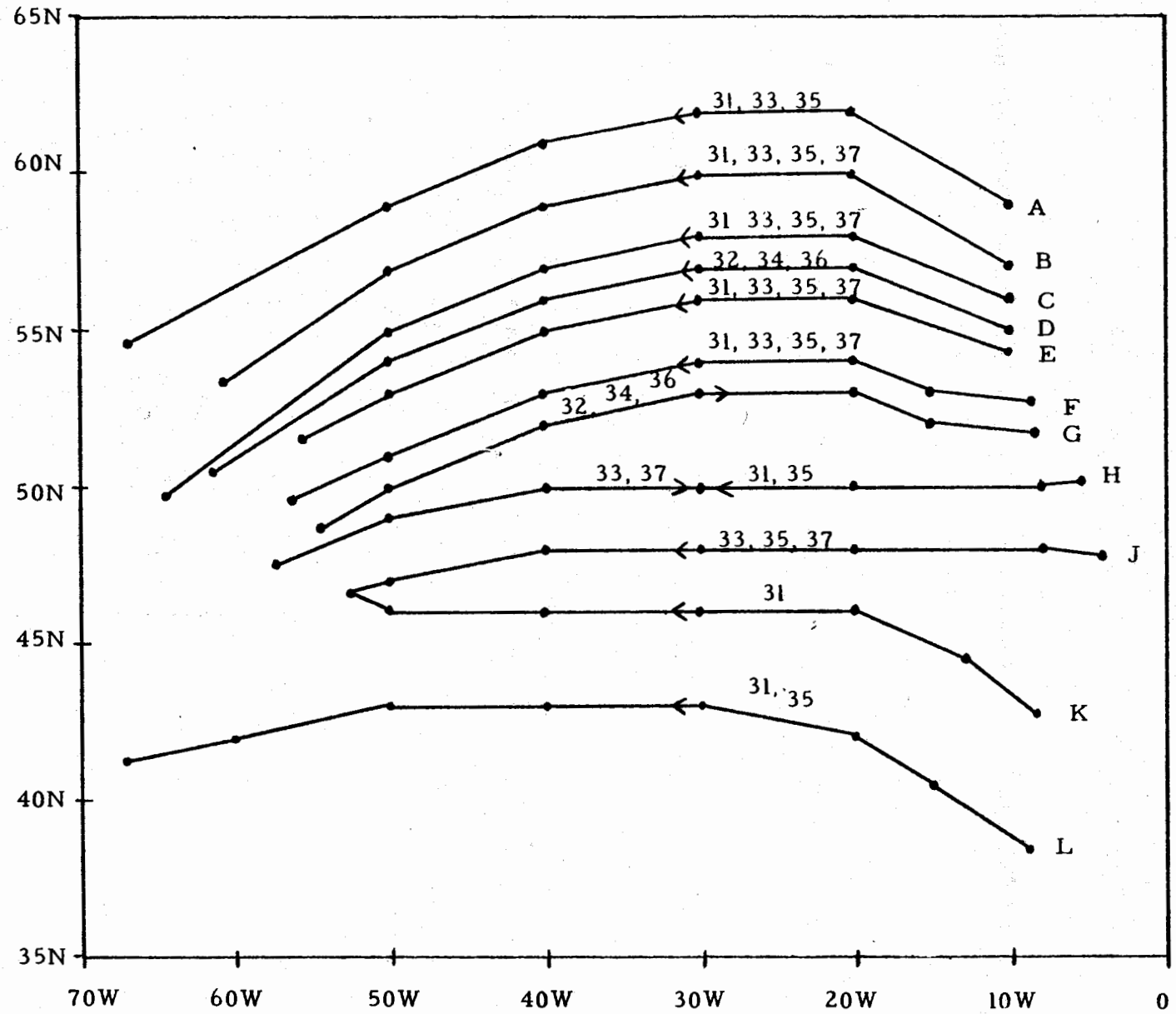

FIGURE 8
DETAILED PLOT OF OTS TRACKS SHOWN IN TABLE 2 (JULY 6, 1978; 1100Z-2200Z)

TABLE 4

Statistical Measures of Eastbound Track Traffic Errors Measured from Shannon and Stornoway Radars

Source of Data	Number of Flights	Mean OCA Bdy. Error	Standard Deviation	MNPS Requirement
Shannon	544	1.56nm S	3.80nms	S.D. = 6.3nms
Stornoway	400	0.16nm S	4.89nms	

TABLE 5

SUMMARY OF SOME LARGE EXCURSIONS MEASURED IN INITIAL PHASE OF MNPS PROGRAM

1	2	3	4	5	6	7
Date	FL	Deviation nm	Category	30 nm	50-70 nm	Traffic Movements to Date
Jan 8	380	55	1	1	1	921
14	330	40	5	1		1612
14	310	46	4	1		1612
24	350	47	1	1		2764
Mar 2	330	30	5	1		7478
17	350	180	3	1	1	9415
26	350	50	1	1/2	1/2	10577
30	370	60	5	1	1	11094
Apr15	300	55	1	1	1	13409
19	290	120	4	1	1	13992
21	330	60	1	1	1	14203
23	310	40	1	1		14575
May13	370	60	4	1	1	17857
14	370	55	2	1	1	18031
15	340	100	5	1		18205
19	370	38	4	1		18900
20	290	130	4	1	1	19074
Jun 7	370	40	1	1/2		22528
8	380	30	1	1		22748
17	340	70	2	1	1	24728
Jul11	350	60	3	1	1	26950
25	370	30	4	1		32274
29	330	38	1	1		33024

Notes:

1. Column 4 refers to the categories defined by the Scrutiny Group.

   Cat 1. Normal navigational errors (including equipment failures)
   Cat 2. ATC Loop errors (including clearance problems)
   Cat 3. Equipment control errors (including waypoint/autopilot problems)
   Cat 4. Unauthorized to fly MNPS (repeatable).
   Cat 5. Retrofitting or subject of Government Assurance (unrepeatable).

3. The numeric values in Columns 5 and 6 define the weighting applied to individual gross error events in the Mathematical analysis. Weighting of 1/2 indicates failure or error was reported to ATC in flight.

4. Column 7 provides the approximate total number of flights observed by the monitoring radars before each gross error event.

In addition to meeting MNPS requirements, NAT OTS traffic desiring favorable routing must be able to accept Mach speed assignments, since aircraft in the same track (flight level and route) are separated longitudinally by this method. In essence, such Mach assignments allow aircraft to fly closer together longitudinally than would be permitted under ordinary oceanic procedures. This reduced separation is accomplished by being very precise about entry points to a track used by many aircraft and by having good knowledge of how these aircraft will progress along the assigned route. Aircraft may only enter tracks at intermediate points or specify their own Mach if controllers can provide them with projected 20 minute longitudinal separations between leading and following aircraft at all waypoints rather than the 15 minutes (or less when slower aircraft are following faster aircraft) allowable with Mach separation.

OTS traffic is cleared for its entire oceanic flight prior to entry into oceanic airspace. Aircraft are cleared for a single altitude for the whole route, but requests for changes in altitude can be made enroute and will be granted if controllers have adequate knowledge of nearby aircraft positions.

3.2.2 Random Track NAT Traffic

Caribbean and polar traffic merging with crossing traffic or running counter to the OTS direction requests its own random route. Where these routes conflict with the OTS, such aircraft often are required to fly low altitude segments (e.g., flight level 290) to avoid conflicts.

Merging with OTS tracks by random traffic is generally not feasible because OTS traffic is generally closely spaced. Inserting an aircraft into an OTS track requires that at the least the aircraft ahead and behind the potential insertion point be separated by at least 40 minutes, allowing 20-minute separation between the inserted aircraft and fore and aft aircraft. Note that inserted aircraft cannot operate at Mach separation since Mach separated aircraft must enter a track over the same ground based (radar or other navaid) fix.

Random-track oceanic traffic is cleared through all contiguous oceanic FIRs on its entry to an oceanic control sector, but it is not guaranteed a conflict free flight without reclearance except in the case of Shannon border. It may be cleared to a point at one altitude and then to another point at another altitude within an FIR at the discretion of controllers. In the special case of Shanwick-Gander traffic, clearances are often issued for the flight through both FIRs.

Random NAT traffic is most constrained by its inability to obtain desired altitudes. Polar, Caribbean, and counter-track traffic is seldom constrained from flying desired ground tracks until within potential conflict of OTS traffic. Conflict is often resolved by flying this

traffic at Flight Level 290. Although carriers flying random tracks may also carry equipment that conforms to MNPS standards, it is difficult for them to merge into the mainstream OTS traffic flow. It may be impossible to do this type of merging without some type of surveillance of aircraft because converging aircraft experience different meteorological conditions and other uncertainties that make the planning and execution of Mach-separated merges difficult.

3.3 NAT Navigation Aids

NAT is serviced by at least the following primary navigation aids:

INS systems.

Omega (and possibly VLF) radionavigation coverage.

VORs, DMEs and NDBs along the boundaries of the regions, are shown schematically with triangles in Figures 3 and 4.

Radars located at:

- Keflavik (Iceland)
- Stornoway (Scotland)
- Shannon (Ireland)
- Gander (Canada)
- Lajes (the Azores)
- Whitehorse (Florida, USA)
- Patrick (Florida, USA)
- Richmond (Florida, USA)
- Key West (Florida, USA)
- Moncton (Canada)
- Sydney (Canada)
- Goose Bay (Canada)
- San Juan (Puerto Rico)
- Bucks Harbor (Maine, USA)
- Winthrop (Mass., USA)
- Suffolk (N.Y., USA)
- Bennshall (Virginia, USA)
- Jedburg (South Carolina, USA)

Table 6 is a partial summary of on-board equipment in use on the NAT as obtained from a survey conducted within this study. Seven air traffic services (ATS) centers--Gander, Prestwick, New York, Santa Maria, San Juan, Miami, and Reykjavik--coordinate traffic, and six associated radio communication stations provide VHF and HF ground-to-air links that relay messages between aircraft and the ATC facilities.

The bulk of aircraft entering or departing the NAT does so under radar surveillance. Exceptions include:

Some Caribbean traffic that enters or departs between San Juan and Miami radar coverage or enters or departs to the east of San Juan.

Some polar traffic and northern track traffic that enters Canadian or Reykjavik airspace.

Table 6

OCEANIC NAVIGATION/HF COM EQUIPMENT

CARRIER		747	L1011	DC10	DC-8	707
#1 (KLM)	No of A/C	NA		NA	NA	
	Nav Equip.	Triple INS (DELCO)		Triple INS (LTN 58) Dual RNAV (Collins ANS70)	Dual Doppler (CAN MARCONI) Single Omega (NORDEN ONSVII)	
	Com	COLLINS 618T-2		COLLINS 618T-2	COLLINS 628T-1	
#2* (Lufthansa)	No. of A/C	10		11		15
	Nav. Equip.	Triple INS (NA)		Triple INS		Dual/Triple INS
	Com	NA		NA		NA
#3 (Swissair)	No. of A/C	NA		NA		
	Nav. Equip.	Triple INS (DELCO)		Triple INS (LTN-58) Dual RNAV (COLLINS ANS70)		
	Com	618T-2*		628T-2		
#4 (Air Canada)	No. of A/C	NA	NA			
	Nav. Equip.	DUAL INS (LTN-72)	DUAL INS (LTN-72)		DUAL INS (LTN-72)	
	Com	618T-2/ 628T-1	618T-2/ 628T-1		618T-2/ 628T-1	
#5 (Iberia)	No. of A/C	NA		NA	NA	
	Nav. Equip.	Triple INS (LTN-72)		Triple INS (LTN-72)	DUAL INS (DELCO)	
	Com	628T-1		628T-1	618T-2	

*Being replaced by 628T-1

3.4 Accuracy and Reliability of NAT Navigation

Radars at entry points (Ref. 5) are being used to estimate how well jet transports can navigate across the OTS, based on their arrival point after oceanic crossing. Tabular data from Ref. 5 were shown in Tables 4 and 5. The statistics taken there indicate that the standard deviation of the lateral error in arriving flights is less than 5 nmi. Some errors of greater than 30 nmi were observed. Out of 33,000 eastbound flights, 23 were observed to be in this category between January 1 and July 31, 1978 and only 2 of those reported navigation failure in flight. Ten of the above flights were found to be improperly equipped for MNPS operation.

Literature from major INS manufacturers (see Ref. 6) indicate that existing systems are achieving 3,000 hr of mean time between failures. Omega manufacturers (see Ref. 7) predict similar MTBFs. MNPS systems must have two operating primary systems on NAT entry, but such systems may not always be entirely independent. For example Omega systems can share antenna, and INS systems share CDUs. The readily available data are not such that it is possible to compute theoretical system reliability, but it is most desirable that this be done in the future.

Some examples of human errors that can influence navigation performance include the erroneous issuance or recording of a clearance, erroneous inputs into aircraft navigation systems, failure to cross-check equipment during flight, failure to report inconsistency of two primary navigation systems, failure to fly aircraft according to course indicators, etc.

3.5 NAT Navigation Financial Information

Aircraft using the FIRs serviced by Canada, Denmark, Iceland, Ireland, and the UK are billed for navigation and communication services that they use. Canada has a navigation charge of about US$ 45 per flight through the NAT. The UK charges approximately US$ 72 per flight, and Iceland and Denmark levy a charge collected by the UK. Total navigation and communication charges for a NAT flight are about US$ 200. The labor associated with the ATS facilities is the major component of the navigation charges. The United States does not bill users directly for its share of navigational services.

Short-range navigation aids on the European and North American coasts serve both domestic and oceanic functions. The relative need for either use is not known. Some aids on Iceland and Greenland serve primarily low-altitude aircraft. Costs of some of these facilities are charged to oceanic traffic.

NAT aircraft, in addition to their normal complement of equipment for domestic use, must carry some combination of navigation units capable of very long-range overwater operation. The lowest cost MNPS system available today would be two Omega units at a total price of

approximately $100,000 installed or two INS units at approximately $200,000. Typical operating costs for such units are US$ 1 per flight hour for Omega, and four dollars or so for INS. Indirect costs associated with delays, need to reroute, and the like due to failed equipment are unknown but was not mentioned as a problem by any operators responding to study questionnaires issued to NAT users.

4 CEP NAVIGATION

4.1 Routes

As with NAT, the bulk of CEP traffic navigates on organized tracks. However, these tracks remain geographically fixed, although the flight levels and directions used on the routes are varied to accommodate traffic flow peaks. Also, as with the NAT organized tracks, composite separation is used. Figure 9 shows an outline of these tracks. Each track begins at a VOR fix under radar surveillance. The heavy track traffic (some 80 to 130 aircraft per day) moves between the coast of California in the United States and Hawaii. Lesser numbers of aircraft fly between Canada and Hawaii merging with the tracks at their western end. There is also merging traffic that flies between Northern Asia and the North American Coast directly. Very few aircraft (i.e., several per month) coming from the Southern Hemisphere actually cross the tracks on a North/South route.

An aircraft crossing the tracks from the south or from the northwest will generally arrive in the CEP with an altitude that could conflict with other aircraft. Such aircraft contact and receive clearance from the Oakland or Honolulu ATS facilities. These aircraft may have larger navigation error than organized track aircraft which generally only fly 2,000 nmi or so on long range-aids. Since some navigation errors (such as INS errors) tend to grow with time it is not clear whether very long-range flights (e.g., from Japan or Australia to North America) could meet MNPS standards at the ends of their flights as easily as aircraft flying shorter routes.

MNPS requirements are not in effect on the CEP. Hence, there is no single specific international requirement concerning the accuracy with which CEP aircraft navigate. In large part, however, CEP aircraft are equipped about the same as NAT aircraft, with double and triple INS units, omega units, and so on. As with the NAT, controllers believe that there are occasional aircraft flying the CEP without adequate long range navigation equipment.

4.2 Navigation Aids

Traffic entering or departing the CEP in the region of Hawaii and the U.S. coast enter and leave the track under the surveillance of radar located at:

San Pedro (California, USA)	Honolulu (Hawaii, USA)
Paso Robles (California, USA)	Kokwee (Hawaii, USA)
Half Moon Bay (Calif., USA)	Maui (Hawaii, USA)
Crescent City (Calif., USA)	Mt. Kaala (Hawaii, USA)
Salem (Oregon, USA)	Seattle (Washington, USA)

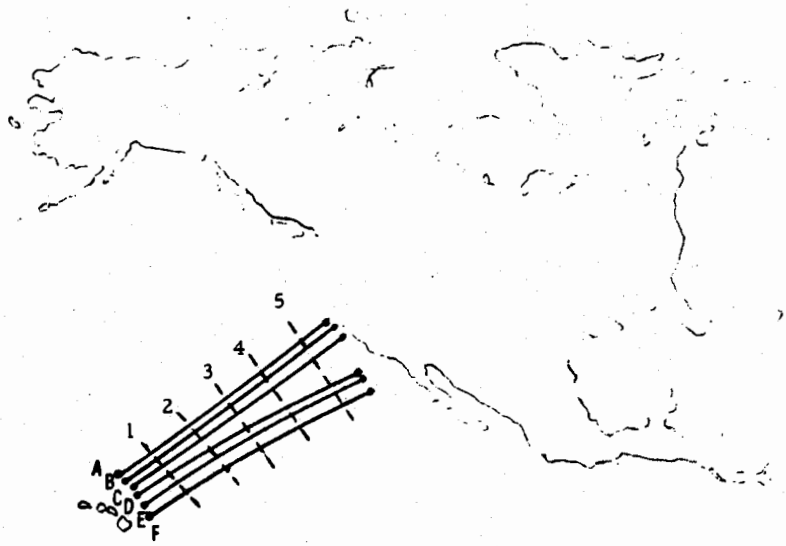

FIGURE 9
OUTLINE OF CEP FIXED TRACKS

End Point	Reporting Points--1	2	3	4	5	End Point
APACK	TRACK A ABSOL	ADENI	ADMEN	ABNER	AMILL	ALCOA
N24 03.0	N27 18.2	N29 56.0	N32 22.6	N34 36.1	N36 34.8	N37 50.0
W156 19.0	W150 59.2	W146 08.9	W141 03.6	W135 42.1	W130 04.1	W125 50.0
BITTA	TRACK B BANDY	BEATS	BEGGS	BAKON	BLUFF	BEBOP
N23 32.0	N26 31.8	N29 06.8	N31 30.7	N33 41.9	N35 38.6	N37 00.0
W155 29.0	W150 27.4	W145 37.3	W140 32.9	W135 13.3	W129 38.1	W125 00.0
CLUTS	TRACK C CHEAK	CITTA	COGGS	COPPI	COSTS	CLUKK
N23 00.0	N25 45.8	N28 18.9	N30 41.2	N32 51.1	N34 46.9	N36 05.0
W154 39.0	W149 56.5	W145 07.2	W140 04.2	W134 46.8	W129 14.5	W124 50.0
DENNS	TRACK D DANKA	DEROK	DEZZI	DOPPS	DONER	DUETS
N22 22.0	N24 39.2	N26 50.4	N28 50.6	N30 38.4	N32 12.4	N33 04.2
W153 53.0	W149 11.4	W144 12.4	W139 02.1	W133 40.3	W128 07.3	W124 31.0
EBBER	TRACK E EXAMS	ENGIN	ENTTA	ESCRO	EKTAS	EDSEL
N21 43.0	N23 51.9	N26 01.6	N28 00.7	N29 47.8	N31 21.6	N32 14.5
W153 09.0	W148 41.3	W143 43.4	W138 34.9	W133 15.4	W127 45.2	W124 05.9
FITES	TRACK F FABBY	FADER	FESTO	FEARS	FONZA	FOOTS
N20 49.0	N23 03.3	N25 08.2	N27 02.7	N28 45.6	N30 15.6	N31 07.9
W153 00.0	W148 10.4	W143 12.0	W138 03.8	W132 45.6	W127 17.5	W123 32.8

Figure 10 is an approximate schematic of the coverage provided by these radars.

Figures 11 and 12 indicate the VOR/DME and NDBs available for entry and exit to the CEP. Mach number assignments are frequently used on the CEP tracks. Omega coverage exists in the CEP. The majority of CEP traffic uses INS navigation. Although a 1974 survey (Ref. 8) showed a large usage of Doppler, Loran A and C, Celestial Navigation, and Consolan as shown in Table 7, discussions with controllers and users of the airspace indicate that these statistics have probably changed considerably in the intervening 6 years.

4.3 CEP Navigation Accuracy and Reliability

CEP navigation accuracy data is available from an FAA project conducted in 1973-1974 (ref. 9). Since that time there may have been improvements in on-board navigation systems. The FAA obtained lateral errors with standard deviations of approximately 7 nmi in the 1973-1974 study. Table 8 is reproduced from that study. Some of the occasional large errors found in the CEP study were correlated with specific users. Data were obtained on 72 flights that were 30 nmi or more off course. Results were as follows:

Crew errors	57
Equipment failure	11
Weather Problems	1
No Traceable Explanation	2

Fourteen other flights also had large deviations, but no data concerning causes were obtained from operators.

4.4 CEP Financial Information

The United States, which provides ATS services in the CEP, imposes no charges for navigation services. There are no known differences in costs between aircraft operators in the CEP and those in the NAT, since basically the same navaids are used by commercial operators.

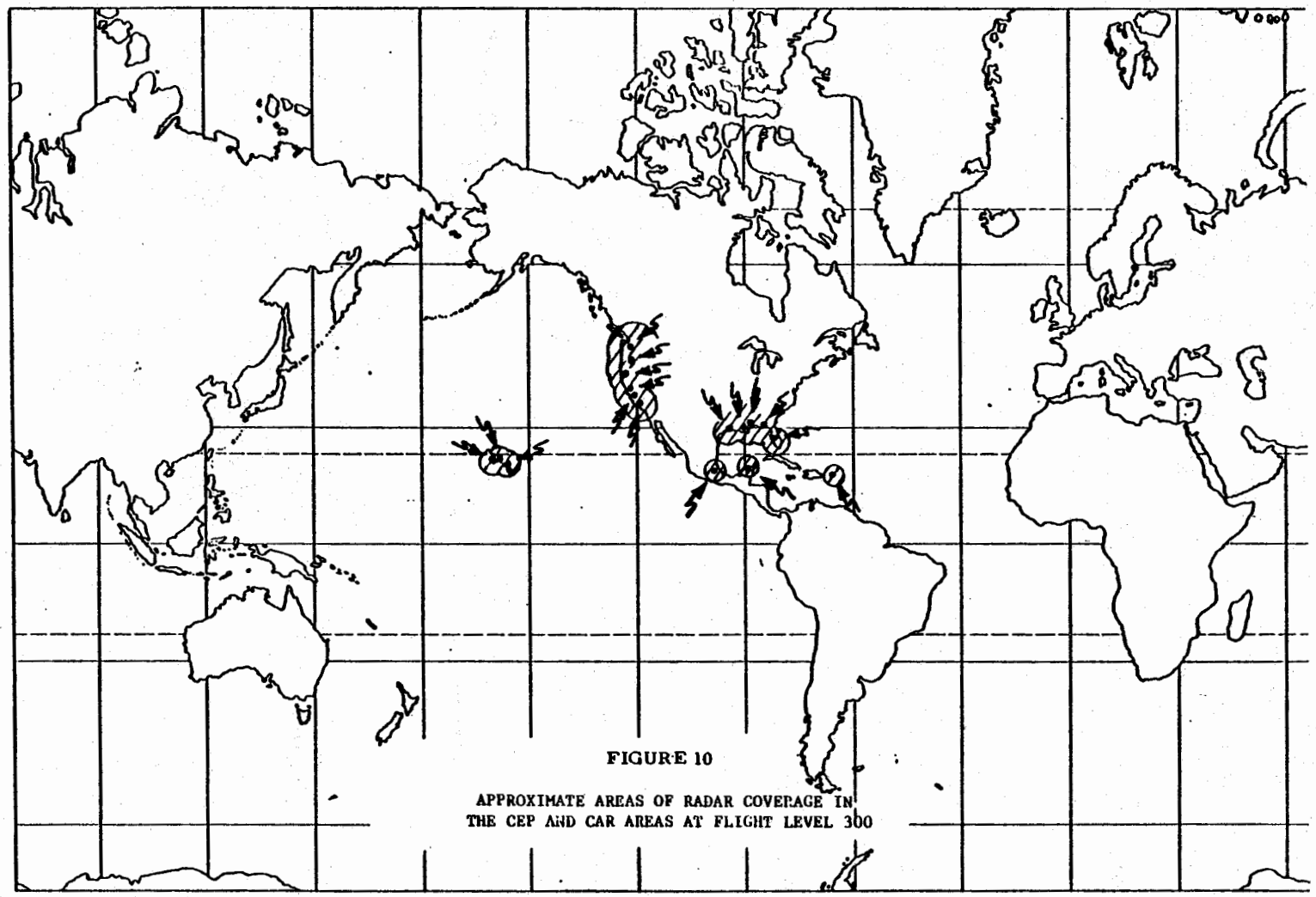

FIGURE 10

APPROXIMATE AREAS OF RADAR COVERAGE IN THE CEP AND CAR AREAS AT FLIGHT LEVEL 300

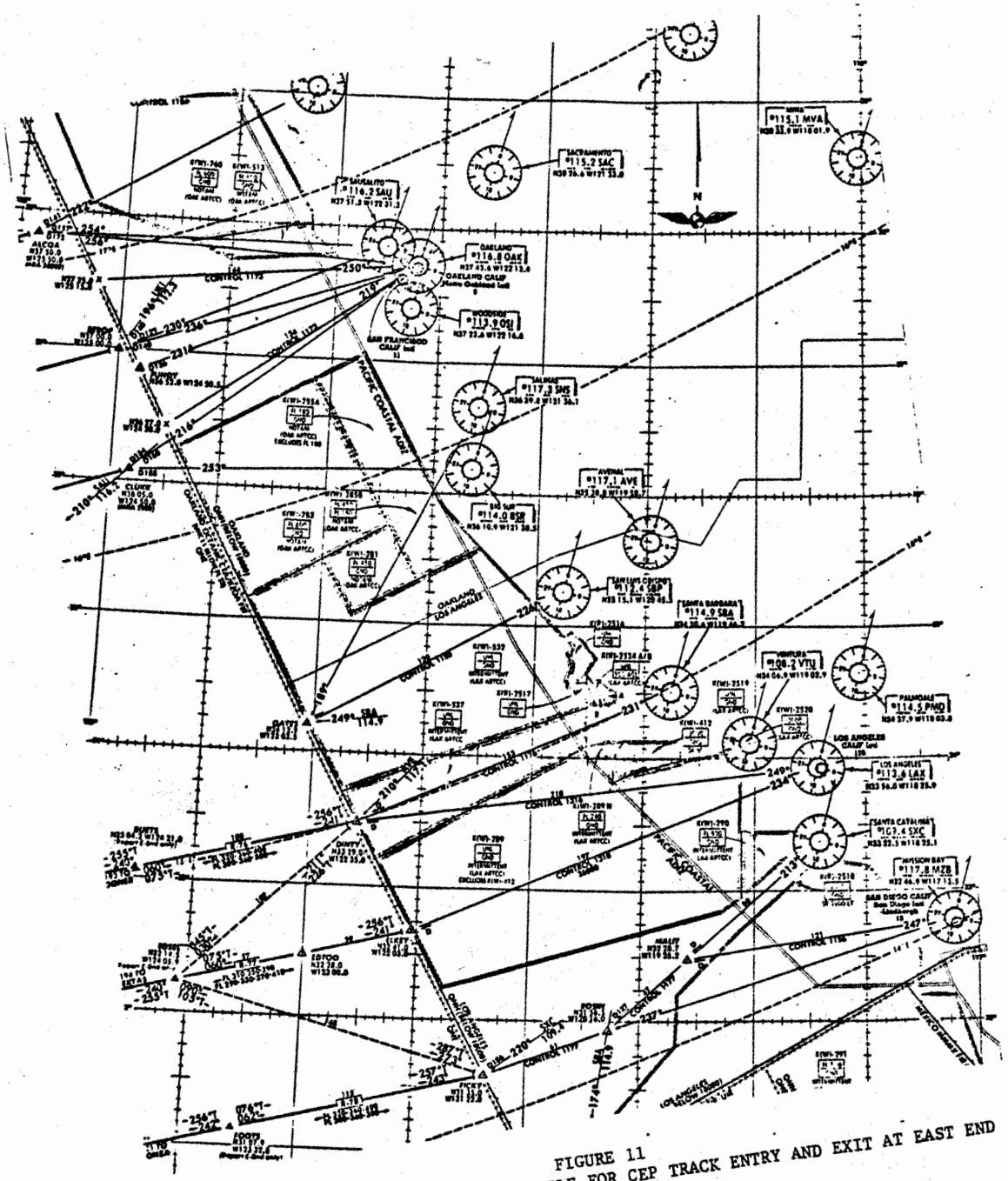

FIGURE 11

LAND BASED NAVIGATION AIDS AVAILABLE FOR CEP TRACK ENTRY AND EXIT AT EAST END

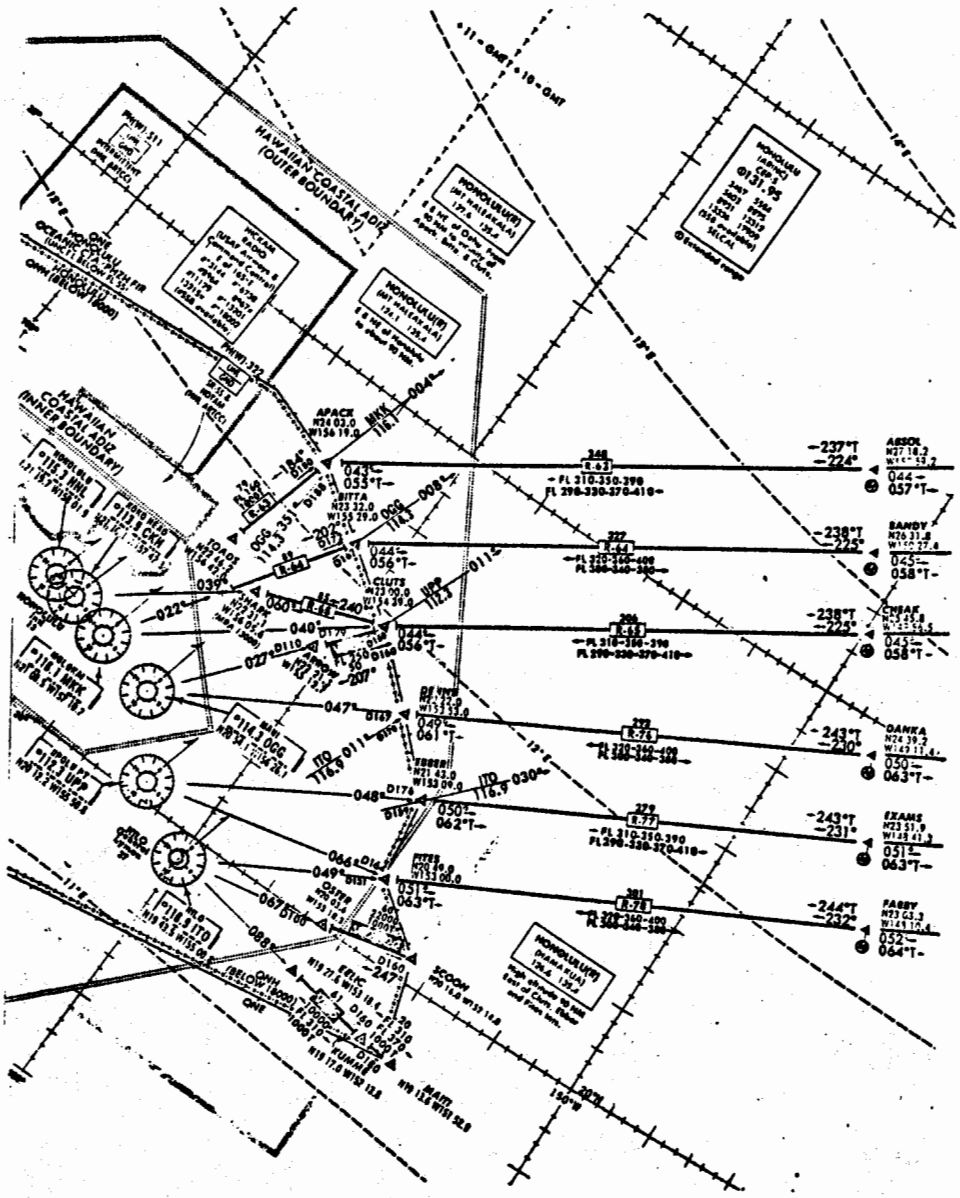

FIGURE 12

LAND BASED NAVIGATION AIDS AVAILABLE FOR CEP TRACK ENTRY AND EXIT AT WEST END

TABLE 7

SAMPLE OF NAVIGATION EQUIPMENT USED IN THE CEP IN 1973/1974
(from Reference 8)

Navigation System	Percent of Sample	Percent of Failures
INS	58.2	1.3
Doppler NAV System	33.9	6.7
Doppler (Sensor Only)	11.6	7.6
LORAN C	12.8	8.4
LORAN A	27.4	1.7
Celestial	21.3	.08
Consolan	30.7	.03

TABLE 8

SUMMARY OF LATERAL DEVIATION DISTRIBUTIONS BY DATA COLLECTION SITE FOR THE CENTRAL EAST PACIFIC

Data Collection Site	Direction of Flight	Number of Observations	Standard Deviation (nmi)	Percent of Lateral Deviation Greater than or Equal to: 30 nmi	50 nmi	75 nmi
Oakland	E	3,435	6.98	0.84	0.35	0.09
Los Angeles	E	4,147	6.79	0.48	0.15	0.02
Honolulu, Pahoa	W	8,478	6.34	0.58	0.05	0.01
Ocean Station Vessel November	E & W	3,543	7.90	0.76	0.17	0.03

5 CAR NAVIGATION

5.1 Routes

Caribbean routes fall into two groupings. There are (1) longer oceanic routes that require very long-range navigation aids (such as INS or Omega) and (2) airway routes served primarily by high-power non-directional beacons and/or VOR/DME transmitters. Approximately 500 scheduled aircraft fly daily in this area. Most fly only on shorter over-water segments in the Miami and Houston FIRs.

Figure 13 depicts the FIRs and many of the CAR routes. Most aircraft can get their desired routes, although desired altitudes are not always available. Since over-water route lengths such as those across the Gulf of Mexico are less than 1,000 nmi, the fuel penalties paid for an unfavorable altitude do not appear to be as severe as on long NAT or CEP routes.

Many of the routes shown in Figure 13 merge or diverge in over-water airspace. Since most of these routes are operated with Oceanic separation minima of 100 nmi lateral separations, 20-min longitudinal separation, and 2,000 ft vertical separation, the total number of routes available in an area is not a good measure of how much traffic can be handled. For example, in regard to the two routes shown in Figure 13 that go from GNI (New Orleans) to TAM and TUX in Mexico, it would be necessary to clear aircraft using one route 20 min or more after a lead airplane had used either route.

A major problem that arises frequently in the CAR route structure is the need to reach cruise altitude before departing radar coverage and entering the high altitude route structure and/or crossing an FIR boundary. Flights leaving the Miami area, for example, must often spiral to altitude before being sent south over Cuba. Heavy jets operated by Eastern Airlines are spiraled as often as twice a week for 14-min periods before being released.

Long routes in the Gulf of Mexico, such as A-6 from Galveston, Texas, to Cozumel, Mexico, or A-49 from New Orleans to Mexico City require NDB navigation over 700 nmi stretches between ground-based radionavigation transmitters. There are several published routes between the New York area and the San Juan area, such as A-23 and A-20, which have 1,400-nmi stretches between the NDB transmitters defining their routes. Most of these routes operate according to oceanic separation standards.

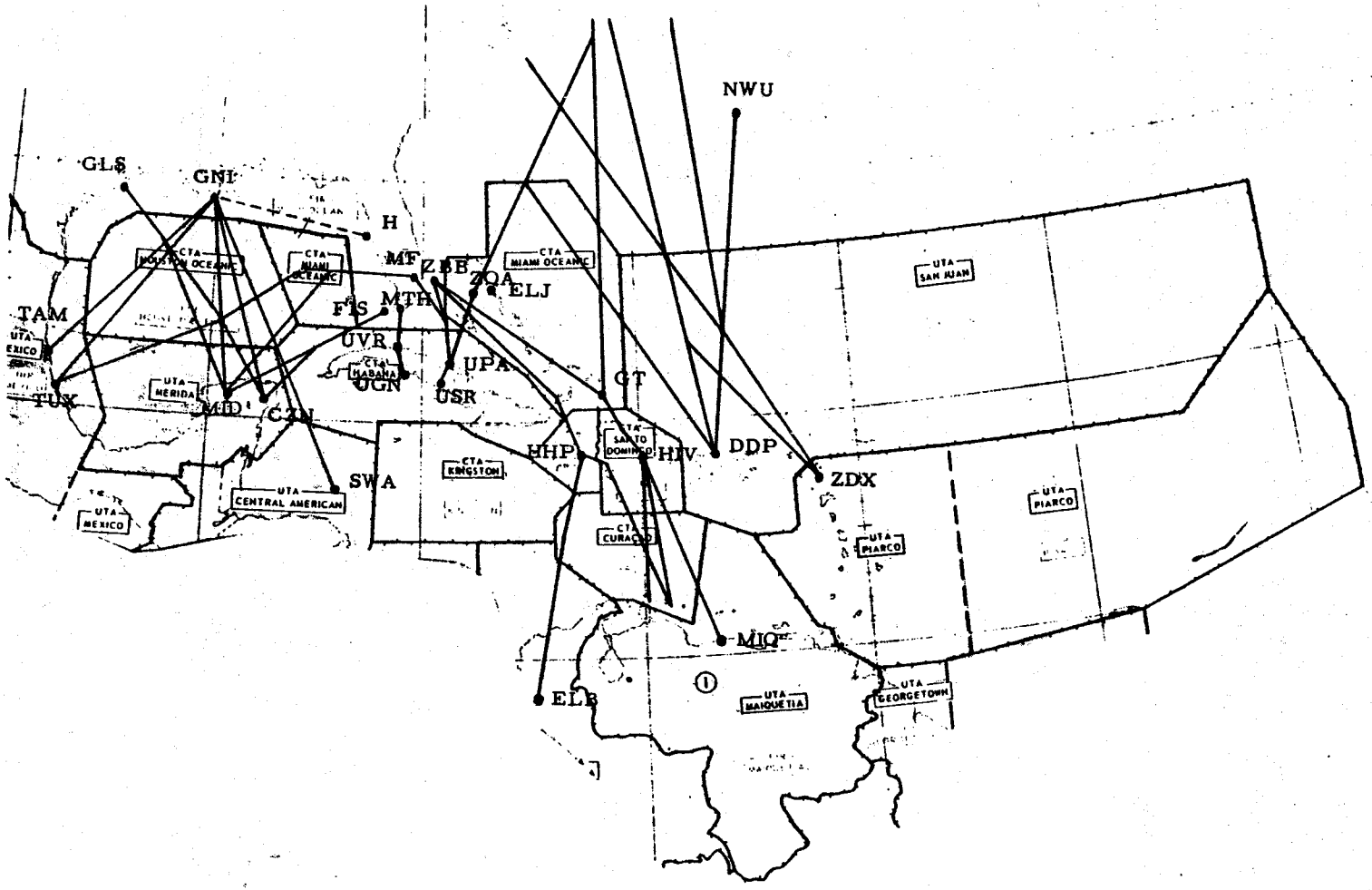

FIGURE 13

SELECTION OF MAJOR ROUTES AVAILABLE IN THE CAR

Piarco and San Juan handle long over ocean flights that fly miscellaneous tracks bound for or coming from Europe and Africa. Much traffic observed in this study moves along coastal areas to utilize accurate land-based navigation services and avoid carrying life rafts and other equipment required for extended overwater flights.

Some aircraft in the Gulf area now request routing not on the established NDB routes, permitting shorter or more convenient flight paths. This can impose problems for a system that, unlike the NAT or CEP, is crisscrossed by fixed NDB routes. The mechanical procedures required to assure oceanic separations can become very complex if steady streams of crossing or merging traffic are all given their requested altitude. Hence controllers use extensive altitude separation and time margins between aircraft crossing the same intersection at the same altitude.

In some cases CAR routes are being flight checked to permit operations that are separated according to domestic standards. Inspection agreements must be made where a route crosses an international boundary. For example, Houston Center has considered realigning A-49, between Mexico and the United States and operating several parallel routes at non-oceanic route widths. This, however, would require joint inspection agreements between the United States and Mexico (Ref. 1).

5.2 Navigation Aids

The primary navigation aid in the Caribbean is the non-directional beacon. The Gulf coast, the Florida east coast, and San Juan have extensive radar coverage in the United States. Merida and Mexico have radar that provides coverage for aircraft in the region of the Yucatan coast according to questionnaire responses from Mexico. Published aeronautical charts show no enroute radar facilities available in other coastal areas. Figure 10 shows approximate radar coverage in the CAR.

The FAA has planned the implementation of secondary radars along the corridor serving Miami-San Juan via installation of remote units on Grand Turk Island and one other location to be determined (such as Eleuthra). Mexico has planned an additional en route radar site between Mexico and Merida to provide coverage of the whole northern Yucatan coast.

Some Canadian and U.S. air carriers operating in and through the CAR have indicated that they carry Omega equipment in that area. Omega and closely related Very Low Frequency (VLF) equipment is being used in the Gulf of Mexico by low flying helicopter operators. Carriers have indicated they have, or are installing, single units.

5.3 Special CAR Control Problems

Visits to various CAR facilities revealed special problems unique to the CAR. These included:

Flight management of low flying helicopters servicing oil platforms in the Gulf.

Operation of very high performance business jet aircraft (often being ferried) by crews with limited familiarity with procedures or required languages through CAR FIRs.

Transport aircraft entering FIRs without prior notice, possibly due to communication limitations.

Many aircraft flying the CAR area prefer to operate VHF only (i.e., they do not wish to carry HF radios), but this can result in operating limitations since VHF reception is marginal in many island areas and across the Gulf of Mexico at low jet altitudes (e.g., 29,000 ft).

In addition, there is some concern that there are insufficient routes to efficiently handle increasing traffic using current separations. Aircraft flying the San Juan-Miami corridor, the North Gulf coast to Mexico City or the Yucatan, and the New York to Caribbean traffic frequently arrive in groups. Such aircraft are generally altitude separated on their requested routes.

5.4 CAR Financial Discussion

Only the most limited financial data is available on CAR costs, so no explicit costs will be presented. The significant costs in the CAR navigation system appear to be the procurement and operation of high-power NDBs. Aproximately 10 key NDBs prescribe routes in the Gulf of Mexico. The East Coast of the United States has approximately five NDBs supporting CAR routes. Approximately another 30 NDBs and 39 VORs ringing the Caribbean define the major routes considered in this study. The extent to which these devices are used as terminal aids and/or the degree to which they support marine navigation is unknown.

The FAA performs flight inspections of some CAR navaids. No separate cost data for this function was available.

A separate document (ref. 9) contains user charges levied in the CAR. These user charges are often lump sums encompassing air traffic services, communications and navigation facilities.

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AC NO: AC 120-33
DATE: 6/24/77

ADVISORY CIRCULAR

DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION

SUBJECT: OPERATIONAL APPROVAL OF AIRBORNE LONG-RANGE NAVIGATION SYSTEMS FOR FLIGHT WITHIN THE NORTH ATLANTIC MINIMUM NAVIGATION PERFORMANCE SPECIFICATIONS AIRSPACE

1. PURPOSE. This Advisory Circular sets forth acceptable means, but not the only means, for operators certificated under Parts 121 or 123 of the Federal Aviation Regulations (FAR) and operators utilizing large aircraft under FAR 135.2, to obtain approval to operate within a specific airspace over the North Atlantic designated as the North Atlantic (NAT) Minimum Navigation Performance Specifications (MNPS) airspace after 0001 Greenwich Mean Time (GMT), December 29, 1977.

2. REFERENCES. Federal Aviation Regulations 91.1, 121.79, 121.355, 121.389, 121.405, 121.411, 121.413, 121.415, 121.427, 121.433, 121.443, 121.445, 123.27, 135.2, AC 121-13, AC 25-4, AC 120-31A and ICAO Annex 2.

3. INFORMATION.

a. The concept of the MNPS was proposed on a worldwide basis at the International Civil Aviation Organization (ICAO) 9th Air Navigation Conference. The objective of MNPS is to ensure safe separation of aircraft and enable operators to derive maximum economic benefit from the improvement in navigation performance demonstrated in recent years.

b. The MNPS concept is scheduled to be implemented on a regional basis, taking into account particular regional operating conditions. At the September 1976 Limited North Atlantic Regional Air Navigation Meeting, criteria for MNPS, and the introduction of these criteria within parts of the NAT Region, effective at 0001 GMT, December 29, 1977, were agreed upon. (This date corresponds to the initial decommissioning of Loran-A in the NAT Region.) The area concerned is designated as the "NAT-MNPS airspace."

Initiated by: AFS-223

c. NAT-MNPS airspace is defined as follows:

(1) Between latitudes 27°N and 67°N.

(2) The Eastern boundaries of Santa Maria Oceanic, Shanwick Oceanic, and Reykjavik Flight Information Regions (FIR).

(3) The Western boundaries of Reykjavik and Gander Oceanic FIR's and New York Oceanic FIR East of longitude 60° W.

(4) Between FL 275 and FL 400.

d. Contingent upon supportive statistical data, the lateral separation of aircraft in the NAT-MNPS airspace is scheduled to be reduced in October 1978, from 120 nm to 60 nm, and the 2000-foot vertical separation retained. For users of the NAT Organized Track Structure (OTS), this should provide additional tracks nearer the optimum track.

e. When establishing the MNPS concept, it was decided by ICAO that all operators desiring to use the MNPS airspace must show that navigation equipment and procedures to be used are capable of continuously complying with the specifications. In the case of operators certificated under Parts 121 or 123 of the FAR's and operators utilizing large aircraft under FAR 135.2, it is the responsibility of the Federal Aviation Administration (FAA) to make this determination. Acceptable means of showing original compliance with the MNPS requirements are contained herein. Continued compliance is the responsibility of the operator.

f. As established by ICAO, the minimum navigation performance specifications required to operate in the airspace listed in paragraph 3c are listed below. [An operational interpretation of the requirement is in brackets after the specification.]

(1) The standard deviation (one sigma) of lateral track errors should be less than 6.3 nm.

(2) The proportion of the total flight time spent by aircraft 30 nm or more off track should be less than 5.3×10^{-4}. [The proportion of the total flight time spent by aircraft 30 nm or more off the cleared track should be less than 1 hour in 1900 hours. (Note that 30 nm is half of the lateral separation; thus, an aircraft with such an error is closer to the adjacent track than the cleared track.)]

(3) The proportion of total flight time spent by aircraft between 50 and 70 nm off track should be less than 1.3×10^{-4}. [The proportion of the total flight time spent by aircraft between 50 and 70 nm off the cleared track should be less than 1 hour in 8000 hours. (Note that between 50 and 70 nm off track is equivalent to flying on the adjacent track.)]

g. If in-flight equipment unserviceability reduces the navigation capability below the MNPS as established by ICAO, Air Traffic Control (ATC) should be immediately advised so that any necessary adjustments of aircraft separation may be accomplished.

h. In evaluating a navigation system for compliance with ICAO MNPS, consideration should be given to maintaining the high level of navigation performance listed in paragraphs 3f(2) and 3f(3). It should be noted that flight time spent between 50 and 70 nm off track [3f(3)] is also flight time spent more than 30 nm off track [3f(2)]. Applicants should consider equipment reliability and a human errors analysis when evaluating a navigation system for use in the NAT-MNPS airspace.

i. To ensure that safety is not compromised through failure of operators to meet the conditions set forth in paragraphs 3f(2) and 3f(3) above, ICAO is establishing procedures for monitoring of aircraft navigation performance using ATC radars near the boundaries of NAT-MNPS airspace. Lateral errors in excess of 25 nm will be reported for investigation as appropriate. Application of the ICAO MNPS requires contracting States to take appropriate action concerning operators who frequently fail to meet the navigation specifications, including restricting flights or withdrawing approval of those operators to fly in the NAT-MNPS airspace. If there is an excessive number of large errors, it may become necessary for ICAO to increase separation standards until improvement has been achieved.

4. OPERATIONAL APPROVAL.

a. General.

(1) Operators certificated in accordance with FAR 121, 123 or 135.2 desiring approval to operate in NAT-MNPS airspace should contact the FAA office that administers their operating certificate a minimum of 30 days prior to the start of the required evaluation.

(2) Navigation equipment utilized and the associated operating procedures are the choice of the certificate holder. The essential provision is that the combination of equipment and method of operation meet the navigation accuracy established by ICAO for operations within the NAT-MNPS airspace.

(3) Data gathered from operational experience with certain equipment now in service, such as Inertial Navigation Systems (INS), have demonstrated the capability of meeting the NAT-MNPS. It is anticipated that dual INS systems can be approved for operation in the NAT-MNPS airspace without

further evaluation if the equipment has been installed, operated and maintained in accordance with Appendix G of FAR 121.

(4) Until more operational experience is obtained, OMEGA, or a combination of OMEGA/VLF, should not be authorized as a sole means of navigation within NAT-MNPS. Either OMEGA or OMEGA/VLF may be used as an update method for another navigation system previously approved by the FAA. If a combination of OMEGA/VLF is proposed as a means of updating another previously approved navigation system, it should be demonstrated that the system is capable of operating with OMEGA only for update information. The combined navigation system performance, not just the updating means, should be evaluated for operation in NAT-MNPS airspace.

(5) Since VLF communication stations are not dedicated to navigation, the use of VLF alone as a means of long-range navigation, or as a sole update means to other methods of navigation, should not be authorized within NAT-MNPS airspace.

(6) Approval to use a navigation system for flight in NAT-MNPS airspace does not constitute approval for that system in accordance with Appendix G to FAR 121. However, credit may be given for flights and evaluations conducted during MNPS certification towards gaining FAR 121 approval.

b. Procedures.

(1) Approval to operate within the NAT-MNPS airspace by use of navigation systems other than that listed in paragraph 4a(3) should be based upon in-flight data acquisitions and in-flight evaluations that demonstrate NAT-MNPS compliance.

(2) Data acquired during in-flight evaluations should be tested for overall navigation system compliance with the NAT-MNPS by use of the statistical methods detailed in Appendix 1.

(3) Data gathering and evaluation flights should be conducted in the NAT-MNPS airspace over typical routes for which approval is requested. However, after sufficient operating experience has been gained, a portion of the flight testing may be conducted as outlined below in paragraph 4b(7).

(4) The flights should be conducted over a period of not less than 30 days to allow for exposure to varying environmental and atmospheric conditions.

(5) The proposed system should be utilized for navigation purposes. However, the currently approved system should be monitored and used as necessary to keep the aircraft within present lateral offset limitations.

(6) A maximum of either two or four independent observation points per flight may be utilized to acquire data when conducting flights through MNPS airspace. These points are:

(a) For aircraft not equipped with INS:

1 Overheading the inbound VOR/DME/NDB gateway.

2 A reliable radar fix upon initial acquisition by ground-based radar as the aircraft approaches the inbound gateway.

(b) Aircraft equipped with INS:

1 The observation points listed in (6)(a)1 and 2 above plus two additional comparisons to INS that have a minimum of 1 hour separation, and are at least 1 hour prior to either fix mentioned in (6)(a) above. Any INS comparison should be at least 1 hour past the outbound gateway.

2 The INS equipment used for this comparison should have shown a composite error rate of less than one nautical mile per hour averaged over the entire flight without any update. The comparisons should be post corrected, based upon the INS error rate experienced during flight.

(7) Flight testing should be conducted in the MNPS airspace over representative routes. Alternatively, flight testing may be conducted over other geographical areas provided the following conditions are met:

(a) In the case of radio-based navigation systems, the applicant shows by simulation or analysis that the radio signal environment in the area used is no better than that in the MNPS airspace. The simulation or analysis of the radio signal environment should include such factors as the number of stations, signal to noise ratio, station geometry, and any other pertinent factor(s). The signal environment in a given location may be artificially rendered less desirable so as to meet the above conditions through manual station deselection in the airborne receiver.

(b) In the case of navigation systems which have errors that tend to increase as a function of time, the duration of test flights should be at least as long as a typical flight through MNPS airspace.

(c) Data points should be separated in time by at least 60 minutes, and should be overhead VOR/DME stations.

(8) If an applicant's equipment (including antenna type and location) is installed on an aircraft in a manner that duplicates the installation and operating performance of the same type equipment installed on the same type aircraft under an existing Supplemental Type Certificate (STC), credit may be given for data available from previous flights with the already approved system. The applicant's operating procedures and training should be

equivalent to that of the operator already approved to use that system in the NAT-MNPS airspace. The credit given is for previously demonstrated navigation system equipment performance. This could decrease the number of flights required to obtain data if a satisfactory level of navigation performance is demonstrated. In this instance, the graph in Figure 3 of Appendix 1 would be used.

(9) Upon successful demonstration of the required level of certainty to meet the criteria, the operator's operations specifications will be amended to permit operations within NAT-MNPS airspace with the navigation system(s) demonstrated.

5. EXPANSION OF MNPS TO OTHER OCEANIC AIRSPACES. In time, MNPS may be imposed on other oceanic airspace. The specifications imposed would be determined by the amount of air traffic anticipated, navigation aids available, etc. Specifications for other oceanic airspaces may or may not be as demanding as those imposed over the North Atlantic. Approval to operate within the NAT-MNPS airspace does not constitute approval to operate within any other MNPS airspace that may be imposed in the future.

J. A. Ferrarese

J. A. FERRARESE
Acting Director
Flight Standards Service

APPENDIX 1. COMPLIANCE GRAPHS FOR NAVIGATION SYSTEMS ATTEMPTING MNPS APPROVAL

1. BACKGROUND.

a. A mathematical analysis was used by ICAO to ascertain that the target level of safety would be achieved in MNPS airspace with 60 nm lateral separation if certain requirements for navigation system performance were met. These requirements were calculated in the mathematical analysis to be those listed in paragraph 3f of this circular. This appendix deals with a means of demonstrating compliance with subparagraph 3f(1) which states that the standard deviation (one sigma) of lateral track errors shall be less than 6.3 nm.

b. An extension of the mathematical analysis was used to develop a fairly simple means for the FAA and the operator to determine whether or not the performance capability listed in subparagraph 3f(1) has been demonstrated.

c. The mathematics used was that of "sequential sampling." This has the advantage of determining when satisfactory performance has been demonstrated as a function of the observed navigational accuracies. Thus, a system which consistently achieves superior accuracies will "pass" sooner than a system which is just marginally acceptable. This is a mathematically sound and more equitable means of compliance than one in which an arbitrary number of flights is set beforehand, and that number is fixed no matter how well or how poorly the system performs.

2. THE "PASS-FAIL" GRAPHS.

a. The "Pass-Fail" Graphs are shown in Figures 1, 2 and 3. On these graphs are plotted successive points of the sum of the absolute value of lateral navigation errors (y-axis) versus the number of independent observations taken (x-axis). Figure 1 is a graph which depicts the entire evaluation process for mathematically determining the acceptability of a navigation system for MNPS operation. Figures 2 and 3 are enlargements of the applicable testing method concerned. Figure 2 applies to navigation systems which have never received prior approval for use in MNPS airspace. Figure 3 can be used to assist in determining satisfaction of MNPS criteria for applicants requesting credit for data gathered during a previously successful evaluation - see paragraph 4b(8).

b. As an example for a system that has never received prior approval, assume that three independent observations were taken on the first evaluation flight. The three lateral navigation errors were 4 nm left of track, 1 nm left of track, and 3 nm right of track, respectively. The first point is plotted at 1 on the x-axis and 4 nm on the y-axis; the second at 2 on the x-axis and 5 nm of the y-axis; the third at 3 on the x-axis and 8 nm on

the y-axis. (Note that the errors always add whether right or left; they do not cancel.) Data points from other flights continue to add sequentially - see Figure 2.

c. As in the sample, the first data points will fall in the "Continue Testing" band. As more data points are added to the graph, a trend will normally develop toward the "pass" or "fail" region, depending on the observed navigational accuracy.

d. Once the series of data points reaches the "pass" line and/or extends into the "pass" region, satisfactory performance has been successfully demonstrated. (Mathematically, the "pass" line was calculated so as to provide 95% certainty that the navigation system meets the MNPS.)

e. If the series of data points reaches the "fail" line and/or extends into the "fail" region, unsatisfactory performance has been demonstrated with 95% certainty. The operator should then either withdraw the application or rectify the problem(s) and start the evaluation flights over from the zero-zero point on the graph. (It is not permitted to restart at a position on the graph which takes into account previous data points where the navigation system was accurate, but ignores previous data points which showed inaccuracies.)

f. It should be noted that the x-axis is labeled "number of INDEPENDENT observations." In this case, "independent" means that navigation errors for two or more successive data points must not be correlated. In order to insure that this procedure has been met, guidance has been given in the body of this circular regarding an acceptable means of taking observations which can be considered independent.

g. Should the sequential sampling procedure not yield a conclusion (pass or fail) after 200 independent observations, the testing should be terminated. The adequacy of the proposed navigation system should be determined by the following Chi-square test procedures

$$D_1 = \sum d_1^2 + d_2^2 + d_3^2 + \ldots\ldots\ldots\ldots\ldots\ldots + d_{200}^2$$

$$D_2 = \sum d_1 + d_2 + d_3 + \ldots\ldots\ldots\ldots\ldots\ldots + d_{200}$$

where d is the value of the individual lateral errors. Positive or negative errors must be consistently applied throughout the sampling procedure. If a deviation to the right is considered positive on one flight, it must be a positive error on all subsequent flights. D_1 is the sum of the square of

each lateral error observed; $d_1^2 + d_2^2 + d_3^2$ etc. out to d_{200}^2. D_2 is the algebraic sum of all of the 200 lateral errors observed. As an illustration, assume that the data in the sample shown on Figure 2 had not yielded a pass result after 200 independent observations. Then, $d_1 = -4$ nm; $d_2 = -1$ nm; and, $d_3 = +3$ nm.

$$D_1 = \sum (-4)^2 + (-1)^2 + (+3)^2 + \ldots\ldots\ldots + \text{etc.}$$

$$D_1 = 16 + 1 + 9 + \ldots\ldots\ldots + \text{etc.}$$

$$D_2 = \sum (-4) + (-1) + (+3) + \ldots\ldots\ldots + \text{etc.}$$

$$D_2 = -5 + 3 + \ldots\ldots\ldots\ldots\ldots\ldots + \text{etc.}$$

$$\text{Variance, } f^2 = \left(D_1 - \frac{D_2^2}{200} \right) \div 199$$

If f^2 is equal to or less than 46.36, the system is acceptable.

Figure 1

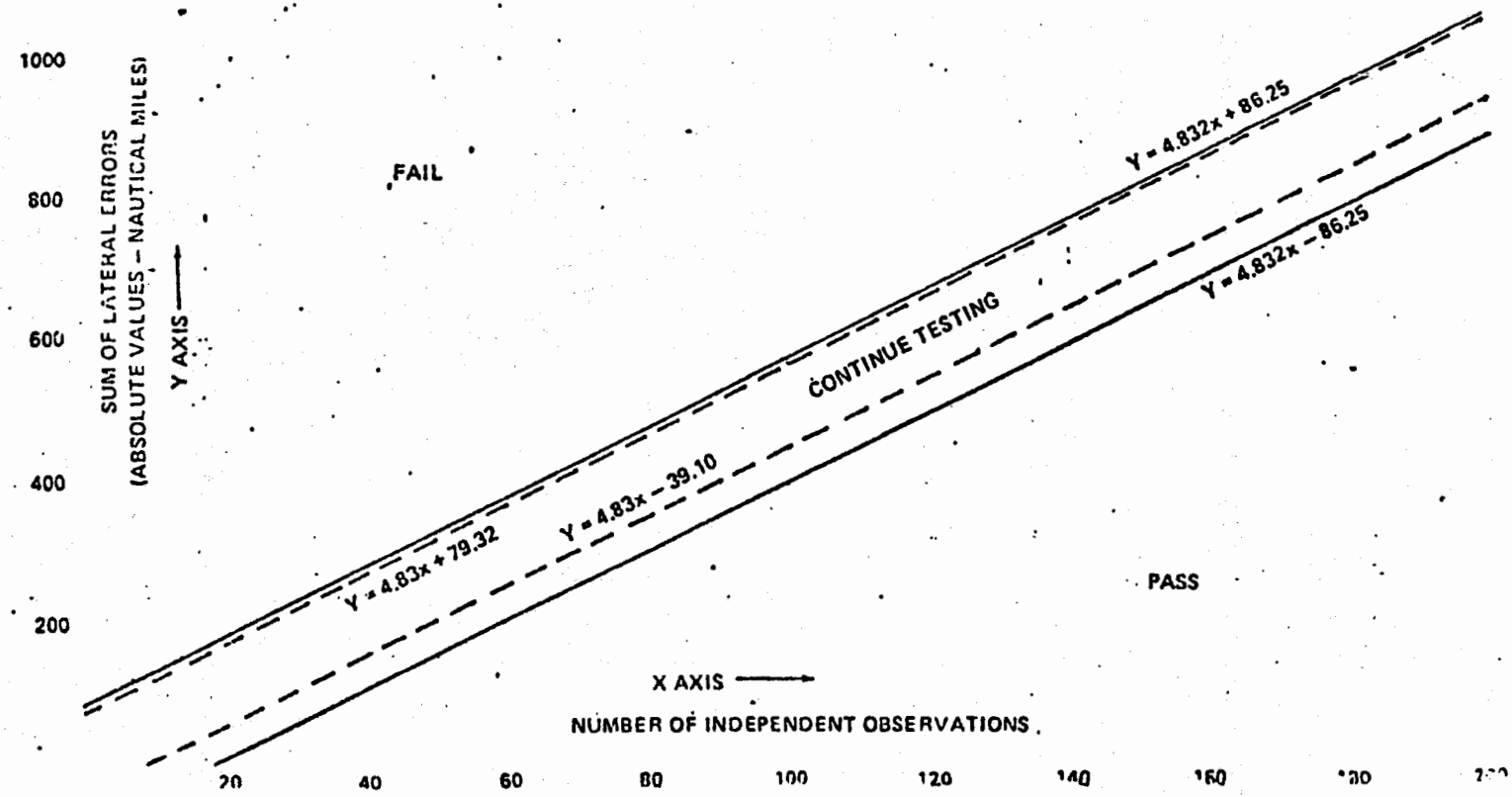
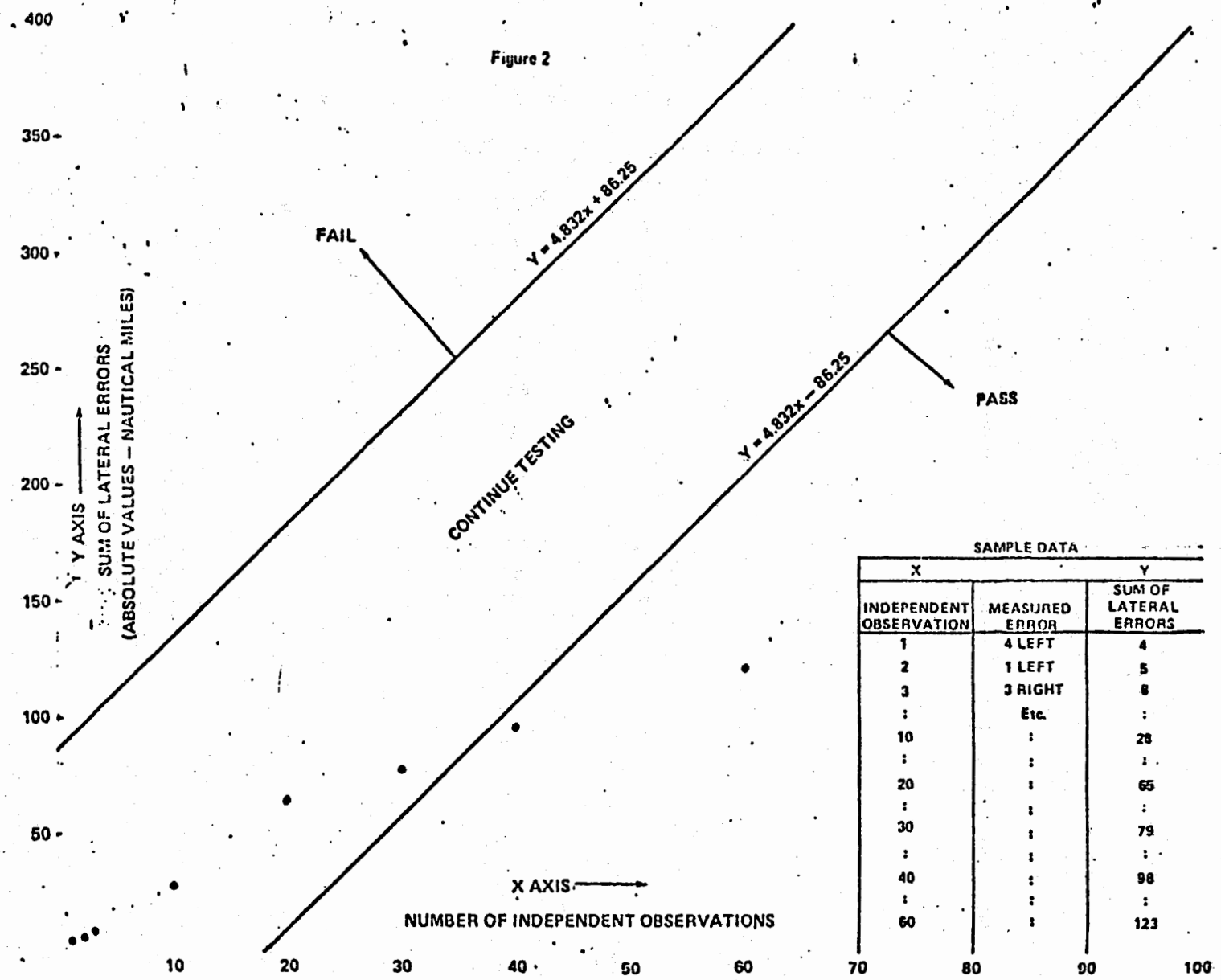

1000
800
600
400
200
SUM OF LATERAL ERRORS
(ABSOLUTE VALUES – NAUTICAL MILES)
Y AXIS
FAIL
CONTINUE TESTING
PASS
Y = 4.832x + 86.25
Y = 4.83x + 79.32
Y = 4.83x – 39.10
Y = 4.832x – 86.25
X AXIS
NUMBER OF INDEPENDENT OBSERVATIONS
20
40
60
80
100
120
140
160

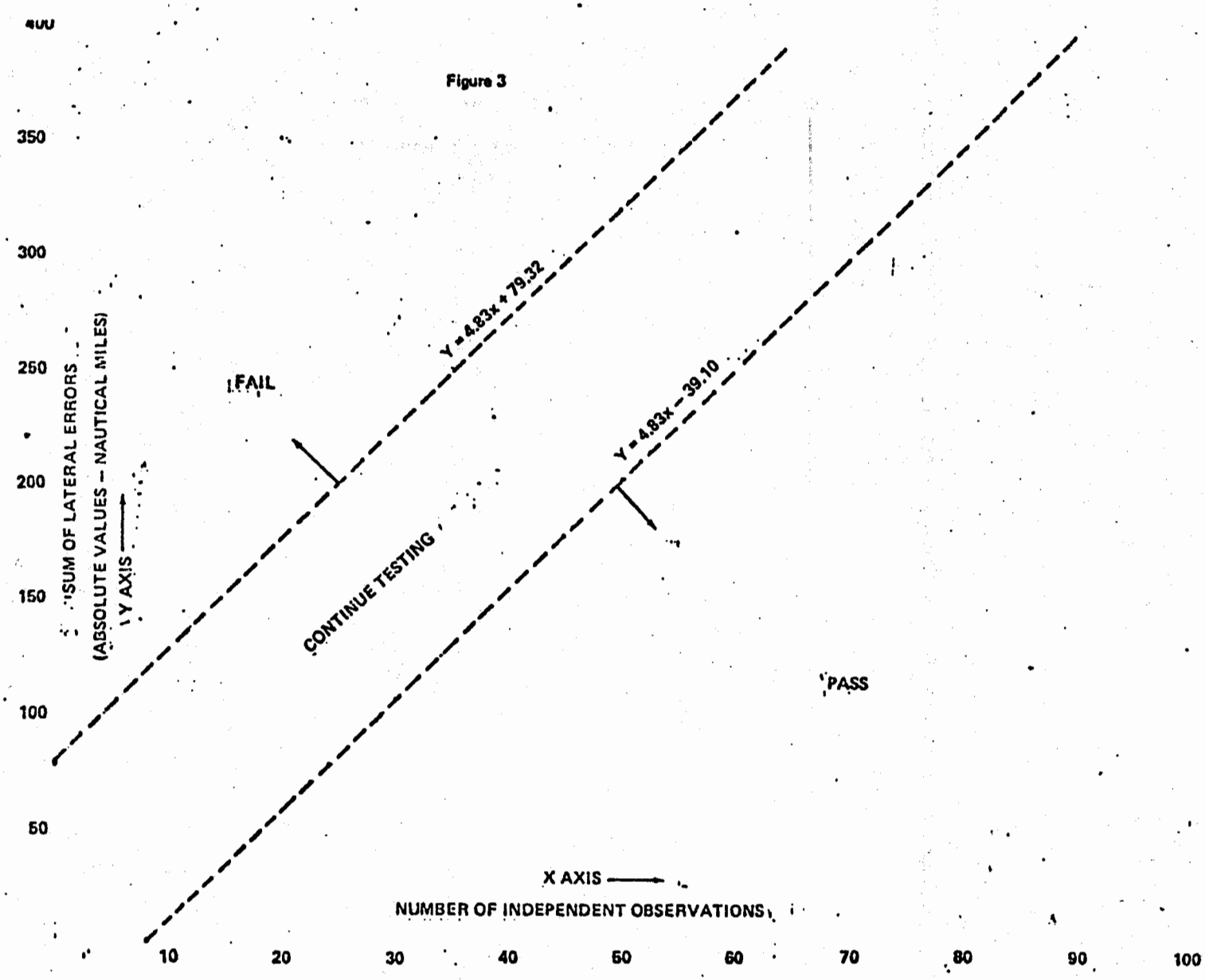
Figure 2



SAMPLE DATA

X		Y
INDEPENDENT OBSERVATION	MEASURED ERROR	SUM OF LATERAL ERRORS
1	4 LEFT	4
2	1 LEFT	5
3	3 RIGHT	8
:	Etc.	:
10	:	28
:	:	:
20	:	65
:	:	:
30	:	79
:	:	:
40	:	98
:	:	:
60	:	123

Figure 3


400
350
300
250
200
150
100
50
SUM OF LATERAL ERRORS
(ABSOLUTE VALUES – NAUTICAL MILES)
Y AXIS
FAIL
Y = 4.83x + 79.32
CONTINUE TESTING
Y = 4.83x – 39.10
PASS
X AXIS
NUMBER OF INDEPENDENT OBSERVATIONS
10
20
30
40
50
60
70
80
90
100

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