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APPLICATION OF VLF NAVIGATION AND AUTOMATIC CALIBRATION OF BAROMETRIC ALTITUDE SENSING TO GENERAL AVIATION AND A NATIONAL UNIVERSAL COORDINATE SYSTEM FOR THE GUIDANCE AND CONTROL OF AIR TRAFFIC

BY

G. B. LITCHFORD

December 1969

Prepared under Contract No. NAS 12-2071 by
LITCHFORD SYSTEMS
Northport, N.Y.

for

ELECTRONICS RESEARCH CENTER
OF
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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FOREWORD

This report was prepared by George B. Litchford of Litchford Systems under Contract NAS 12-2071 with NASA Electronics Research Center. It describes new electronic means for providing general aviation with improved navigation and ATC capabilities at greatly reduced costs. These means are comparable with VORTAC and can be realized by evolutionary implementation over a decade or so.

Although the views expressed here are those of the author, much credit is due Mr. Wm. O'Keefe of NASA and Professor J. A. Pierce of Harvard for encouragement and assistance throughout the study of a difficult subject. As noted on pages A-1 and A-10 the value of this report lies mostly in the improvement of communications among scientists, engineers, pilots, and governmental agencies to determine the value of the suggestions contained herein.

Theoretically, at least, it appears that a national savings (government and private sources), totaling possibly several hundred millions of dollars by 1990, can be realized if the utilization of VLF coordinates for ATC, navigation and proximity warning are validated as feasible. It will cost a relatively insignificant sum to determine the feasibility of this concept. A brief summary of a national VLF system is available to the reader with limited time in Appendix A. Similarly, the means suggested to calibrate the elusive height data sensors, so essential to ATC and collision prevention, is suggested. What is now "open-loop" vertical separation measurements can, with the concepts given in this report, be monitored, calibrated, and safe vertical separation can be assured. Although selected especially for airspace users that are forced to employ very-low-cost equipments (to be cooperative with ATC), these techniques are equally applicable to all airspace users.

I. INTRODUCTION

The objective of this task of Contract NAS 12-2071 is to outline the plans for experimentally testing the VLF concepts of Omega for application to general aviation guidance and control problems. These plans are presented in this report, and the use of the "oblique-parallel" nature of the Omega coordinates for direct Area Navigation are discussed. The potential use of the Bell Telephone Laboratories (BTL) tone data-link for reporting coordinates to the ground or to other aircraft are also examined. Automatic position reporting of Omega coordinates for general aviation usage can provide air traffic control (ATC) data, navigation data, as well as hazard warnings such as, for example, ATC conflicts between like-equipped aircraft. A national aviation time standard is proposed for such functions as a "roll-call" concept synchronized each 10 seconds.

A previous preliminary study by Litchford Systems (reference 1) outlined some possibilities of the use of Omega in general aviation applications. However, several other electronic applications were discussed in the CR-1240 report, and the purpose of this new task is to expand this area conceptually and analytically so that, when testing is contemplated, orientation toward an overall system objective will occur. Recent flight demonstrations (reference 2) by Professor Richard McFarland of the University of Ohio using a small Bonanza aircraft have clearly demonstrated (under a grant from the U.S. Army) the practicality of direct, simple flying of "raw" line of position (LOP) data of the existing Omega signals. The output of an Omega receiver was connected to a course deviation indicator (CDI), and the stations of Trinidad and Forestport, N.Y., were used in the flight demonstrations witnessed by NASA personnel and several others. Undisturbed Omega LOP reception on busy airports, in deep valleys, behind mountains, etc., indicated some major potential advantages of Omega for general aviation application.

Based on the work performed by Professor McFarland and conferences with Professor J. A. Pierce of Harvard University, the concepts presented in this report now have an even more practical and significant meaning than before these simple flight demonstrations were successfully completed. The cost of testing many of the ideas that can lead to an objective assessment of a U.S. VLF navigation system are relatively small. However, at some stage, a great deal of validated data will be needed prior to any decision to take a major, national step in aviation facilities—namely, configuring a compatible but special group of 3 or 4 VLF (Omega-type) stations, ideally located to cover the contiguous U.S. area (the original 48 states).

This addition to the Omega system would be compatible with, synchronized with, and otherwise not competitive but complementary to the existing plans for a world-wide installation of 8 Omega stations. Improved sampling rates needed for aviation application (ATC), accuracy, lower-cost receivers, better "geometrics," simpler receivers, stronger signals covering U.S. only, less diurnal effects, etc., would be the goals and advantages of this new (call it "Omega-A") or modified Omega signal.

The logic behind the specific ground installations, the reduction in long sample periods, etc., require some understanding of the "Basic" Omega program. A good orientation on this subject can be obtained from reference 3. Fundamentally, Omega is a system composed of 8 stations around the world that share time on an intermittent-continuous wave (I.C.W.) frequency such as 10.2 kHz or 13.6 kHz. By measuring the phase angle difference between, for example, the 10.2-kHz signal from, say, Trinidad with that from Hawaii, one obtains LOP's that are "equa-phase" contours, when the relative phase angle of the two 10.2-kHz tone signals is measured. Since each transmitter emits for about 1 second, about 10,000 "zero-phase-crossings" occur. These transmissions are received in vehicles and compared with a common reference signal for phase differences. The long 1-second transmissions are integrated to obtain a precise measurement of each LOP intersecting the vehicle position. This creates some time delay in processing, since the fresh samples are about 10 seconds apart, and with an integration of, say, 3 samples, about 15 to 30 seconds of delay can exist.

For low aircraft speeds this is not too serious, but in high-speed jet aircraft, special "rate" measurements are needed. In precipitation static and other "noisy" conditions, the integration of the thousands of samples (phase crossings) effectively eliminates these problems according to Professor Pierce (reference 2). Some 10 to 14 years of data recorded at Harvard University in Cambridge, Mass., confirm the concepts, which go back 30 years to a Radux system. The significance of the recent flight evaluation of the direct flying of an LOP is significant, since the many other important advantages of Omega from an operational and user viewpoint seem to overcome this disadvantage. Such Omega features as effectively straight LOP's, non-convergence of LOP's, constant heading, constant course sensitivity, constant intercept angles, and Omega "raw" LOP tracks hundreds of miles long are available without continuous frequency and course selection changing as in the VOR.

Because the Omega lanes are organized as ATC criteria naturally require, an air-to-air separation criterion exists (the oblique-parallel nature of Omega). Adjacent air traffic lanes based on Omega have the same sensitivity, separation, etc. One of many VOR limitations is associated with the fact that the origins of some hundreds of polar-coordinate NAV signals are not on a national grid but randomly located for local and often ancient reasons. Many disadvantages of VOR and VOR-DME are circumvented by the inherent uniformity of Omega coordinates and the uniformity throughout the nation. Irregular station spacing, characteristic of a wide area VOR system, is a limitation in Area Navigation. A reading of the TERPS manual (Terminal Instrument Procedures) will clearly demonstrate the limitations of angular convergence, non-uniformity of spacing of polar coordinates, line-of-sight limited navigation facilities, etc. Similarly, an FAA report (reference 4) describes these polar coordinate limitations.

Obviously, Omega needs much development before application to general aviation on a national basis. Meeting a possible $500 to $1,000 price range for an Omega Area Navigation receiver and display typifies the goals of such developments. Such a low cost Omega unit could in the future replace (1) the VOR receiver and displays, (2) the DME transceiver and displays, (3) a polar coordinate-to-rectilinear course line computer (CLC), and (4) a special "Area" display. The total cost of these four VORTAC elements is much higher than that of the airborne elements required for an Omega system. The need to run several tests and evaluations is evident. The purpose of these tests and studies will be to evaluate, quantify, and justify any decision. Otherwise, a rational decision on Omega's use by general aviation is not obtainable. However, the impact of a successful Omega Application to U.S. aviation is enormous, probably saving billions of dollars over 2 to 3 decades and providing the much needed major increase in capacity of ATC-Navigation services.

Since some 300,000 airspace users may be affected (including the military and the airlines), the undertaking cannot be a minor one.

A. <u>ECONOMIC ADVANTAGE OF VLF NAVIGATION OVER VORTAC</u>

At one stage, if the new "Omega-A" stations are installed for a U.S.-only configuration, compatible with the world-wide Omega, then some major expenditures (perhaps as much as 100 million dollars) will be involved. Some several tens of millions more may be involved in other related Omega matters, such as encouraging the design of a really low-cost receiver display with modular design that is suited for mass production. Before reaching this significant decision point (before implementation), laboratory flight tests must be undertaken, brass boards fabricated, monitoring studies performed, measurements made, etc.; this will cost probably a few million dollars.

However, when one looks ahead 20 years to the massive problems facing aviation expansion in ATC, the overloading of the VORTAC system and the SSR system are quite likely. Line-of-sight facilities require ever-increasing numbers of stations to satisfy the demands for capacity and efficient airspace usage. These facilities will survive but they will not supply all the new capacity demands. An alternative must be found that can co-exist and is operationally compatible with the VORTAC and SSR (Secondary Surveillance Radar) to carry the excess load that is mostly composed of general aviation. The need for a major capacity improvement by efficient airspace usage can be filled by new Omega concepts based on the principles established by the flight test results. If necessary, the Omega airways can be exactly on top of a VORTAC airway. However, Omega coverage areas are enormous, since Omega can be received anywhere without special, local ground stations (for the same coverage 1,600 VORTAC's may be needed). Omega reception at any altitude from on the surface up is possible, yet the accuracy is fully checked by ground monitoring. This VLF characteristic is impossible with VORTAC and could minimize or eliminate the continuous VORTAC flight checking now required.

B. ORGANIZATION OF THIS REPORT

This report discusses some of the reasons why the VOR and VORTAC systems can create airspace overload. Perhaps this occurs operationally even before overload occurs in the electrical sense, which is also possible with DME. Because of certain VORTAC geometric shortcomings, ATC growth may be limited by the mid-1970's when new airports and low-altitude coverage requirements expose this constriction. Area Navigation is over 20 years old, but it is only now being applied to VORTAC; yet, Area Navigation may not create the desired results, since the errors of VOR elements are very unpredictable when they must be considered over a full 360 degrees of navigational coverage.

Today we use only selected VOR radials that are monitored and flight-inspected frequently to keep them in alignment. Thus, only about 10 percent of the area cover of a VOR is ever used. The errors can be controlled on these few selected VOR radials. Once the use of 360 radials is authorized (as in reference 4), each required to be exactly 1 degree from the other for full Area Navigation coverage and applied to parallel airways, terminal approach, etc., VOR problems will obviously show up.

We will also discuss some of the pilot display problems and solutions when Omega is used for general aviation aircraft; furthermore, some of the national installation problems are outlined of an "Omega A" system for the U.S.-only coverage. Finally, some detailed tests, evaluations, studies, etc., will be suggested as a means of starting a critical examination of technical and cost areas to justify or void a large step in national planning for civil general aviation facilities. Much of the testing can be done with the existing Omega environment if the tests are highly controlled.

The diurnal effects of the VLF part of the radio spectrum need cautious examination. This aspect of Omega (the diurnal lane shift effect) first appears as a handicap, but in practical (operational and ATC) usage, diurnal effects may be eliminated much as the use of altimeter (pressure setting) reporting eliminates the variables in height reporting, altitude separations, etc. In fact, the proper use of Differential Omega techniques is probably less hazardous than the current use of (differential) pressure altitude height determination. An earlier portion of this report discusses means to also bring height measurement (ATC vertical separation by barometric data) under better control. The two concepts are fully compatible and the same system solution can suffice for both. An automatic diurnal correction signal multiplexed with the Omega signal is also suggested.

Thus, this report covers a modified Omega (U.S.-only) system and the reasons why the VORTAC system and SSR systems will need strong backup for added capacity and complementary support in the near future. Omega can probably achieve this without conflict with VORTAC.

II. A NATIONAL VLF COORDINATE SYSTEM FOR ATC AND NAVIGATION

The existing airways system is fully predicated on the VORTAC system. This system, which was implemented in the post World War II days with VHF Omnirange (VOR) initially, had only radial lines of position that emanated (as spokes from a wheel hub) from selected ground reference points. A so-called "Victor Airway" is the sequential connection of these radials from one station to the next. Such a concept was easy and attractive to initiate, particularly in the late 1940's when ATC problems and the tremendous growth of general aviation and the airlines as we know them today were unheard of.

About 1955, an agreement was reached to co-locate another Omnirange-DME system (operating at L band), so that the two would be co-located and the two airway systems would coincide. This second system, known as TACAN, was started by the military and included (in multiplexed signal format) a distance measuring service (DME) function. Thus, a combination of the DME portion of TACAN with VOR (Omnirange) provided a polar coordinate (or R-θ) system. When only the L band (angle-DME) TACAN is used, this also represents an R-θ system. Since the two systems were co-located, the polar coordinate systems coincide and do not conflict with each other—a very serious worry at the time of the disputes over TACAN that were finally resolved by a so-called VORTAC committee that reported a solution to cabinet level. The obvious civil-military differences were clearly exposed at that time, and the compromise solution was as much political as it was technical and operational.

The VORTAC system and particularly the number of VOR stations continued to grow. The needs for a VOR were probably the most influential in establishing a new navigation facility. However, these needs often were for some localized problem, such as a let-down to an airport or a segment of a Victor airway, and little overall national planning of the multiplicity of overlapping polar-coordinate systems was undertaken. The system simply grew with each CAA and FAA budget, and it fulfilled local Victor airway, airport, and ATC needs without thought for such modern innovations as Area Navigation, ATC vectoring, channelization problems, interrelated geographic (latitude and longitude) reference coordinates between stations, or anything as comprehensive as a nationally integrated set of navigational coordinates that could be used by all.

In fact, the baselines between the VORTAC stations have no pattern such as a rectilinear grid of hundreds of stations, nor were they ever considered in this sense. Had the spacing between the VOR stations been constant, or corresponded to some grid plan, many possibilities would exist for several simple Area Navigation concepts. Only the simple use of the VOR-radial---that is, to fly toward the station after selecting a given radial (VOR LOP) and then to pass over the station obtaining a "to-from" indication---and subsequently flying away from the station (on the reciprocal or perhaps a newly selected radial) are the main applications. Another deterrent to the expansion of VHF systems are the vagaries of propagation at these frequencies. A good VOR navigational signal (360 degrees of precision angular data) needs a reflection-free site. Furthermore, the useful range is limited by the radio horizon. Basic VOR is simply not capable of supplying signals of any quality at large distances or at low altitudes.

When ATC problems became increasingly serious, a standardized use of VOR and VORTAC evolved in what is known as the TERPS. Here, the use of the VOR and DME are described for each localized and specific circumstance. For example, a positional "fix", used for navigation and ATC reporting, can be defined as two overlapping radials from two VOR stations. These crossing radial LOP's define at their crossing a positional fix for pilots. Aircraft on Victor airways may report passing the fix, may be controlled to (but not beyond) the fix, may hold over the fix, etc. This and similar means became (and still are) the fundamental and basic tools of ATC. Navigation is the foundation of ATC. Thus, a poor or limited navigational facility creates a poor or limited ATC system.

A. LIMITATIONS OF VOR AIRWAYS

VOR as a basic ATC tool has many drawbacks for future geographical growth to cope with increased ATC volume and to serve an increased spectrum of types of airspace users. If, for example, one assumes a ±3 degree error for the VOR (as the FAA* and ICAO do on a nominal basis, since errors are greater in some cases and less in others) and assumes that the "fix" is located so that it is 10 miles from one station and 20 miles from another, then the fix is geometrically described so that one dimension is about twice that of the other (Figure 1).

If the fix is at 5 miles to one VOR and 5 miles to the other, and if the geometry of the crossing LOP's is optimized, the "granularity" of the fixing error is greatly improved. It can be readily shown that this uncertainty in "fixing" accuracy can vary in area as much as 100 times, depending on the spacing of the VOR stations, the angle of the LOP overlapping "cuts," and other highly variable aspects of this type of navigation and traffic control.

Since VOR uses a VHF transmission, it is limited to a short range of about 30 to 40 miles depending upon topography and geography. Elevated local terrain has effects such as an obstruction horizon cutoff. Normal radio horizon effects permit re-use of the same VOR radio channels well beyond their respective VHF horizons, but this results in a rather confused means of channelization and usage of the system. This limitation on coverage means that an area like New York may contain as many as 40 to 50 VOR stations to provide all the future navigation and ATC services for the area's growth.

As shown in Figure 2, the ATC system is based on control "sectors" that are defined by earth coordinates made up of the VOR-DME systems in the area. Thus, a pilot must continuously switch frequencies and work on complex geometric relationships

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* See, for example, references 4 and 5 for the following VOR errors: general aviation units ±4.5°, airlines ±3.1°, combined population of general aviation, airlines, military CDI errors ±3.8°—all error figures are 95% probability or 2 sigma.

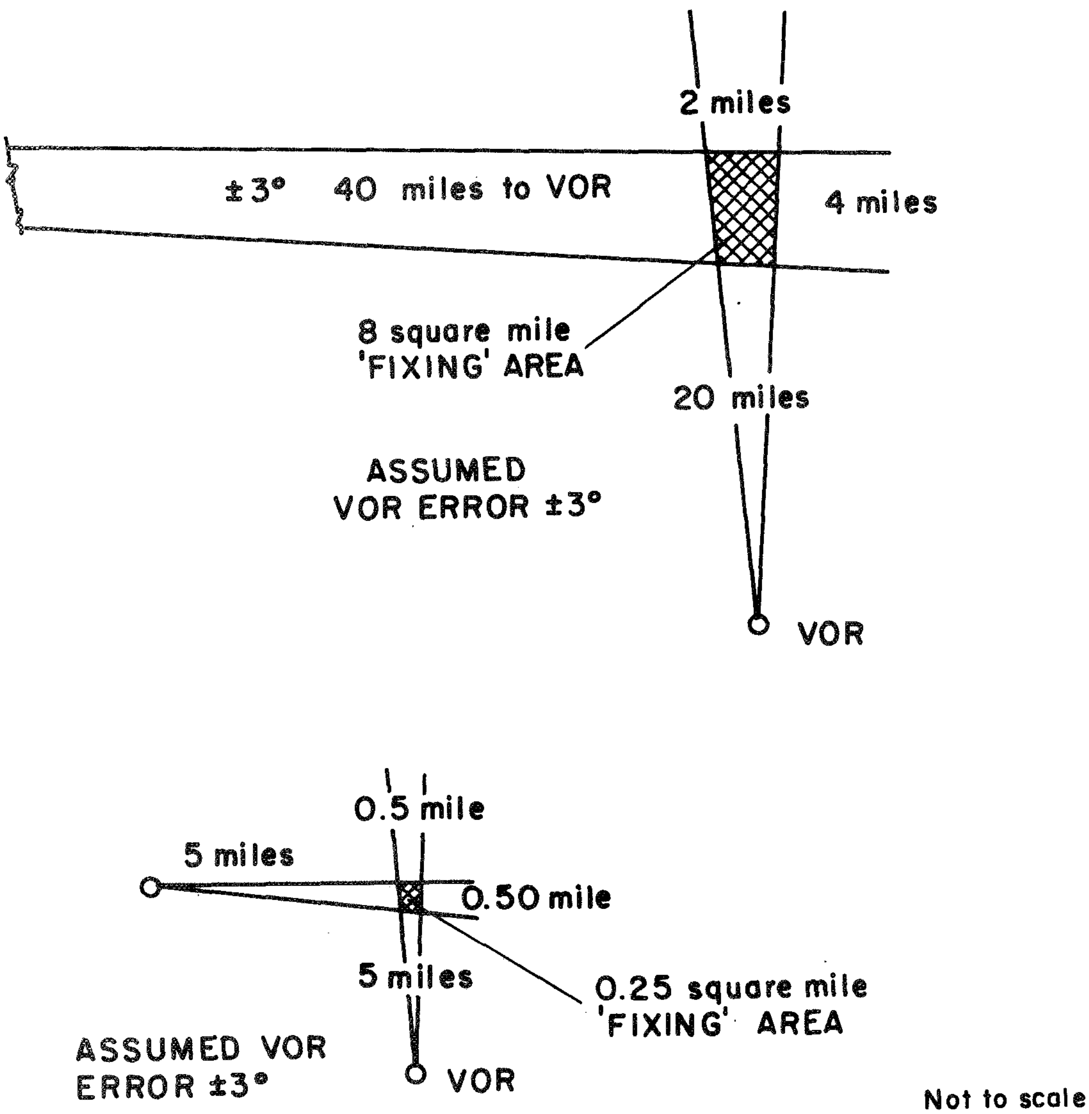


Figure 1.
TYPICAL VARIATIONS OF 1:32 IN ATC FLYING ACCURACIES WITH POLAR COORDINATES

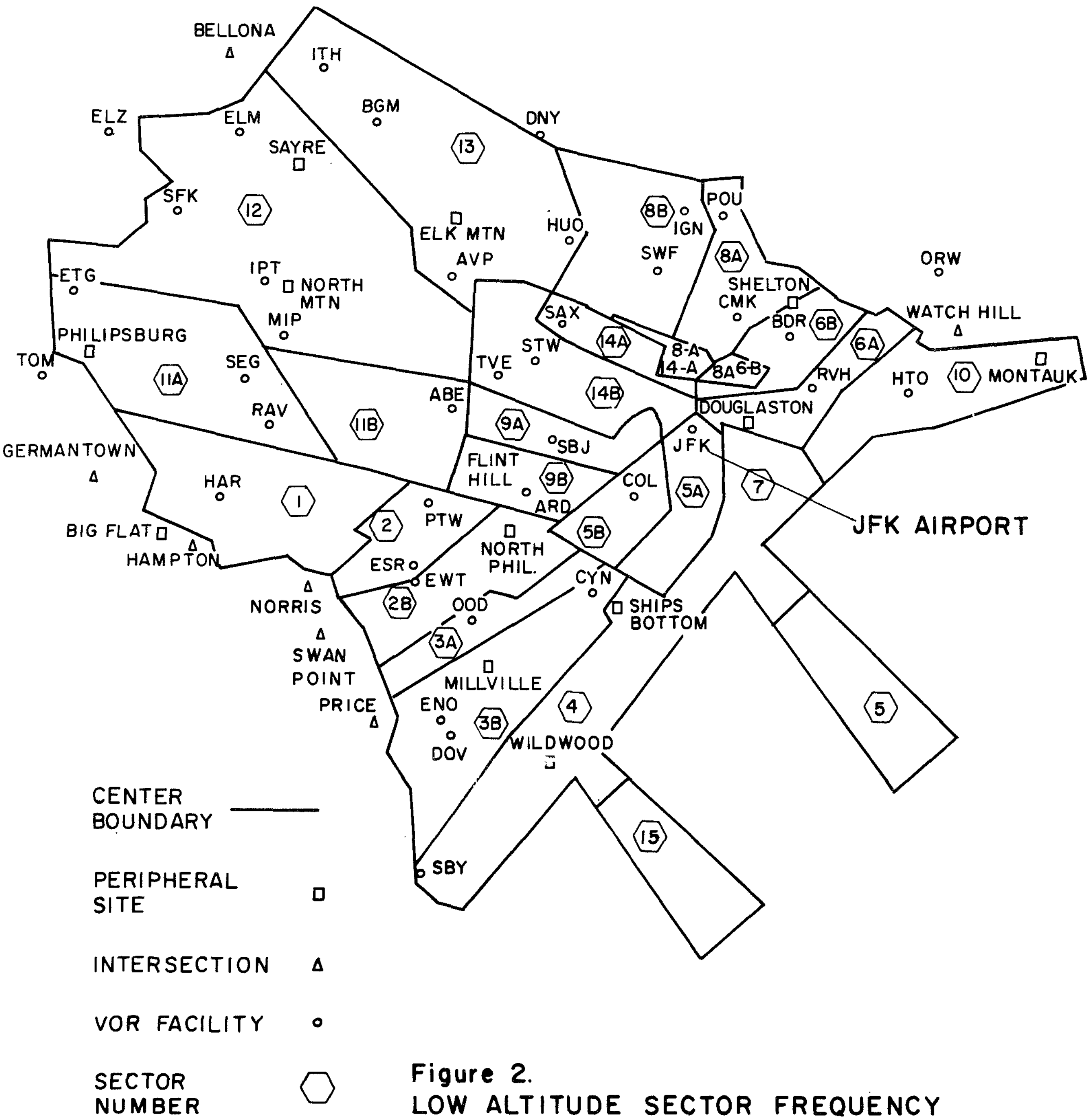


Figure 2.
LOW ALTITUDE SECTOR FREQUENCY CHART OF NY SECTOR CONTROL BOUNDARIES

to obtain reporting "fixes." The ATC ground control is similarly bound by these "sector" definitions, since they are essential to the safety of the operation. Although the SSR system uses a cooperative radar equipment on the ground to "interrogate" an aircraft transponder (for replying to the radar), this is a surveillance system that does not offer any direct guidance or control data to the pilot. SSR is also constrained to the geometry of the VORTAC navigation system, which is the basis of ATC, since only VORTAC provides track and position information to the pilot.

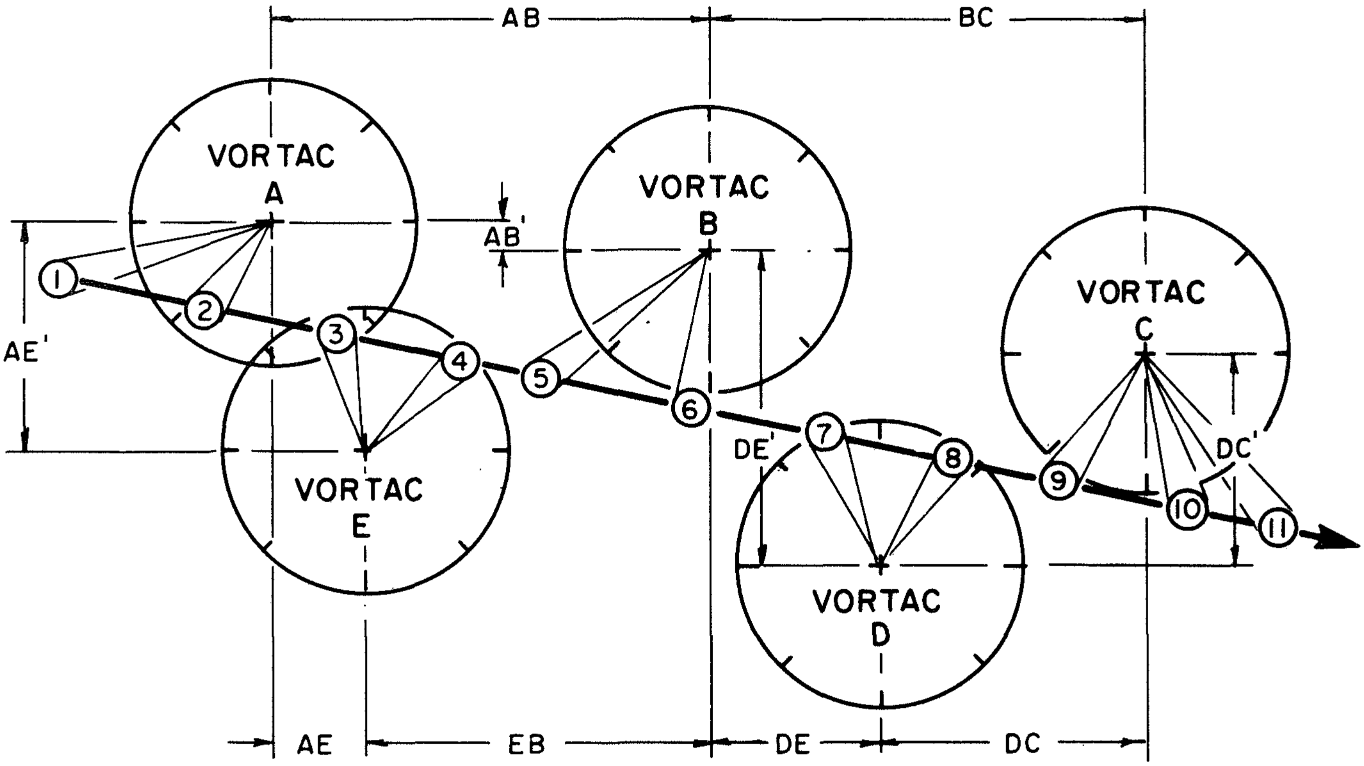
Air Traffic Control is essentially the control of multiple aircraft for efficient and safe movement in a given area. Since each control or instruction must be done relative to other aircraft, obstructions such as mountains and to desired runway approach tracks, ATC must be defined in terms of ground LOP's, radials, ranges, (DME), or both, from the VORTAC network. Thus, the VOR angular dilutions, the wide variation in accuracy, fixing dimensions, etc., must be considered in ATC, and the conditions of large errors are mostly in series with the least error condition on a given flight track.

For ATC capacity computations, we can, therefore, not assume the best "fixing" or positioning accuracy (say, at only 5 miles from a VORTAC station with a ½ x ½ mile fixing accuracy). If this accuracy prevailed throughout the ATC area needing added capacity, things would appear more optimistic or, putting it another way, to assure this accuracy in VOR 4 to 5 times as many stations must be added. Otherwise, completely new facilities, such as PVOR, would be required. Obviously, another 2,000 VOR stations is unreasonable. Thus, the future ATC capacity of VORTAC rests with the multilobe VOR achieving about ½ degree absolute accuracy at all azimuths, not merely an rms of ½ degree by arithmetically averaging 360 degrees of data. Thus, assuming a specific routing in the ATC area, say, from a specified Victor airway to a specific runway on a specific airport, the aircraft will pass through a wide variation of fixing accuracies. To control this aircraft safely and to space it with regard to preceding and following aircraft, essentially the worse (or near worst) case must be assumed (Figures 3 and 4). Otherwise, the spacing and number of aircraft in a given area become excessive with regard to their ability to position and guide themselves so as to avoid other aircraft safely in all parts of the area. The above example of a high accuracy on fixing (½ x ½ mile) must be tempered with a fixing error, say, at 30 miles composed of a crossing (second) VOR at 20 miles or about 3 miles by 2 miles in dimension, or a total of 6 square miles. This "fixing-error-area" compared to the above (area) error of 0.2 square mile establishes a 2400 percent difference. Basically, in ATC where a track traverses a spectrum of fixing and navigational accuracies, all track control will probable assume the 6-square-mile figure rather than the ½-mile figure for obvious reasons. AC 90-45 (reference 4) describes clearly this variation of positioning accuracy with the aircraft track from as low as 1 mile to as great as ±4 miles.

The future growth of the VORTAC concept in the next two or three decades is severely limited by the operational problems of frequent VORTAC radio channel changes, continuous resetting of the CDI for new LOP's and lack of any standardized pattern of multi-station locations, line-of-sight, and overhead signal deterioration. It is admittedly doing a respectable job at present but, as demonstrated by most theories of system capacity, overload and intolerable delays occur with only a small increase in loading when operating in the 80 to 90 percent (of capacity) region. Past growth of 20 percent (say, from 60 to 80 percent of capacity) misleads many to think another 20 percent of capacity is possible beyond 80 percent when, in reality, only chaos and system breakdown will occur.

B. VLF-NAVIGATION COMPARED WITH VORTAC NAVIGATION

We will examine a complementary concept of introducing a new VLF system for use in the contiguous United States based on the experience gained from the Omega system. This new VLF system will extract the best parameters of the Omega world-wide system and will be compatible with both the world-wide Omega and the VORTAC concepts in an evolutionary manner over the next two to three decades. It further will be shown that for the lowest



The area navigation track is illustrated by typical position fixes of 1 to 11.

Position 1 is determined by VORTAC A (range and angle).

Five VHF channels as well as five L-band channels must be used in pairs for accurately tracking fixes such as 1 to 11.

Position 3 must be determined by AE and AE'' coordinates and by VORTAC E range and angle data.

The transition for position 2 to position 3 depends on precise registry of VORTACs A and E.

The area navigation computer must know 4 to 5 digits for each latitude and longitude and it must know 3-digit numers on all VOR angles.

The area navigation computer computes a continuous path from two origins, each with individual errors and random spacing.

Thus, ten precision 4 to 5-digit numbers for station spacing must be inserted into the area navigation computer as well as the track desired in R θ coordinates from 5 randomly located polar coordinate sources using 10 different RF channels.

Figure 3.
COMPLEXITY OF AREA NAVIGATION USING VORTAC

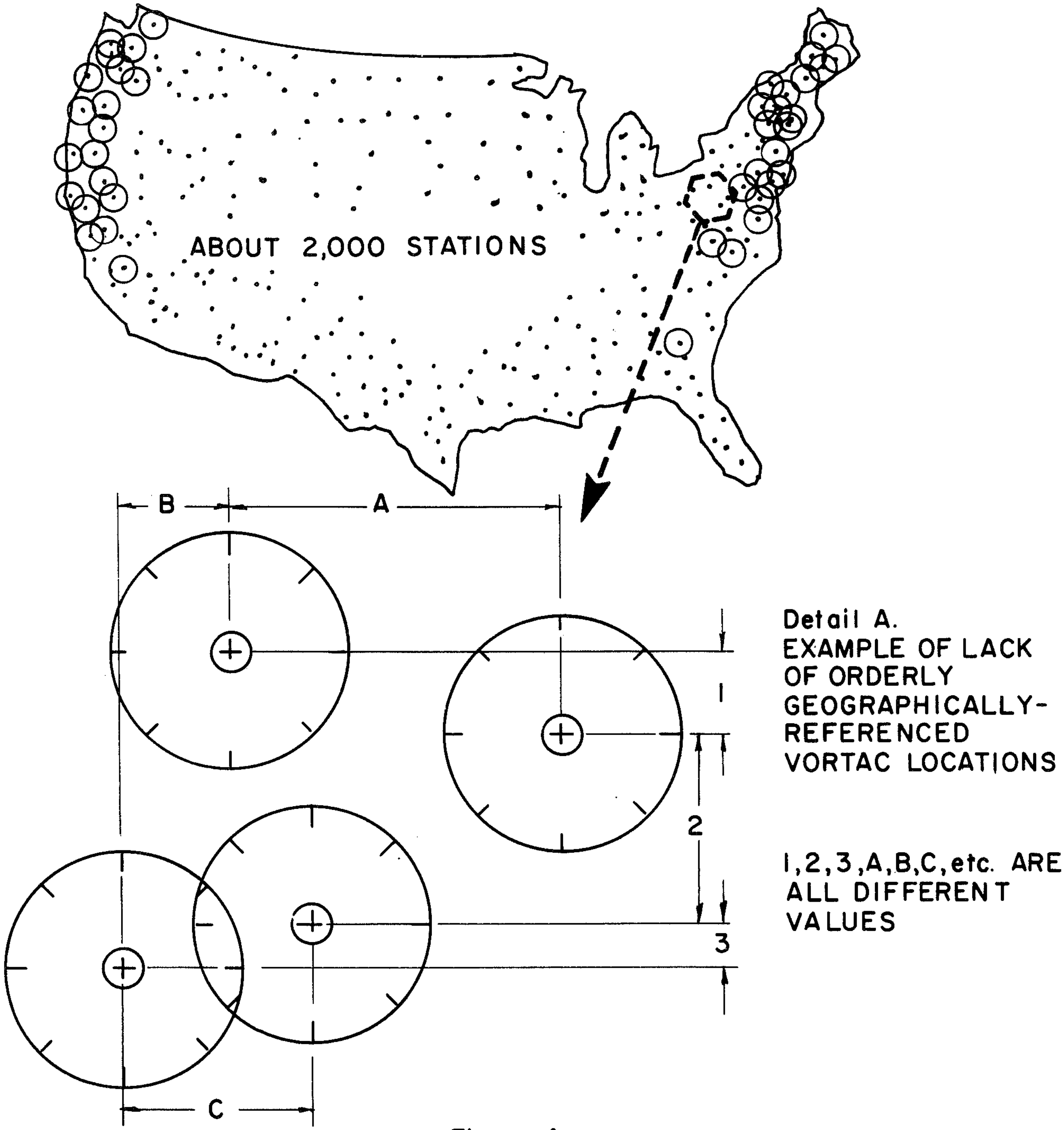


Figure 4.
TYPICAL 1990 DISTRIBUTION OF
VORTAC AND VOR IN THE U.S.

possible user cost, general aviation (even the lowest cost aircraft) can be provided full navigation, automatic identity reporting, automatic position reporting, and some form of proximity warning. All this information will be derived from VLF coordinates in a total-system approach that is compatible with national plans for extended, centralized, ground-based ATC authority. Both the airlines and general aviation can utilize the dual LF/VORTAC concept in harmony, creating an overall marked increase in usable airspace and ATC capacity, and making allowance for growth in the populations of all users of the airspace. Thousands of small airports will have improved services with the VLF "all-altitude" coverage. The 300,000 general aviation and perhaps 5,000 airline aircraft that are projected for the 1985-1990 time frame require urgent action in the early 1970's since extensive, politically complex and long development and implementation cycles exist for such navigational facilities.

Although VOR can be improved (as is now under way with the doppler techniques, state of the art antennas, multi-lobe, azimuthal patterns, vertical directivity, and similar techniques for improved angular accuracy), the fact remains that some 1,200, 1,600, or perhaps even 2,000 stations will possibly be needed by 1990 to "cover" the nation adequately. This is an enormous burden to carry forever since operation, testing, modernization, etc., of each and every station has occurred in the past and will continue in the future. An enormous annual VORTAC operating and maintenance cost already exists. The costs for modernizing and relocating existing VORTAC's, adding new VORTAC's, and the annual maintenance and flight test figures (projected for two to three decades) can amount to several billion dollars.

With but 4 properly located VLF navigation stations, the entire United States can be blanketed with redundant navigation data consisting of 5 to 6 LOP's (actually only 2 are necessary). The Omega coordinates (locally) have a constant granularity, offer simple, direct LOP flying, and avoid channelization problems; furthermore, they cost the general aviation aircraft about ½ the VORTAC costs (see Figure 5 for a summary comparison).

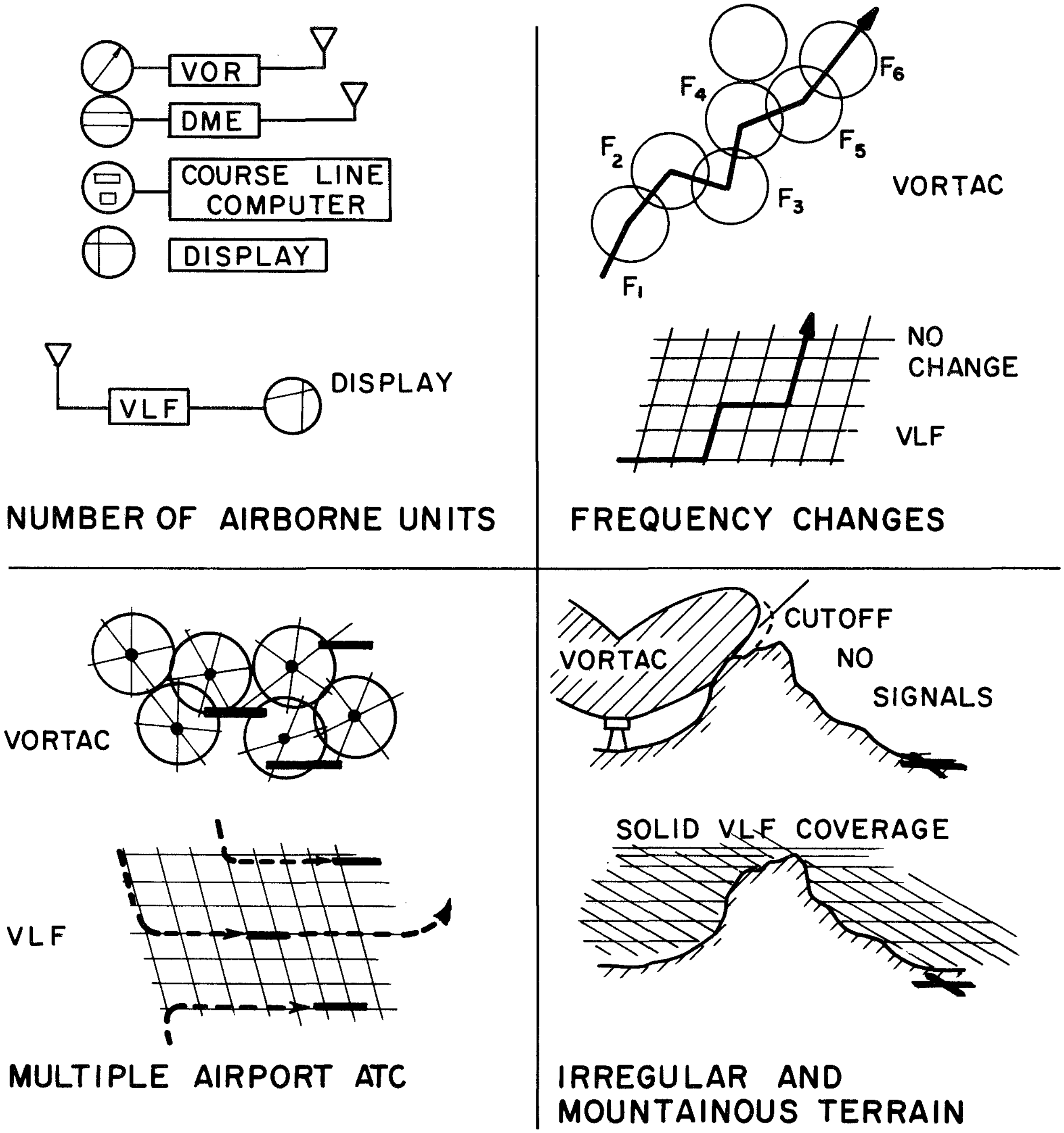


Figure 5.
AIR TRAFFIC COMPARISONS OF
VORTAC vs VLF

Reducing the needs for the expansion and modernization of VORTAC to only essential ones (say, 400 stations) and taking up the slack with VLF Omega can create large savings, increased capacity, and ease the "crisis" of general aviation. We will examine some of these virtues of the VLF concepts shortly, but we should first look at the details of wide scale implementation of VORTAC concepts.

C. AREA NAVIGATION USING VORTAC

For many years, polar coordinate "converters" or computers have been built that will modify the range and angle data from the point source of the VORTAC station into any flight track or course line that may be desirable. These have appeared in the form of "Course-Line Computers" (CLC), pictorial displays, R-θ converters, and such trade names as VAC (Vector Analog Computer), and "Omnitrack." In each case the following general elements are essential in addition to the basic VOR receiver in the aircraft.

I

An airborne distance measurement equipment (DME), consisting of an L band transmitter and an L band receiver with crystal-controlled channelization for about 80 stations. These stations must be interlocked with VOR channelization so that range and angle come from the same ground point. To supply DME service, an added ground element is placed at every VOR consisting of a complex high-power L band transmitter-modulator-antenna combination.

II

An airborne range-angle computer that is in the form of a small digital computer or an analog-servomotor system. This VORTAC Area Navigation element, though it appears to be simple, is complicated by the fact that the angular errors must be tempered somewhat with range and that the coordinate positions of each VORTAC ground facility must be inserted exactly if it is to be related to any other ground reference points (such as referencing two or more VORTAC stations to each other). Approaching airports on computer-defined airways requires complex geometric referencing and computing. This results in a somewhat complicated and costly airborne R-Θ computer device. A very low cost CLC sells in the region of $3,000, a cost to which must be added a VOR receiver display and DME interrogator display element (see Figure 5).

III

Pilot display of VORTAC area information is not as simple as the display of VOR information, since in Area Navigation an entire area is usually displayed rather than a simple display of Victor airway track deviation which is possible in the normal cockpit instrument typified by the omni-beam indicator (OBI) and the course deviation indicator (CDI) (ID-249 and ID-250). Normally, a servo-driven map-chart display (or other complex display media) is utilized for VORTAC Area Navigation--for example, back-projection screens, CRT, etc.

IV

Only computer track data is displayed in the Area Navigation display for the pilot to follow. "Raw" data must also be displayed to him to avoid possible computing errors and to assure the validity of inputs to the CLC. This credibility assurance requires a VOR "raw" display, DME "raw" display, channelization of VOR, channelization of DME, and some form of test signal to assure that this combination of some 10 elements is working. For safety reasons a failure of even one element cannot be permitted in Area Navigation. To detect a failure immediately, raw VOR-DME and course data are as essential as the Area Navigation display. It is likely that in dense traffic IFR authorizations dual DME, dual VOR, and dual computers will be required for pilot convenience in going from one VORTAC to another without loss of track guidance or in case a failure of any of the 3 critical elements occurs.

These four additional elements required for converting the simple VOR system into an "Area Navigation system" are in reality only a localized-Area-Navigation system versus a wide-Area-Navigation system (such as we will examine shortly). The ground and airborne equipment costs of VORTAC Area Navigation and compatible Area Navigation ATC equipments prohibit the majority of general aviation from benefiting from their use. This is likely to remain so indefinitely, creating a dilemma because "area" usage rather than "radial-only" usage is necessary to increase ATC capacity on a national basis.

Although a good VOR receiver for general aviation use can be purchased for around $700, the DME is in the $1,500 category by the time it is installed and locked to the VOR channelization scheme. The computer element is another costly item, in the $3,000 to $5,000 region. This is based on such simple display products as the VAC, which typifies probably one of the lowest-cost and rather ingenious approaches. Once Area Navigation is widely used, dual VOR and dual DME will be required for adequate operational flexibility and to assure a recovery of an aircraft in closely spaced multiple aircraft situations. Furthermore, if multi-lobe VOR transmission is eventually required to obtain better accuracy, this will require additional airborne equipments and possibly new VOR receivers of greater cost and complexity. Essentially, the general aviation pilot and/or owner will have to pay a price of about 5 to 10 times the cost of VOR-only to enter and enjoy the benefits of VORTAC Area Navigation and ATC. The SSR transponder (ground surveillance and proximity warning) can be even more valuable in ATC and costs about $1,000.

This high cost of expanding the capacity of ATC by means of Area Navigation and SSR is completely acceptable to the airlines because it offers greater utility of the aircraft and the airspace; furthermore, greater safety and expedition is offered by the ATC authority to those who use the three additional Area Navigation elements (in addition to the VOR). An airframe cost of 4 to 20 million dollars can justify several of these additional features in the avionics, because some rewards and benefits come from each added cost. By 1980, airline electronics may cost about $750,000 per aircraft.* An owner of an airframe

* Page 262 of the 1969 House Hearings on Aviation Facilities Maintenance and Development.

costing less than $15,000 cannot justify an additional $8,000 to $10,000 to install Area Navigation equipment based on VORTAC, because it is not economically viable in most cases. It is probable that features in addition to Area Navigation [ATC, Identification, altitude-reporting, proximity warning of nearby aircraft (PWI), etc.] can be engineered into an integrated, single, airborne avionics unit using modern, total system concepts that will produce in an aircraft services capable of all these functions in the cost region of from $1,000 to $5,000. A limited basic unit would cost possibly $1,000 to $2,000.

D. <u>AVOIDANCE OF "SLANT-RANGE VORTAC ERRORS" WITH VLF NAVIGATION</u>

Another interesting by-product of the VLF national navigation system proposed in this report is the avoidance of the complexities of correcting VORTAC slant-range errors. Since the DME portion of VORTAC measures only slant-range, the computed Area Navigation airways (at high or medium altitudes) that come near the station are in error. Reference 4 requires the elimination of slant-range error in the design of the CLC or Area Navigation displays. This infers a three-dimensional computation since, in addition to VOR and DME data, height data must be entered into the computation of the horizontal track position.

With VLF, the signals are effectively the same at all altitudes as well as on the surface. There may be some slight vertical curvature of a VLF position signal; this error, however, will be far less than, say, the 4 miles of slant-range DME error created by an aircraft passing over a VORTAC station at an altitude of 24,000 feet. Even in the general aviation CLC design, this VORTAC correction must be included by 1971. In VLF LOP flying, there is no requirement for correcting slant-range errors. This is done because these errors do not exist in the same geometric sense--that is, in VORTAC the errors vary considerably with altitude and position and are complicated by a multiplicity of individual referencing points. In fact, the "differential," "composite," or the "centralized" automatic diurnal corrections of VLF navigation data will compensate for all errors in the system on a total national basis. Thus, VLF avoids this serious complication of VORTAC.

E. THE DILEMMA OF VORTAC EXPANSION AND LONG-TERM FUTURE USAGE

Every effort must be made to sustain the present VORTAC system and even to retain it as a complementary system in the future. Criticizing VORTAC does not infer its destruction but illuminates its limitations--limitations that must be supplemented by other more productive and less costly means. However, with the previously discussed limitations and others not detailed here (such as the fact that no new VHF channels can be made available), the future growth and commitment to this facility for another two to three decades is obviously limited. It will take at least 5 to 10 years after the decision has been made to implement a new service before this service (such as a new national VLF facility) will become operational. However, hopefully, the VOR and VORTAC with some limited modernization can carry the load until then.

To fully understand the dilemma of VORTAC expansion and long-term future usage, the concept of "queuing-theory" delay must be identified. Essentially, this well-known concept states that delays or denial of service at a traffic load which is 90 percent of capacity will be many times those experienced at 70 percent of capacity--that is, as the full VORTAC Area Navigation system capacity is approached, the denials and delays do not increase linearly but rise at astronomical, compounded rates near 90 to 95 percent of capacity. The system breaks down as far as its design capacity is concerned when demand approaches the full capacity of the system. There are well known mathematical analyses of similar systems, well validated by sad experiences. Telephone exchanges, airports, tunnels, highways, etc., clearly demonstrate this phenomenon; thus, it cannot be avoided by regulation but only by total system planning with major increases in capacity. Accuracy, coverage, channelization, costs, complexity, and number of ground installations all combine to limit the practical, realizable capacity of VORTAC.

However, many planners and regulators do not realize these facts or assume that somehow they will be voided in their particular instance. This will not be the case in aviation use of VORTAC because its definition of the airspace, its geometric limitations, number of possible radio channels, propagation characteristics, etc., have identifiable limits that will probably be exceeded by even the 1970-1980 projections of aviation growth. The increase in air traffic of 300 percent can simply not be handled efficiently without excessive delay with such a system as VORTAC, and a supplemental and complementary system must, therefore, be introduced.

Since the time it takes for development, implementation, and usage can easily be 5 to 10 years, an immediate search for a new, high-capacity facility without these various constraints on growth must be undertaken on a large scale, commensurate with the obvious penalties if such a facility is not provided. This implies a single, identifiable program costing perhaps a few million dollars per year for development. Implementation costs of 100 million dollars for 5 VLF-Navigation ground facilities would be a small fraction of the cost of modernizing 1,000 to 2,000 VORTAC stations over the next two decades.

F. INTEGRATION OF VOR AND VLF OMEGA FOR GENERAL AVIATION

The large-capacity Omega navigation facility (operating at VLF and costing less than $2,000 to $5,000 for the airborne equipment implementation in small, general aviation aircraft) offers another national LOP system for providing fixed navigation and guidance to integrate the randomly dispersed VOR stations so they could all be tied together in a national grid or lattice. Effectively, the VLF-Omega "A" (new, U.S.-only, 4-station system) will provide the function of the current DME with superior performance and without many of the DME's limitations (pulse loading, channelization, lobing, line-of-sight operation, interference, etc.). Once installed, this VLF lattice (coordinates) would be monitored and controlled by so-called "differential" or "composite" techniques using the interlocked VOR system voice channel to eliminate the diurnal shift of the lattice on an integrated national basis. A centrally located VLF station could provide the phase-coded message for automating this diurnal data; thus, all receivers or all differential sources could be corrected from one central point in the nation. The percentage of diurnal shift in 10 minutes is relatively less important than the percentage of shift of the barometrically defined vertical separation criteria.

The use of continuous, barometric corrections for providing vertical separation is an exact equivalency of the VLF differential system. Both can be easily corrected by voice or automatically in the new system concept. Certainly vertical separation will remain the greatest tool in the inventory of ATC devices for the control and safe separation of aircraft. Altitude monitoring and operation of the VLF system would both be semi-automatic to eliminate the known variations that exist. Outlines of this technique and programs to test and develop the optimum means for implementing them will be discussed. However, a national manual (non-automatic) condition can be made by using a simple Omega receiver at each VOR station. This reading would provide periodic (every few minutes) corrections orally or electrically, whichever is desired.

Thus, the VOR should be retained by general aviation and supplemented with a low cost (equivalence of a VOR receiver) VLF Omega receiver. This added unit will then provide an equivalence of a dual VOR and a DME and will use the national time-sequencing of Omega stations, relayed on VOR for certain functions, for a "total" timing. Such a system concept permits the use of "roll-call" identity and aircraft reports (using VHF tone data) of altitude and position. Furthermore, with the use of these combined Omega-VOR coordinates, a simple PWI will be provided as possibly a suitable low-cost collision avoidance system.

Air-to-air signaling to maintain optimum separation on common tracks, though not a PWI or CAS function as such, is still very effective in adding capacity by eliminating today's complex "rate" and flow control techniques that are inefficient in airspace and radio spectrum consumption. These two (VOR and

Omega) concepts are mere elements of a larger "total" ATC system plan including new landing systems and other elements and must all be tailored to this end. No single element can be considered an end item in itself with its objective being a significant change in the national ATC-IFR system and facilities.

Furthermore, the collision avoidance system's development to date that follows the presently accepted technique (reference 6) has no direct coordinate ties with any existing earth-referenced system. Just as the marine field has learned through years of abortive attempts, the addition of the marine collision avoidance system (marine radar) has only added to the total number of collisions of all types, and the annual rate of 1,700 collisions a year or a 7 percent annual rate persists. Leaders in marine traffic control now recommend shore-based, earth-referenced systems wherever possible. Although such an exorbitant rate of collision is acceptable in the marine field, it cannot be accepted by aviation. The relating of the fluid coordinates of a vehicular pair (in proximity conditions) to earth references as an inherent part of any PWI concept is essential. PWI, or any "air-to-air" signaling (the latter being more descriptive), must tie directly to the ATC system and be a supplemental cockpit check or coordinate aid to the ATC system.

This objective (as in the case of the marine experience) is impossible to achieve without a common national coordinate system that relates each aircraft to the other. This coordinate system also ties track, altitude, and intentions into an overall ATC system, permitting direct air-to-air checks on spacing between aircraft as well as centralized ground control checks. This joint function, if accepted for, say, air-to-air spacing on common tracks, must be an integral part of the new ATC system, but is not now possible with the hundreds of uncoordinated VORTAC's.

It is readily possible with a national grid of oblique-parallel lattice lines with constant spacing, constant geometrics, constant LOP crossings, and constant granularity to provide this wide area traffic coordination. Every coordinate point is related directly to every other coordinate point without going through complex airborne or ground-relayed coordinate conversion. This overcomes the problem of relating air traffic movements using VOR 1 to traffic on VOR 2 that cross or come in proximity with each other, because no two VOR's are spaced or aligned like any other 2 VOR's. All VOR pairs differ from one another. A complex pair-to-pair VORTAC coordinate conversion is needed since station location, baseline spacings, etc., are not now part of the VORTAC data usable in the cockpit. Thus, a major point in considering the future of VORTAC is that these much-needed new functions do not appear as part of the current VORTAC system because it grew over the last 20 years "like Topsy" with little overall, total-area navigation and control planning.

This is not to be critical of past VORTAC decisions, because the obvious 1975-1985 ATC crisis that we clearly anticipate today--created by 200,000 limited IFR general aviation aircraft, over 1,000 jumbo jets, and some 6,000 conventional jets--was not evident in 1945-1955. Thus, the 15 to 25 year old decisions of 1945-1955 have actually served well, and they can be partially extended but must be supplemented with new national air traffic guidance and control concepts with more of a "total-system" approach to encompass the ATC, CAS, PWI, identification, altitude reporting, etc., needs of all the airspace users, including 100,000 to 200,000 small general aviation aircraft, not just the airlines. The concepts herein detailed have this as their objective. They admittedly require a great deal of field testing, "brass-board" engineering, and theoretical study and analysis of their future value.

Application of a national coordinate system in ATC to airliners as well as general aviation must be considered, because airspace conflicts can occur between these two classes as well as between members of each class. The useful IFR airspace is now approaching limitations that suggest that a traffic growth of even a small fraction (much less than the 300 percent projected) will result in airspace saturation as now defined by TERPS or the AC 90-45 documents (reference 4). Regulatory efforts restricting the largest number of aircraft (the unwanted majority, as someone has called them) may take place with unnecessary political and safety consequences.

With general aviation acquiring 1,500 transponders a month for the ATC surveillance function, an imbalance between Area Navigation capacity and surveillance can occur as airspace (positional uncertainty) is more accurately defined by SSR than by VORTAC. Without an equivalent, companion, high-capacity, superior coordinate system, adequate, multiple, separated flight tracks cannot be defined using coordinates that converge, vary two orders of magnitude in accuracy and do not conform to any uniform distribution of multiple VORTAC spacing of ground facilities.

G. INTEGRATED VLF NAVIGATION WITH VORTAC OFFERS MAXIMUM COST BENEFITS

Assuming that the present airspace usage in any area such as the Northeast Corridor (4 to 5 such areas exist today), which stretches from above Boston to below Washington, typifies most future national problems, plans must provide for integrated ATC coverage and maximum use of the airspace by all users at all altitudes to merely meet air traffic capacity demand safely. This dense area now has perhaps 100 VOR's or VORTAC's which are randomly located with respect to each other, and each with varying accuracy and coverage. To utilize these 100 odd VORTAC's in any "area" concept results in geometrically tying their coordinates into a most costly network (both) as far as airborne equipments and ground installations are concerned. (Adding the three additional airborne elements to VOR gives a total of five elements for Area Navigation. Similarly, the addition of Doppler or multi-lobe precision VOR ground facilities provides angular accuracy within usable tolerances.) This VORTAC Area Navigation solution could easily cost far more than the VLF solution, since hundreds of ground stations (doppler, VORTAC, and tens of thousands of airborne installations) are involved.

The expenditures (government and private) to extend the VORTAC to full-area coverage concepts will thus cost much more than the VLF concept herein suggested, and yet leave the high risk of VORTAC system overload, pulse density, saturation shortage of channels, etc., along with a very clumsy coordinate system. One to two thousand independent sites do not make for good planning.

It is suggested that before this massive national investment in VORTAC modernization occurs (with most of it privately financed by purchasing the four new Area Navigation elements), a plan be considered to leave the VORTAC "as-is." Instead, new capacity is to be provided by using a "total-area" Area Navigation concept, such as Omega A, which must be exhaustively tested first. Major cost savings can accrue that represent billions of dollars over the 1975 to 1990 time period. This avoids the costly modernization of VORTAC and limits the total sites to perhaps 400 to 500.

It is expected that the "proof of concept" of the VLF system and its integration with existing, not modernized, VOR can be determined for a relatively small cost in the immediate future, since the basic type of Omega VLF signals exist already and cover the entire Eastern Seaboard of the United States. The New York-Trinidad LOP's that operate at 13.6 kHz typify the type of signals that could be provided over the entire United States by optimizing all we know now about the VLF concepts. Tests of automatic diurnal correction could be readily implemented on the existing Trinidad-Forestport pair, because about 50 percent dead time currently exists in the format. Based on the years of Omega experience and data collection, many improvements in a U.S.-only Omega are possible. Professor Pierce of Harvard, the pioneer of Omega and utilization of these VLF frequencies, has laboratory and field test results indicating that most of the VLF problems have now been solved, and that not only will the world-wide application of VLF-navigation be quite successful, but a new, complementary, U.S.-only VLF chain based on Omega principles would be possible. Much stronger signals, reduced diurnal effects, better LOP crossing angles, differentially corrected data, and a more frequent positional updating are the main improvements.

H. "TIME-OF-ARRIVAL" CONCEPTS INTEGRATED WITH OMEGA

Since Omega VLF navigation signals use a common time standard for all aircraft and all ground units, it is possible for the ground to receive an aircraft transmission that is separately and individually contained in a given time-slot (say, a 10-millisecond slot or a 40-millisecond slot for the BTL-VHF Data Link). Utilizing multiple, split sites on the surface, it is possible to establish the location (origin) of this emission. All other emissions in other time slots are similarly measured. Although altitude cannot be measured in this way (because "time-of-arrival" concepts are not suited for vertical geometric reasons), an independent lateral position determination is most practical. The time-of-arrival of the aircraft signal at, say, three dispersed sites will be different at each of the sites (Figure 6).

The time T_1 to S_1 will depend on the distance between S_1 and the aircraft; similarly, the times of arrival at S_3 and S_2 will each be independently determined by their respective distances, $T_3 + T_2$, to the emitting aircraft. If a tone signal (a triple tone-coded signal such as the BTL is probably excellent) is received, the three phase comparisons of this multi-tone signal at a common point permit the computation of $T_1 - T_2$, $T_2 - T_3$, $T_3 - T_1$, etc., to take place by means of a computer. Sites S_1, S_2, and S_3 can be tied to the computer by landwires, preserving signal phase integrity. These multiple time difference computations will supply a single, unique solution, which is the exact location of the emitting aircraft. Time-sharing using time slots permits separate positional measurements on about 50 to 100 aircraft per each VHF channel.

The aircraft emission also contains Omega LOP, identity, and altitude data. Thus, the time-of-arrival (actually the time differences of three arrivals) computations can independently check the LOP data to assure it is correct and within given or established tolerances. Airborne equipment errors, data encoding errors, differential setting errors, etc., are thus all independently checked. This is a "semi-surveillance" system concept much like the SSR, but it could complement the SSR transponder concepts by reducing some of the future traffic load. The use

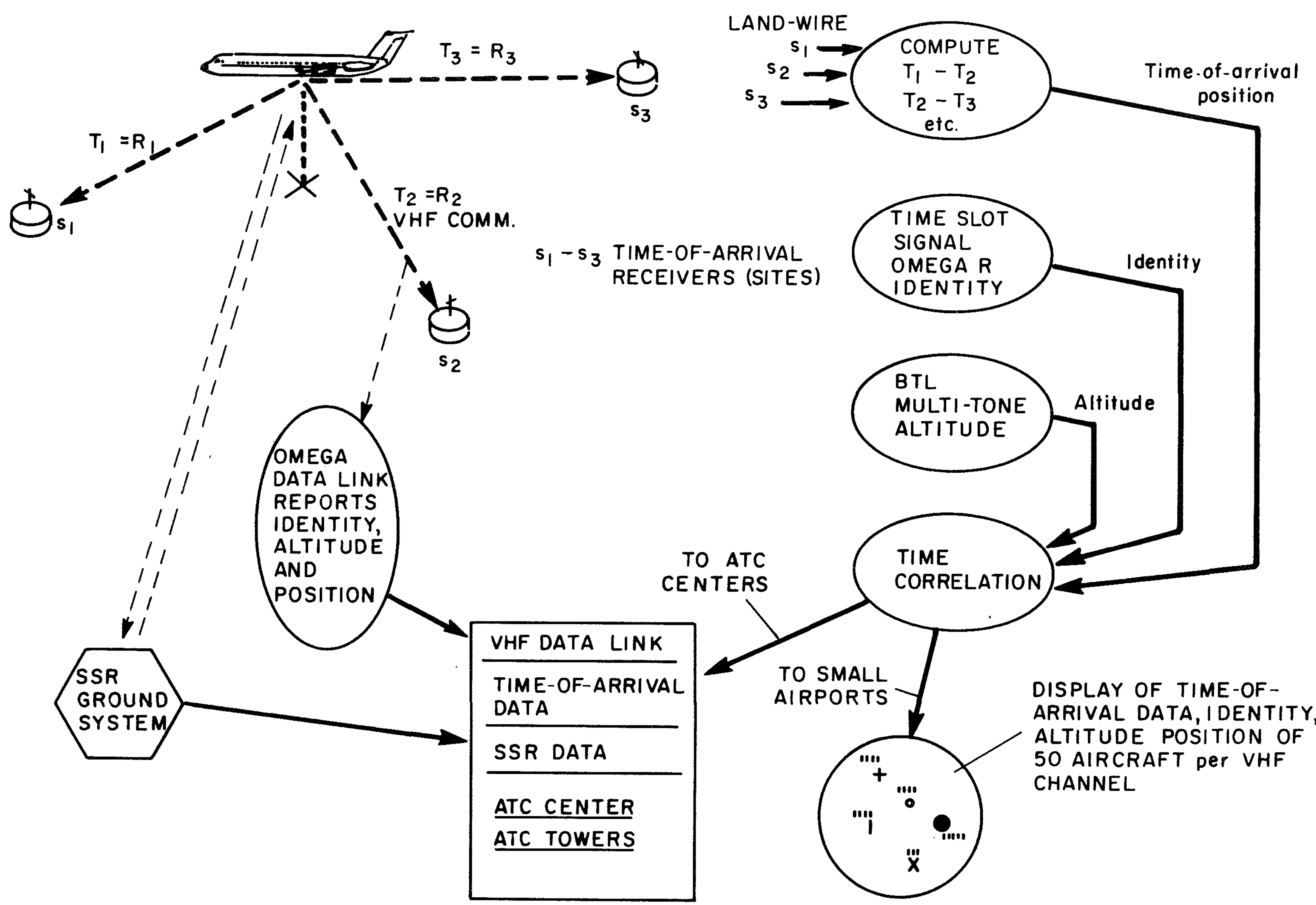


Figure 6. INDEPENDENT TIME-OF-ARRIVAL CONCEPT FOR MONITORING GENERAL AVIATION VHF TRANSMISSIONS AND FOR LOW COST SURVEILLANCE DISPLAYS

of time-of-arrival redundancy of SSR signals is not adequate because two aircraft can transmit at the same time; this is avoided in a time-slot or time-ordered VHF roll-call.

A time-of-arrival surveillance system can function on its own for low- or high-density areas, giving a NAV-surveillance capability at very low cost over stable telephone lines to small airport towers, flight centers, and other authorities or airspace users that want ATC data.

The Omega 5- or 10-second "clock" used for time-slot assignments (be they assigned sequentially on navigational coordinates or identity) can easily be used by all elements timed together over telephone lines. Phase angle comparison of the 5 x 5 x 4 BTL tones gives a non-ambiguous difference in time of arrival.

III. SOME DETAILS OF A NATIONAL VLF COORDINATE SYSTEM

Figure 7 illustrates some possible locations of four VLF stations to optimize coverage over only the United States. These stations would be optimized on the basis of the Omega work by Professor J. A. Pierce of Harvard, NEL, NRC, and the Navy Omega project office under the DOD. The following parameters would be optimized, based on tests, analysis and studies, for a "U.S.-only" system for ATC, Navigation, air-to-air separation reporting, national timing signal for roll-call techniques, etc.

1. Frequencies in the region of 10.2 and 13.6 kHz of Omega would be used. Professor Pierce suggests that these signals be displaced at least 500 Hz from the basic Omega frequency so that a 13.1-kHz and possibly a 12.7-kHz signal can be selected as examples.

2. More radiated VLF power is possible than at present and a balance of design parameters such as (1) multimode propagation, (2) frequency, and (3) baselines must be achieved in the design (reference 7). Current Omega power levels can be readily increased by 10 to 15 db for the U.S.-only configuration, aiding in reducing costs of thousands of receivers.

3. Short sampling periods of ⅓ to ½ the present 10-second period.

4. A national monitoring system is developed consisting of perhaps 20 strategically located sites that can receive and process the details of the VLF navigational signals from the four VLF navigation transmitters. This would assure, on a national basis, that LOP's lie precisely where predicted and charted for airmen and other users. By continuously feeding the multi-sensor information of such a uniformly distributed monitoring system over telephone circuitry to a centralized computer, a real-time computation of diurnal and other effects of ionospheric changes (or any other phenomena affecting accuracy) can take place. An optimized solution for navigation corrections is thus automated and computed continuously in real time. Rapid diurnal changes are followed without delay. Both monitoring and diurnal corrections are realized by the connection of these sites by simple telephone circuits to a centralized computer.

5. The distribution of the nationally computed diurnal data is also automated using the national aviation data distribution network, such as weather, teletype, telephone, microwave, or other national communications means, so

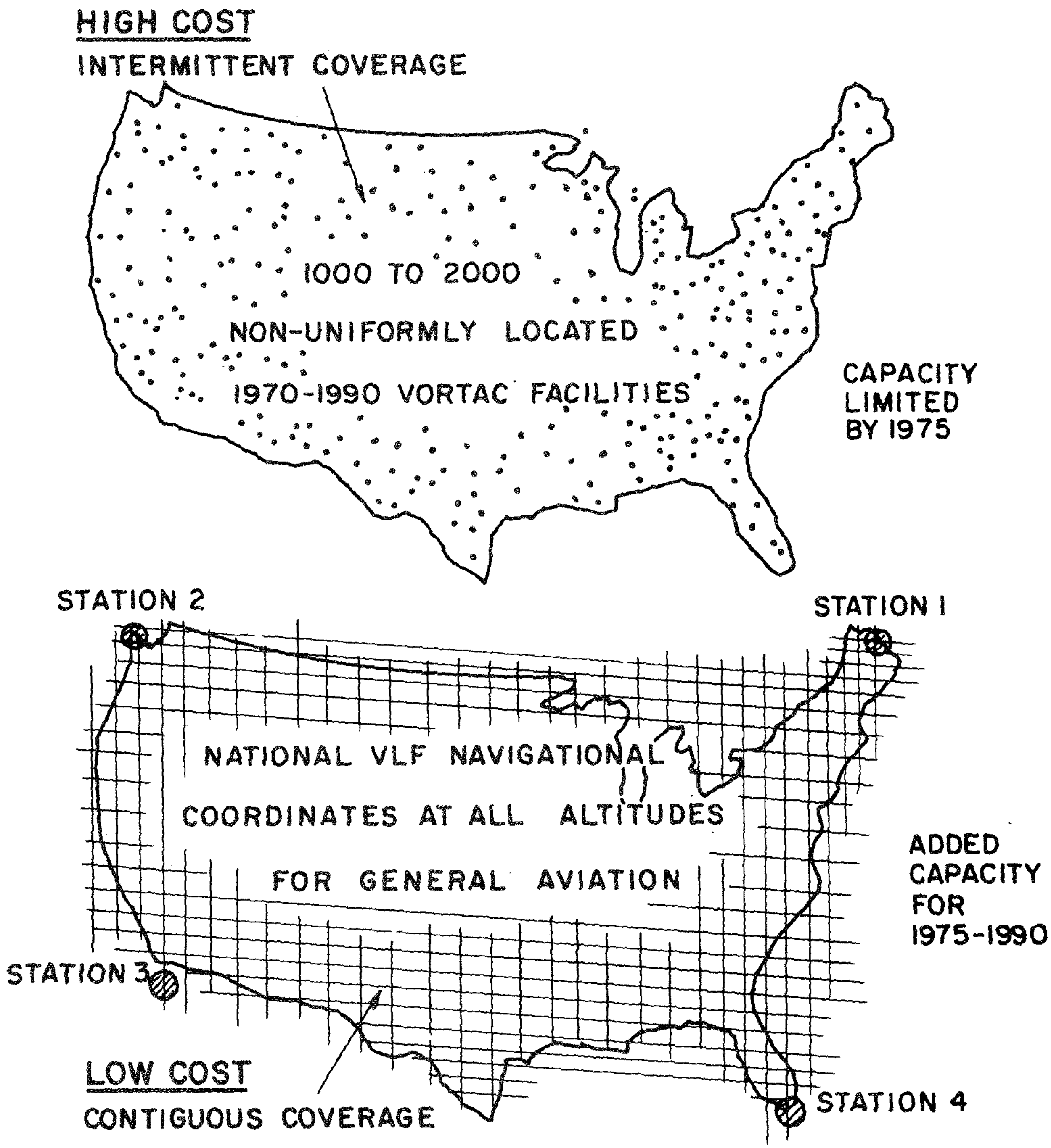


Figure 7. COMPARISON OF 1000 TO 2000 VORTAC STATIONS WITH BUT 4 VLF STATIONS FOR A NATIONAL NAVIGATION SYSTEM

that the instantaneous, yet precise, diurnal correction is available at every locale requiring the data. A centrally located fifth VLF station or possibly a "mix" of the transmission formats of the four stations can convey this data also by radio propagation using a slow, digital message. Thus, VLF radio can also provide the national distribution of diurnal corrections on a roll-call basis.

6. Ambiguity resolution is worked out on a "user concept" of covering only about 3,000 by 1,500 miles (the contiguous United States) rather than the normally 4,000 to 5,000 mile baselines. Geometric or heterodyne methods of ambiguity resolution should both be available. This suggests that local areas of 75 to 100 miles are also significant so that a 2 to 3 kHz difference would simplify and reduce costs to general aviation. Probably a four-step ambiguity resolution technique as in world-wide Omega will suffice for U.S.-Omega.

7. The above suggests a total system optimization with the better signal levels and number of useful LOP crossings because of selection of optimum Omega frequencies, station siting, power, etc., so that lane ambiguity is minimal. Propagation characteristics require that ambiguity steps be conservative, say, by factors of 3 or 4. Power levels of up to 1 megawatt can be considered as in other VLF transmitters. Transcontinental flights would use a lower heterodyne frequency for a 1,500 or 3,000 mile ambiguity resolution, requiring a 4 to 5 speed receiver. General aviation would use either a 2-speed receiver or a 1-speed receiver.

8. With only four stations, the updating can be more frequent, say, every 4 to 5 seconds, thus removing one of the criticisms of the eight-station, 10-second world-wide Omega signal format. Even shorter emissions should be considered because a three-station, 3-second cycle reduces data delays. However, a 5-second cycle is readily locked to existing Omega and should be examined for this reason as a positive compromise.

9. All VOR's can emit the local differential (diurnal) correction, and/or the four-station net itself is corrected by a fifth station centrally radiating a slow, digital phase code diurnal message, so that about every 5 to 10 minutes every segment of the nation is corrected by use of local monitoring receivers and/or by automatic airborne means.

10. As in Omega, the frequency tolerances are maintained to the best possible standards for other functions such as CAS, PWI, air-to-air signaling, and time-frequency concepts similar to many that have been proposed. Typically, a variation between stations of a fraction of a microsecond

and the best absolute time (over months) would be established. Shorter baselines and wide area monitoring should provide this. All 5-second and similar station sequencing signals are, of course, locked to the Omega signal format for the synchronous sequencing of local area (VHF) roll-calls, air-to-air position monitoring, etc. All aircraft will effectively have such a "national clock," for this type of synchronized transmission or reception because, fortunately, Omega VLF type signals are received on the surface at great distances (unlike VHF or UHF). A time frame time synchronization of about 2 milliseconds for aircraft reception of roll-call data is realizable. Message frames of about 900 milliseconds can be readily synchronized.

11. The development of low-cost airborne equipment that optimizes a multiplicity of localized VLF uses rather than the world-wide use of Omega should be stressed. The shorter time intervals between updates also simplify and assure low-cost designs. The use of lower-cost crystal references to relate VLF time-separated transmissions may be possible with 4-second updates. Varying degrees of user applications must be stressed, as marine services might also realize local advantages in harbors, rivers, etc. Airlines may use a sophisticated means of computing five LOP's continuously, thus optimizing accuracy at higher cost.

12. Geometrically site the four new VLF stations to optimize signal levels in the dense traffic areas of the United States, minimize diurnal shifts, provide the best directions for direct (CDI) use of LOP's and consider baseline spacings to have as nearly straight LOP's as possible (we may have to go slightly into Canada and Mexico to realize this).

13. Assure time and frequency relationships with both VOR and world-wide Omega because the four stations will serve as backups and will be integrated into both applications with benefit to all users. Omega is really the use of the frequencies in the 10 to 15 kHz region, using direct tone and phase comparisons for range differences--thus, no new technology is introduced. The increase in VLF frequencies available to everyone adds to each user's choice of applications.

14. "Brass-board" such a pair of VLF stations early, trying the new frequencies, the new ambiguity ratios, the new baselines, the overall effect of diurnal shifts on short baselines, the ability to overcome SID, P-static effects, etc., so that the new optimized signal formats can be standardized. This can be done because there is already a great deal of "dead time" at the existing stations, and these new frequencies can be added so that maybe only

one new station (two at most) would be needed for the initial "proof of concept." This new station must, however, be installed relative to the final configuration and become a part of it when validated and the other three stations are installed.

15. Develop a time-ordered, digital message format to be transmitted on a VLF link to all U.S. aircraft; this format is to be suitable for locally, addressed diurnal corrections.

A. <u>THE AIRBORNE USE OF "OMEGA-A" IN GENERAL AVIATION AIRCRAFT</u>

The basic coordinates of Omega are nearly straight lines for some distance. The amount of curvature for typical direct flights of general aviation aircraft (say, less than 100 to 200 miles) is such as to call for little heading change; normally, this change is within the usual limits of unknown wind conditions. The second LOP lines crossing these first lines are at angles of from about 60 degrees to 90 degrees, making for the "oblique-parallel" crossings. One can portray these directly with a crossed-pointer display much as shown in Figure 8. It can be seen that the normal crossed-pointer display, such as the ID-249 and similar instruments, have two needles, individually deflected but always crossing at 90 degrees. By placing one of the needle movements in a gimbal, and adding a knob for turning this gimbal, the exact replica of the LOP crossing angles can be presented to the pilot. This has many advantages, since the possibilities of both a CDI and Area Navigation display can be incorporated in the same instrument.

If the gimbal arrangement results in the right-left needles always being vertical and the crossing LOP's geometric relationships shown (with respect to the vertical needle at the correct, oblique angle), this makes mental calculation and correlation with charts very easy. The lane spacing on one LOP (vertical needle) will not always be the same as that on the other LOP, creating slightly different sensitivities, but these differences are small enough so that they can be ignored, since this variation may be 20 percent compared with many times (500 percent) for a VOR-CDI. Ease of direct comparison to a chart or use of symbology as in ILS flight following is enhanced.

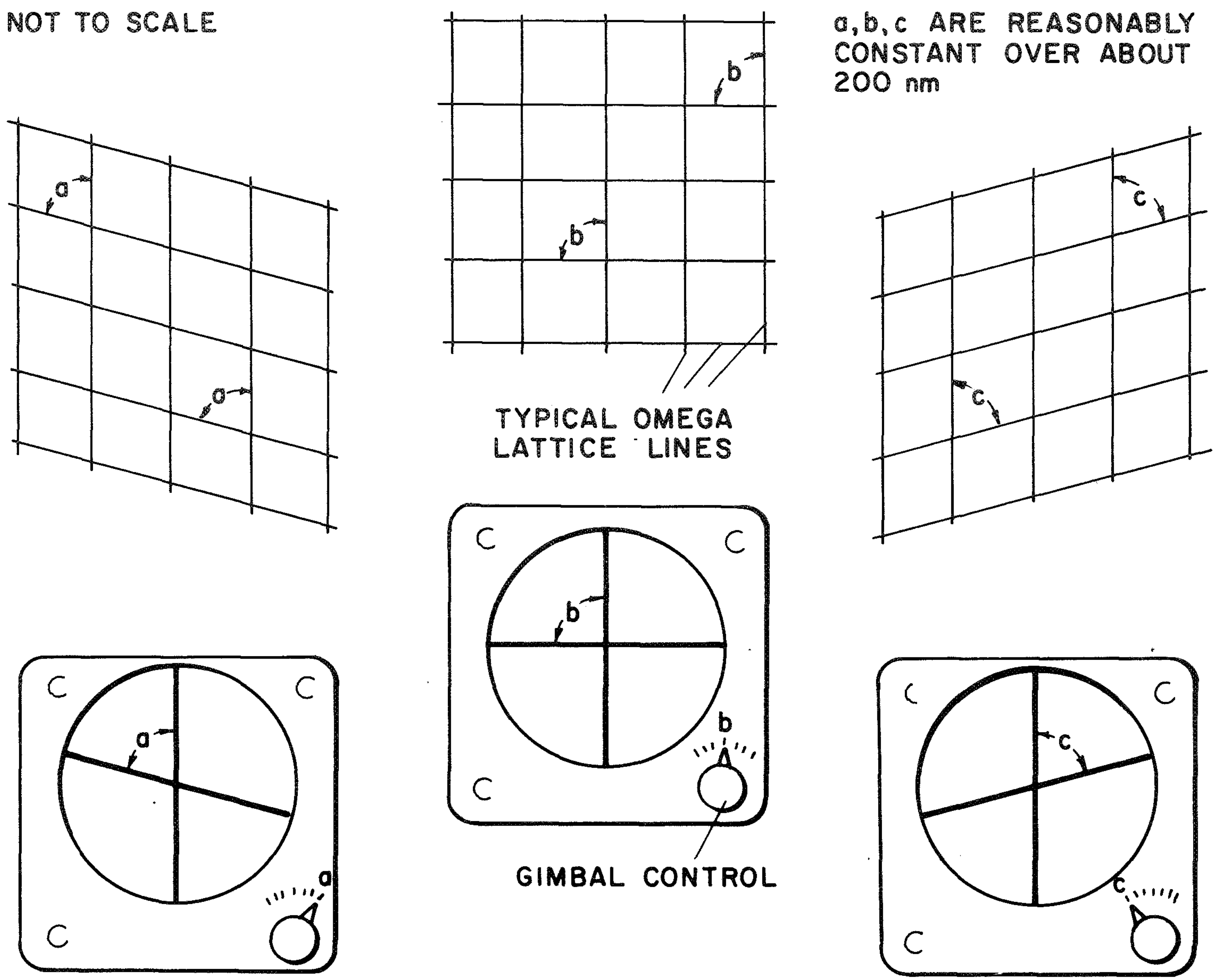


Figure 8. USE OF GIMBALED COURSE DEVIATION INDICATOR (CDI) FOR VERY-LOW-COST AREA-NAVIGATION PILOT DISPLAY

The crossing of the LOP's needle (2) while following the selected LOP for the track (or course) needle (1) creates effectively the same result as the DME does for the VOR but in a much simpler and direct manner. In Omega only one display is needed, whereas in VOR-DME at least three displays are essential. When a turn is made onto another LOP, this can be quickly established with the gimbal-knob, so that the course is again represented by the vertical needle giving the correct (fly to the needle) right-left sensing. Needle sensitivities (miles per inch) can be readily changed, permitting precise or relaxed flight-following matching aircraft performance, weather, and ATC demands.

For example, if a servo-following system is used (driving a phase shifter-phase detector always to zero), once tracking is established and retained, there will be no ambiguity problem. Furthermore, there is the use of two Omega frequencies to create a "coarse" signal by the heterodyning of the two with ambiguities much further apart than in the "fine-only" system. If, for example, the "fine" frequency is around the 13.6 kHz frequency now used (500 Hz higher or lower), then with shorter VLF baselines and better signal-to-noise environments, a second frequency might be chosen that, when beat with the other frequencies creates a heterodyne frequency that is used for the "coarse" that has ambiguities, say, every 50 to 100 miles. The "coarse" is used only to find the zero of the "fine" while all direct control is done by observing only the "fine," thus increasing user accuracy.

The current heterodyne frequency is 3.4 kHz (10.2 kHz beat with 13.6 kHz). Since this is ¼ the higher frequency, it creates a 4:1 ambiguity resolving power. Usually a third frequency is used so that, say, a 5:1 is created so that the total is then (5 x 4) 20:1. If the 13.6-kHz lanes are about 6 miles apart (a lane is simply 360 degrees of phase shift representing the local phase comparison of two Omega station signals), then the (third speed) ambiguities are 120 miles apart—something easily resolved by other means for general aviation. Furthermore, the ground setting and ground correlation of the VLF navigational signal before takeoff does much for assuring Omega accuracies and avoiding any ambiguities, something not possible with VOR, VORTAC, or TACAN.

Thus, for the airborne display end we can have scales of ±2 miles representative of the VOR cross-track deviation-sensitivity (VOR is ±10 degrees), at a distance of about 12 miles from the VOR station. Steps of from 2 to 20 or even 25 miles could be used. If the area is, say, 25 miles by 25 miles portrayed by the crossed-pointer display, then this represents an area of 625 square miles, as compared with but 16 square miles at the higher sensitivity.

Professor McFarland used sensitivities in the region of 2 to 4 miles for full-scale deflection in the flight demonstrations of "raw"-direct Omega-LOP flying (reference 2). A crossed-pointer instrument about 5 inches (or maybe 6 inches) across, rather than the 3½-inch ID-249, offers improved pilot acceptance of a sealed, standardized instrument for Area Navigation, rather than maps, charts, projectors, cathode-ray tubes, servo-driven roller charts (as Decca), etc., none of which are fully satisfactory. The present trends such as the VAC-Butler-aviation instrument is in this direction.

This Omega dual-LOP display can then be flown with two sets (two pairs) of needles, one pair crossing is simply the destination in the displayed area, and the other crossing pair is the present position. The aircraft heading can be shown in the center, and one has the full advantages of an Area Navigation system without maps, charts, cathode-ray tubes, etc. Furthermore, a transparent overlay with a map or track can be inserted with keyed alignment pins that will aid in the direct pilot usage (Figure 9).

B. LEVELS OF PILOT DISPLAY SOPHISTICATION

Thus, in the simplest cockpit display of Omega, something as simple as the mutually perpendicular CDI crossed-pointer will suffice. The ID-249 represents this example and will do very well and is in mass production. It (ID-249), incidentally, has heading already mechanically included and is called a steering computer, since one steers the heading needle to the cross-track

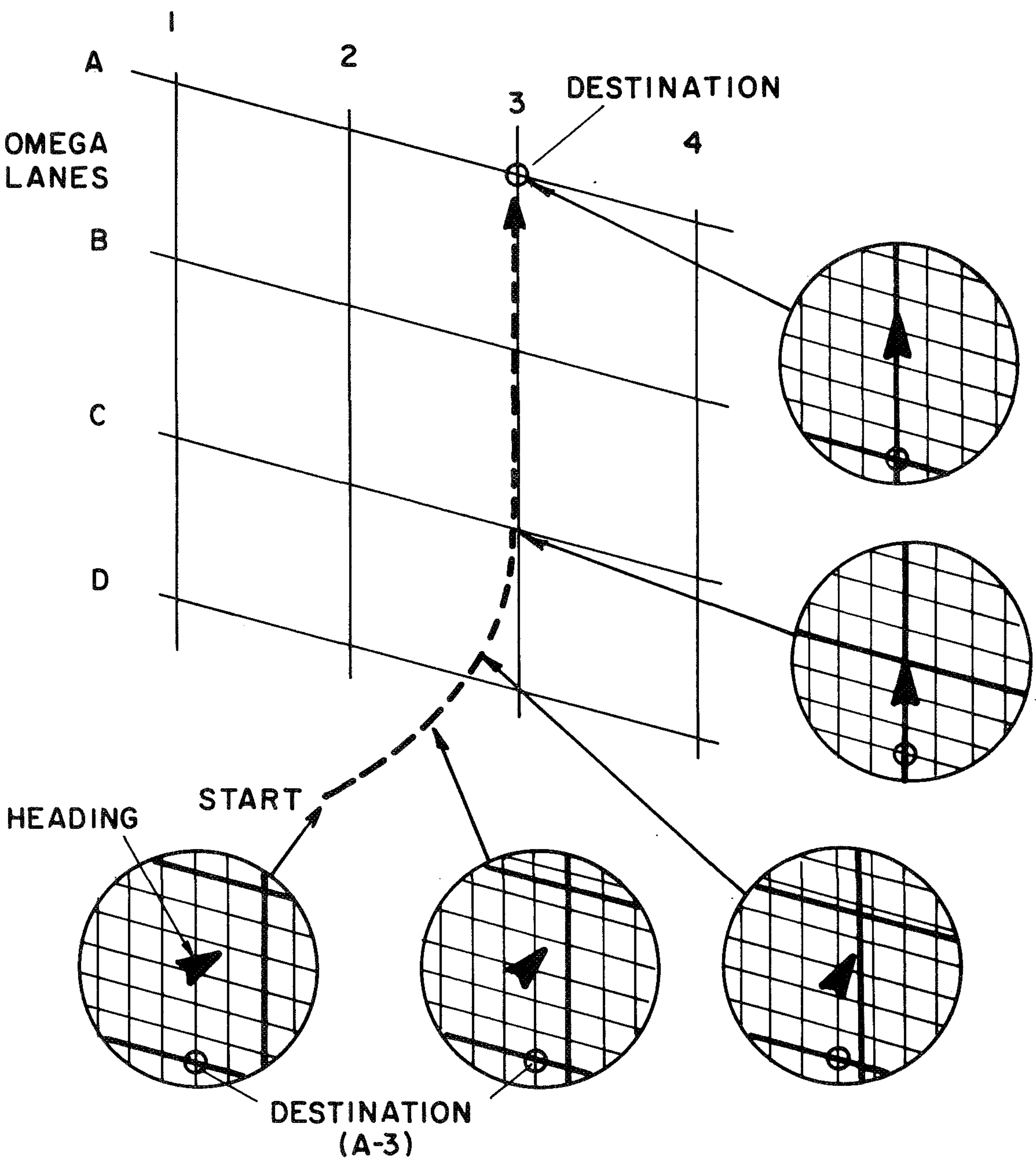


Figure 9.
EXAMPLE OF INTERCEPT WITH LOW COST DIRECT DISPLAY OF OMEGA LINES OF POSITION AND HEADING WITH FLIGHT FOLLOWING TO DESTINATION

deviation needle. Thus, the pilot would simply assume the LOP-crossing angle on the charts and the two LOP's are shown as always at 90 degrees--not a compromise on safety or accuracy.

The next level of sophistication comes when the gimbal is added for orienting one needle from 90 ± 30 degrees with respect to the other needle. The third level of low-cost sophistication comes with the use of airborne scale factors, say, ±2 to ±25 miles in five steps. Transparent map overlays with airways, airports, etc., can be considered the fourth step. The proper range and scale factors must be interlocked in such cases to avoid confusion. A destination pair of needles and a "present-position" pair of needles with heading included can be a part of any of the last three steps. One should be able to fly between these points (crossings of pairs of needles is a point) regardless of LOP direction allowing any flight track shape, straight or curved, though this can be approximated by use of centilanes.

C. FLYING ANY TRACK THROUGH THE CROSSING-LOP COORDINATES

By orienting the display, the flight track can be such as to keep the heading needle related to the destination and the present positions, so that it is indicative of the heading on a line between the crossings of the two pairs of needles. Figures 8, 9 and 13 describe this means of flying any geometric track in the area with scale factors for areas of from, say, 16 miles of display area to even 250 or 2,500 square miles of displayed area (each needle represents in one case ±25 miles or 50 x 50).

This piloting feature is possible since the oblique angles of Omega LOP crossings do not change for any given local area (say, over 100 miles). Furthermore, they can be adjusted quickly by the simple gimbal setting so that by scale factor changes only the pilot can have "Wide-Area-Navigation," "Average-Area-Navigation," and "Precision-Area-Navigation." When in low-density traffic or free of obstruction areas, the direct displayed area is quite adequate on the lower sensitivity scales.

Since the VOR represents 360 degrees of navigational coverage to about 40 miles, which is greater than the 2,500 square miles noted previously, this is commensurate with normal piloting practice. Furthermore, in a VORTAC VOR-DME Area Navigation display of a large area, the actual positioning accuracy varies with range since VOR errors of, say, ±3 degrees are equivalent to ±2 miles at 40 miles. Omega with the usual differential corrections is accurate throughout the displayed area to about ¼ to ½ mile.

The pilot, using constant accuracy data throughout the area of coverage by the Area Navigation display, is on the average better off than with the VOR-DME because of the poor angular accuracy and positional dilution of the VOR at increased distances.

However, as the VOR stations are replaced by improved Doppler VOR stations and multilobe-VOR techniques (such as the D-VOR and P-VOR), then angular accuracies of about ±1.0 degree or even ±¾ degree may be achieved and the local differential Omega and D-VOR are somewhat comparable in accuracy but not in cost. The complete stations that send out Doppler VOR signals or P-VOR signals use larger antenna structures, large counterpoises, more complex signal generation (commutating some 50 or more antennas), etc., so that the national cost to convert all VOR's to D-VOR or P-VOR is enormous, yet must be done if accuracy is to be achieved. High angle use is not improved, and some bad sectors can persist (for example, see the recordings in reference 8 and the errors of VOR noted in reference 4).

Even so, if this is done, the lack of any master plan for multiple VOR locations (baselines between sites) creates siting problems, confuses pilot usage, etc. For the four stations of the Omega-A (U.S. coverage) only four locations need be found that are suitable. Usually, latitude on 1,500 to 3,000 baselines is large. For the national-VOR scheme, even with Doppler VOR, this is not eased, since some 1,000 to 2,000 sites must be found, maintained, protected, inspected, powered, modernized, etc., to fulfill a 1990 objective. This is summarized in Figure 4. Furthermore, if the VOR site is eventually surrounded by a metropolitan buildup of buildings, power lines, fences, etc., the site must finally be moved, and the complexity of changing the R-θ grid, charts, etc., is most difficult. The simplicity of a national, multiple, LOP grid stretching from San Francisco to New York and from the northern reaches of North Dakota to the southern tips of Texas and Florida has enormous attraction in national aviation facility planning. A means to simplify and drastically lower costs of ATC, not only for general aviation but for all users, while increasing capacity and services, must be found for aviation's continued growth.

D. <u>NATIONAL TIMING SIGNAL FOR AVIATION</u>

Along these same lines, the Omega-A chain will have signal timing sequences (just as in the existing Omega signals) where the 10-second timing sequence is repeated precisely and continuously. If one averages the 10-second "clock" of Omega, the accuracy of timing becomes about one part in ten million as the stations are continuously sequenced. The new Omega signal format may contain a special signal to start the clock and to resynchronize all clocks from a precision tone signal emitted with the navigation sequence (say, a 0.2-second burst every 10 seconds interlaced with 1.0-second navigation signals). Even if only one part in ten thousand (not million) is maintained, then the time anywhere in the Omega timing cycle can be established to an accuracy of 1 to 2 milliseconds. This 1 to 2 milliseconds (accurate) sequencing has many possible applications on a national ATC, local ATC basis, and air-to-air basis.

Since all flights are tuned to Omega, all clocks are synchronized to 1 to 2 milliseconds. Since this is about equivalent to 186 miles of transit time, the ability to keep time permits all those aircraft anywhere in each other's proximity (180 miles or less) to have this timing signal. It varies across the nation on a linear basis, which is easily accounted for in its application locally. By assigning time slots as identity reporting slots or altitude reporting slots, many simple low-cost but valuable ATC functions can be obtained from all aircraft as economics will allow for the concept's use by all. For example, if the elevations from zero to 20,000 feet were represented by time slots (10 milliseconds wide) to allow for any timing errors, then there would be a time slot for every 20 feet (1,000 time slots each 10 milliseconds wide representing 20,000 feet). This might be an air reporting (on VHF) mode that is not normally used but is activated in certain occurrences such as a proximity warning from other inputs, even ATC "advisories" of nearby aircraft, etc. Whenever adjacent aircraft might want to monitor each other's altitude, this solution will be quite simple.

Furthermore, the use of the time slots for data-linking messages (using the BTL 5 x 5 x 4 tone system) can create one element of a 100 choice or 100 quantities message in 40 milliseconds. Thus, if the Omega time slots were again divided, this would be 250 time slots, each 40 milliseconds wide. An altitude tone "burst" would come down to ATC, say, in one time slot (dividing height into 200-foot steps, say, from 0 to 20,000 feet). Every 200 feet approximates the accuracy to be expected from barometric sensing of altitude.

E. OMEGA ROLL-CALL OR TIME SLOT EXAMPLE

If one VHF Comm-channel (much like a "Unicom" channel) is used and 50 aircraft occupy it, many voice channels would also be saved. Then there would be five time slots (40 milliseconds long) in each of the Omega 10-second time frames assigned to each aircraft--that is, the count on the roll-call starts at zero-time and counts to 50 in (40 x 50) or 2,000 milliseconds = 2 seconds or 1/5 of an Omega 10-second frame. Then, the second count starts in the second sub-frame, and so forth, so that the count of 1 to 50 has been repeated 5 times in the total-Omega time frame of 10 seconds.

Thus, the 5 sub-frames would each be assigned a message from 100 possible coded messages. A time frame (sub A) might be one combination of three simultaneous tones each selected from the high, medium or low frequency lanes of the 5 x 5 x 4 tones of the BTL* data link message. The first one might be altitude,

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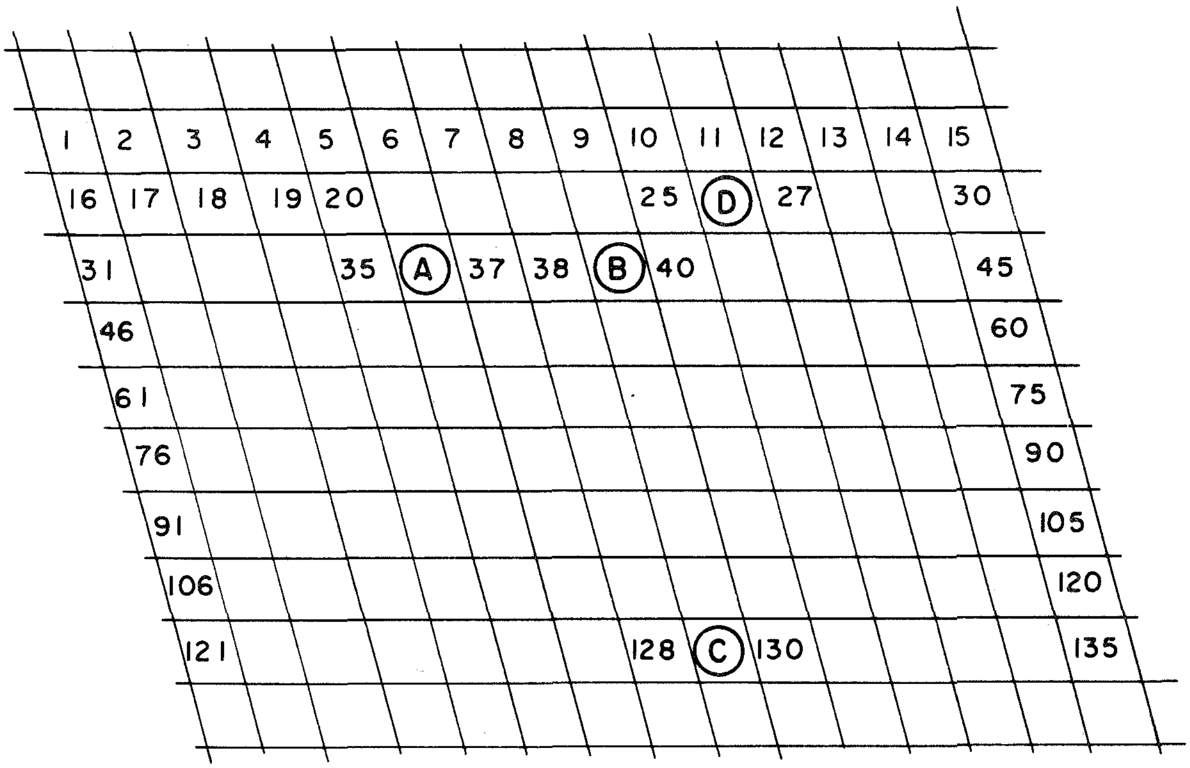
* These tones are (Bell type 401 system): low band - 600, 697, 770, 852, 941; medium band - 1098, 1209, 1336, 1477, 1633; and a high band - 1950, 2050, 2150, and 2250. (All values are in Hz.)

the next might be a report of position, as might the remaining three. Thus, each LOP could be given a 10,000-element resolution (100 x 100) using two "sub-slots" for each LOP. Many choices are obviously possible, but a typical operational rationale is that "time-slot-is-identity" and "tone-code-is-position."

However, this format need not be followed throughout the next 5 sub-time-frames. For example, some of the 5 sub-time-frames could be "time-ordered" by Omega position. Using a simple burst on VHF each aircraft emits in a 5-millisecond slot relating to its position. Two slots can be sequenced in 1 second allowing ±1 millisecond accuracy of slot timing and a simple (non-coded) burst on tone for 4 milliseconds. That is to say, time slot one (0 to 5 milliseconds) is LOP-1, time slot two (5 to 10 milliseconds) is LOP-2, etc., up to LOP-200 (995 to 1,000 milliseconds), giving accurate positional reports of LOP's 1 through 200. Next, the crossing LOP can similarly be transmitted by time-ordered (linear relation of distance vs time) reports. Thus, if all local aircraft "listen in" on the VHF-Unicom to this time-ordered sequence, the pilot hears adjacent aircraft just before or just after his own transmission. Figure 10 illustrates this principle. If the air-to-air listening were a given area (covered by the VHF for air-to-air signaling for proximity warning and spacing along, say, a given airway), then the area could be defined by 100 x 100 or 10,000 elements. If each LOP element is equivalent to ½ mile, then we have an area of 50 x 50 miles represented by 10,000 positional elements, each representing about a ¼ square mile area.

Thus, if a pilot notes a time slot report separated immediately before or after his own report (by three time elements), the other aircraft is in proximity on an LOP that is only 1½ miles removed; when the next crossing LOP report is received (in another sub-frame) and remains also 3 slots removed, then the other aircraft is obviously within 1½ miles on the crossing LOP also. If, say, however, the second LOP report (LOP-2) is delayed by 40 time slots, then the second aircraft is at a safe separation in a given direction (in Omega coordinates). The proximity aircraft is thus 20 miles in the direction of LOP-2 and 1½ miles in



In the roll-call process, Aircraft A (at 36) will hear Aircraft B's roll-call position (39) and noting that it is but three elements (39-36) removed, will be aware of its close proximity. Similiarly, Aircraft D (slot 26) will be aware of Aircraft B's close proximity (at slot 39). If the elements are assumed to be 1/2 mile in dimension, this would place the separations at about 1-1/4 miles. However, in the case of Aircraft C (124) there will be no alarm or concern about a proximity relationship since the nearest aircraft is B. The roll-call resolution can be 200 x 200 elements allowing 5 millisecond constant frequency tone-bursts per element on VHF for the repeating of the Omega position. Thus, the 135 elements shown above are only an example of the 4,000 elements "roll-called" each 8 seconds. Each element can represent but 1/4 square mile using differential or automatic diurnal corrections.

Figure 10. USE OF VLF COORDINATES

the other direction (LOP-1), or obviously at a safe distance.

If an aircraft is on an airway established by direct LOP flying, and if this time slot position reporting mode is used (perhaps alternately with other time-ordered modes), then those ahead and behind the subject aircraft can be clearly indicated (their presence and spacing) in the simplest form. Figure 11 shows simple on-board displays in each aircraft to indicate spacing. Timing with Omega to 1 to 2 millisecond accuracies is the simplest of devices, perhaps costing but $200 to $300 if only the "time-framing" is used from Omega. Such a simple device may in itself be most useful for timing (only) altitude reports, so that one could always filter altitude by time before or after one's own synchronous altitude report, giving a direct indication of vertical separation. In any case, several low-cost applications for proximity display vertically and horizontally are possible.

Thus, by judicious testing and planning of the Omega time frames available at all heights, in all aircraft, at all airports, at all ground stations, not only is air-to-ground data encoded by combining time slots and BTL tones, but so is ground-to-air and air-to-ground (No. 2) location. Time slot positional reporting could be used for air-to-air spacing in ATC and for simple displays of data for ground controllers. The simplest of low-cost ATC displays could be generated at a general aviation airfield without a radar, yet it could create effectively a local ATC display similar to what a radar creates for far less cost, thus giving a local ATC data and PWI to thousands of small U.S. airports.

Some of these concepts are further illuminated with illustrations of signal formats that permit the combination of tone signaling and time slot assignments for (1) identity, (2) air reporting to ground of position, (3) air reporting to ground of altitude, (4) air-to-air proximity reporting relaying relative position and altitude, and (5) air reporting to ground of correlated identity, height, altitude, and any air-detected proximity situation. This provides an optimum balance of low-cost redundant PWI and satisfies the automated ground ATC computation of track

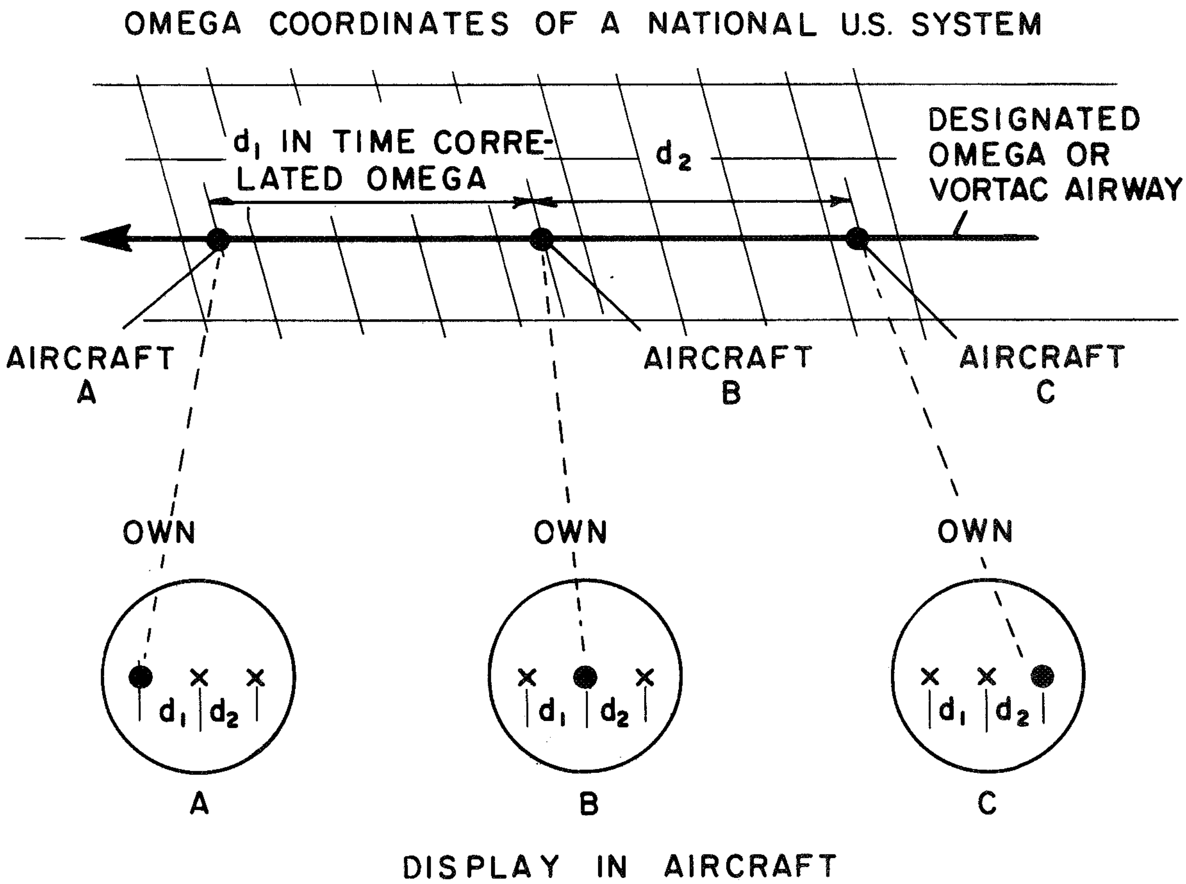


Figure 11.
COCKPIT DISPLAY OF AIR TO AIR OMEGA DATA TRANSMISSIONS USED FOR MAINTAINING SEPARATION ON A COMMON AIRWAY OR TRACK (SAME DATA TO GROUND ON VHF USING TIME SLOTS AND TONE DATA LINK)

schedules, conflicts, collision avoidance, vertical separation, etc., all in common air and ground coordinates. These features would be assigned primarily to the thousands (possibly 50,000 to 100,000 by 1980) of IFR and ATC equipped small general aviation aircraft. Since they operate at the lower altitudes or could be required to, the Omega signals are ideal as they are available at the lowest heights. Localized VHF is used by employing VOR, voice, Unicom and existing VHF channels far more efficiently than at present. Figure 12 illustrates this signal format.

F. AIR-TO-AIR SIGNALING FOR CONFLICT AVOIDANCE WHEN ATC GROUND CONTROL SIGNALS ARE LOST

Even if the VHF coverage (signal data) to the ground (ATC center or tower) for reporting of ATC data should be jammed, shadowed by hills, line-of-sight limited, or interrupted in IFR conditions, the air-to-air function would continue since the VHF signaling between aircraft is synchronized by VLF-Omega and can be used to retain an orderly separation and flow of traffic. If the flow of all air traffic is based on following an orderly "track system" of coordinates, pilots can provide some separations among themselves in times of loss of centralized ATC (not a collision avoidance concept but a positive-ATC-concept of maintenance of track separations). Converging VOR radials would obviously not suffice as tracks, nor do VORTAC signals reach low altitudes or into valleys. Omega parallel tracks might work well, since Omega has highly ordered coordinates (all with the same accuracy, all with the same sensitivity, and all with the same spacing of common tracks). Air-to-air signaling of position in a simple time-ordered position-ordered manner can be interpreted automatically in each aircraft. These simple, low-cost separation displays would keep aircraft separated on individual, non-converging (for 1,500 miles) tracks that have been initially selected so that a small, slow aircraft can do a 180-degree turn for holding on the track without traversing the adjacent track. This separation is easily established with ATC testing and would justify a more permissive ATC function in lower-density airspace.

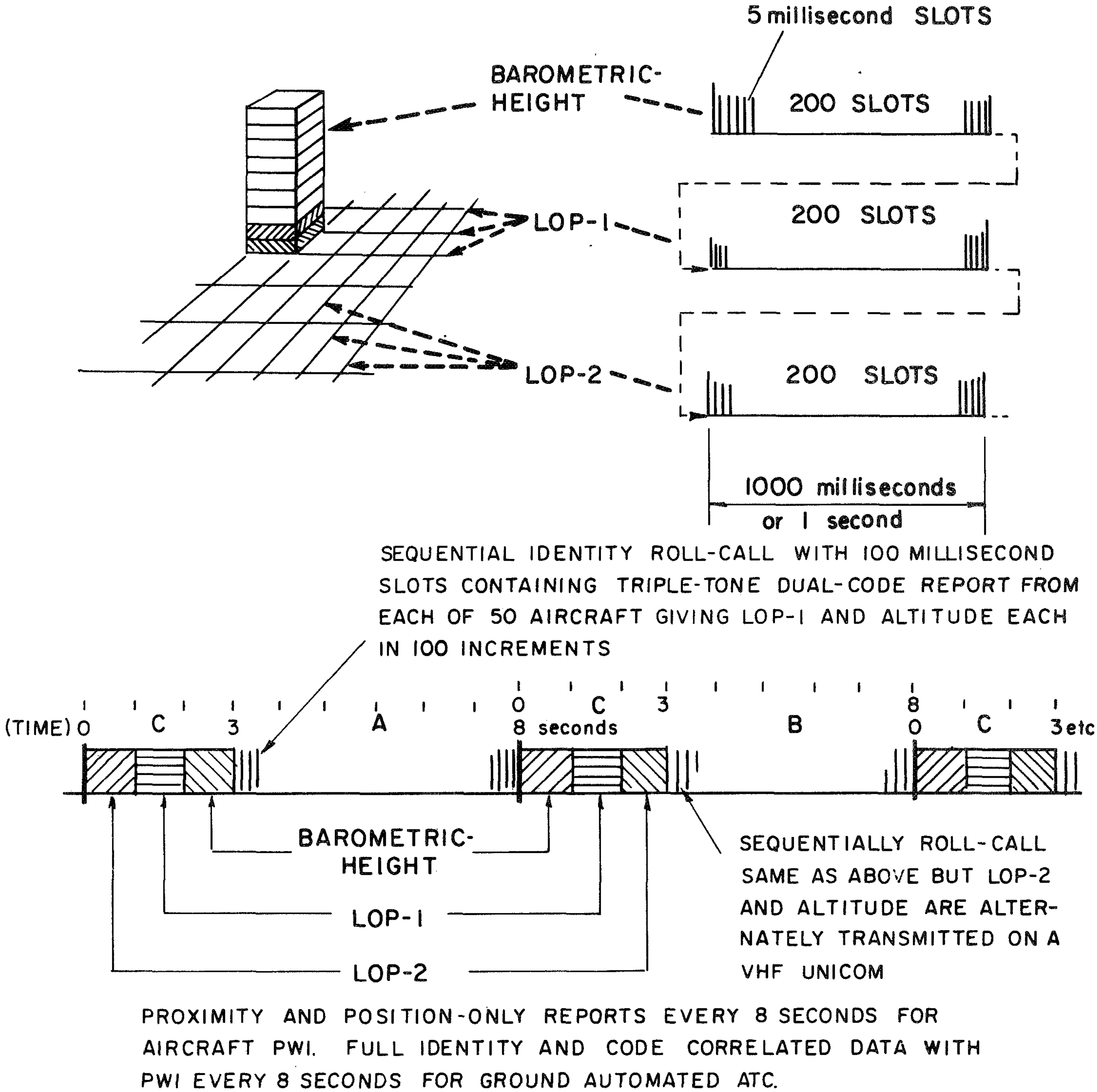


Figure 12. SYNCHRONIZED VHF REPORTING OF PWI AND ATC FUNCTIONS USING OMEGA TIMING SIGNALS AND LOP'S

Air-to-air spacing on Omega coordinate airways using direct Omega LOP's would significantly aid in the total traffic movements and capacity to accommodate general aviation. Omega would be equally of value to airlines but it is stressed here that by achieving a total low-cost, ATC-Navigation system suited to general aviation, the most demanding ATC problem is successfully solved, and airline use would naturally follow. The reverse logic of ATC system design does not work simply because, solving the airline problem first does not assure a very, very low cost solution initially, and thus general aviation is not accommodated.

The time-ordered reporting of the LOP's and altitude from each aircraft can achieve a multifunctional result saving several independent systems. This concept is very basic, since in visual conditions pilots can positively and easily maintain their desired spacing, even in dense traffic while maximizing the flow rate on a set of parallel tracks. This would give a similar function to all aircraft along a specified track so that each could observe others (up and down the assigned track) by a time-ordered display of the simplest type (a series of timed lights would even do) in the cockpit. Such a concept is effectively denied ATC today, since the guidance is from a multiplicity of non-coordinated, independent polar systems, not permitting overall system integration.

G. ATC SEPARATION AND TRACK SPEED CONTROL OF MULTIPLE AIRCRAFT ON THE SAME TRACK

Usually most aircraft want to follow about the same track, since the city origins and destinations are "grouped" rather than randomly spaced. Thus, the maximum flow of ATC traffic is possible by achieving, maintaining, and assuring everyone involved of the safety of the minimum, safe spacing possible. There is no way today for ATC to do this. Open-loop radar vectoring is risky in dense traffic if the radar is lost. Even with VORTAC as a source of direct parallel-separated tracks, separation signals are essential. The idea above of using the Omega time slots to achieve the air-to-air time differences and direct measure of range differences is suggested as a major ATC step.

For example, speed control is essential to maximizing the use of ATC track-space, since each track has a finite width and a minimum spacing must be assured among aircraft on the same track. Track speed control is impossible at present, since only airspeeds are used, and the pilots do not know by direct means their spacings along the track or airway from the trailing or the preceding aircraft. This concept is not a CAS (collision avoidance or proximity warning--most such CAS systems do not assume tracks). It is, however, a concept for the use of air-to-air signals of track position and relative track position giving separation data to each pilot. For maximizing the flow of air traffic and to maintain at all times a positive, safe separation, three major needs exist: (1) surveillance, (2) track following, (3) direct air-to-air separation. Air-to-air data exchange is lacking in most plans.

CAS concepts are mostly based on a poor premise: that somehow the ATC has failed and the aircraft have come too close to each other. In the case of each aircraft reporting in the manner described, full positional data and a parallel non-converging set of coordinates in three coordinates is available. Each coordinate is laminar or rectilinear in shape. This assumes that oblique-parallels are covering LOP's at 90 degrees. Although this is true for this example, the concept is still useful at other LOP crossing angles (Figure 12).

Thus, we might have about 200 elements of LOP-1 along the track direction and 200 elements of LOP-2 as cross-track position (giving the full coordinate position in a 50-mile-square area to ¼ mile or in a 100-mile-square area to ½ mile). Then, height data is available in 100 or 200 foot increments. Thus, we can visualize small cubicles of airpsace into which the area's volume is separated. Each cubicle of airspace, defined in a long baseline VLF system, is approximately the same shape and has approximately the same orientation and the same spacing so as to have uniformity--one of the most essential things in ATC system planning and operation. This is particularly true in a computer and ATC "sector" configuration of a given area (see Figure 2, which illustrates the typical "sectorized" New York ATC area). Thus we have 200 x 200 x 100 or 4 x 10^6 (4 million) of these cubicles that are each ½ x ½ mile by 200 feet (in a total volume of airspace 50 x 50 miles by a 20,000-foot height). This fine, uniform granularity of positional determination is sufficient to increase the airspace utilization, offering large capacity gains over today's VORTAC system, or even the costly expansion of VORTAC. Even if SSR surveillance is improved and expanded, an equivalence in direct cockpit display of position, track, spacing and area coordinates is essential for a true closed-loop concept of safe ATC. SSR tracking only or SSR combined with poor navigation coordinates tends quickly to be dependent upon "tactical" close-control concepts of voice vectoring by ground controllers, overloading ground controllers and ground-to-air data facilities. Pilot cooperation is often minimal in navigation, separation, etc., when close-control concepts predominate. It is essential to put navigation spacing and other ATC functions back in the cockpit. This implies a low-cost airborne solution if all airspace users are considered. Since it is estimated that 80 percent of the aircraft in 1980 may be small general aviation aircraft, the solution must satisfy this type aircraft or it is not truly an ATC solution. Merely protecting, guiding, and controlling airliners is inadequate, since the democratic use of the airspace and the past high risk areas involve small general aviation aircraft.

H. SPEED CONTROL

Now let us assume that the aircraft flying down a track parallel to all other tracks and defined by these cubicles of airspace is able to observe the traffic ahead, below, above, and behind--that is, traffic on his track--and he assumes that cross-track spacings of adjacent tracks are adequate to avoid adjacent tracks, traffic, and be fully independent from such adjacent track traffic. Once a common speed is achieved, all aircraft on the common track will maintain it, since the "spacing displays" permit the pilots to correct relative spacing to keep it constant, which is tantamount to a common track speed. This is achieved by pilots without tactical type ATC ground control instructions. In most types of traffic flow studies (say, maximum highway traffic flow), speed control and separation determine the maximum capacity movements per hour of the system.

The air display of the rectilinear-parallel track or area relative coordinates provides direct spacing and speed control in each cockpit. The display of the Omega coordinates gives the Area Navigation and/or track display, so that lateral deviations are eliminated. Closing, widening, and other descriptions of the wide variation of gaps in air-to-air spacing on a common track is avoided in the concept of the "string-of-beads" displays. With traffic evenly spaced, this uniformity of spacing and speed can be realized, since each pilot can react directly without a ground controller, estimating each condition, "eyeballing" the radar scope for estimating, and then relaying vague instructions to the pilots as he has no direct measure. The independent SSR surveillance system will be assisted as the users will see the more orderly nature of the traffic when observing SSR-ATC ground displays. This reduces the need for air-to-ground voice communications since most communications often relate to the aircraft-to-aircraft problem of maintaining spacing and track deviation.

This concept avoids the need for any "CAS" system as the means exist to maintain direct cockpit display of safe separation information which precedes and voids the need for CAS and is far more productive in ATC capacity. Collision avoidance is a negative philosophy as compared with the positive philosophy of integrated air and ground display of all pertinent traffic to each controller and pilot based on common earth-referenced coordinates and time-synchronized data exchange. CAS assumes a concept of "avoiding" collision, which is an inherent part of our positive concept; mere avoidance of collision may be safe but, not being an integral part of ATC, can greatly reduce capacity. Low traffic density can be safe traffic. However, all the projections are for a large increase in ATC capacity without sacrifice of safety, requiring a more comprehensive and positive concept than those now espoused by the current (CAS) concepts. Direct aid is given on a balanced basis to the pilots, the ground controllers, and to the overall efficiency and safety of the entire ATC system. Since the concept is low-cost and planned for inclusion of general aviation, this user is not excluded but will use airspace commensurate with the missions, speed, and aircraft types.

Basing the ATC system on a CAS concept or any exception to the principles and rules of ATC for all users is poor planning. Orderly progression of the SSR and "wide" Area Navigation concepts will satisfy the future, and increased capacity can be assured safely.

Thus, a low-cost simple means exists in the concepts herein described for speed control as well as air-to-air signaling and spacing. Two aircraft on the same track can achieve all this "on their own," and yet be fully harmonious with a central ATC system such as the SSR transponder system. If, say, a third aircraft arrives on the track by ATC assignment, the pilot establishes his relative track position with respect to the others, based on ATC instructions on spacing and ATC instructed speeds. If many aircraft are present on a given track and ATC requires increased or decreased speed, a message goes to all, and this is executed over a slow time period to avoid any excessive accordion effects of high closing velocity, and would, of course, be in small increments of about 3 to 5 percent of velocity change. Say, 150 knots increased to 155 knots, or decreased to 145 knots, which is a typical condition that might be required by central ATC observing the multiple aircraft, each on a common track and each observing the spacings of all others nearby on the common track.

I. MULTIPLE TRACK INTEGRATION WITH PARALLEL COORDINATES

We have discussed one of the most important aspects of ATC and how VLF navigation Omega coordinates and general aviation usage of a new Omega-A system can greatly aid VORTAC and SSR in the forthcoming years of predicted ATC airspace saturation and overloads. We have concentrated on common track problems of parallelism, spacing between adjacent tracks, separation of aircraft on a common track, and, of course, track speed control by direct pilot intervention in the ATC control loop using "along the track" displays, something readily achieved automatically in the time-ordered scheme herein presented utilizing Omega data transmission.

The next problem is, of course, the merging of two tracks into a single common track. One of the best examples of this problem is the feeding of a localizer track that goes to a single runway from two or more airways. The track from the East may be heavily loaded, and the one from the West is simultaneously lightly loaded. Say a 4:1 ratio exists in the inbound traffic flow from these two directions and the controller desires that one aircraft on the West track merges after each four aircraft on the East track have started down the localizer on final approach. This ratio of merging traffic could be a 1:4, 2:8, or an average of 1:5, 1:3, 1:4, etc. At any rate, the technical problem is maintaining the schedule and spacing of all aircraft, so that the traffic flow is synchronized between the two VLF tracks; thus, the meshing problem is minimized. Often "path-stretching" techniques are used so that by a variable-radius, variable turn-time, spacing errors are corrected, gaining or losing relative to a time-position slot on the common track is the rule of the game.

Omega tracks again are ideally suited for such ATC problems, since a change in track deviation will bring the aircraft to the localizer in quantified gain or loss positional units. Possibly a localizer intercept distance closer or further will suffice. However, the influence of this "meshing" operation is reflected all the way back on each track and, though it can be somewhat easily computed by ground SSR data, it is not easily executed in the cockpit since variables (winds alone) can create different air speeds, denying a good common final track speed or meshing speed. Furthermore, no adequate data transmission means exist to inform each aircraft of all the detailed data that is so obvious with a common track display of all common track aircraft.

This meshing effect, reflected a long way back on the two separate but interlocked tracks, is ideally solved by VLF coordinates (such as Omega), since every Omega track is not made up of a series of independent VOR radials separately generated but is a continuous and geometrically contiguous path computable over hundreds of miles. Every increment of Omega in New York can be exactly related to Omega elements in Philadelphia or Chicago, permitting ATC for the first time to have direct track control of speed and spacing to any distance commensurate with the track convergence where common tracks come together at a common terminal and each must be efficiently controlled to optimize capacity and flow to the runways. Speed and spacing control effected over multiple long tracks (carrying converging traffic to approach a set of parallel runways) are far more effective than final, localizer intercept, split-second path-stretching, and other current ATC practices. Of course, both meshing tracks have the same highly related coordinates since both would use Omega; thus, an aircraft 8 to 10 aircraft back from mesh can be related to another aircraft on another track that may be 10 to 11 aircraft back from mesh; thus, the two will finally space smoothly after mesh.

IV. STATION LOCATION AND CYCLE TIME FOR U.S. VLF NAVIGATION ATC SYSTEM

Basically the Omega-A stations should be located to optimize the transmission times (ground wave area), create the best geometrics of the multiple LOP's, and determine whether U.S. sites or possibly sites in Canada and/or Mexico are required. By locating the stations somewhat beyond the U.S. border (of the 48 states), the near transmission times and the undesired curvature of the LOP's is minimized. This goes back to the original postulation that in its simplest form the "raw" Omega LOP is used with a simple cockpit course deviation indicator (CDI) consisting of two (mutually perpendicular) crossed pointers.

Figures 8, 9, and 13 show that the raw LOP data exemplify simplified operations; this creates an Area Navigation capability by flying only directly on a series of selected LOP's (avoiding any coordinate computations). One must remember that any "centilane" of VLF can be selected and displaced to the center of the CDI. For example, if a flight between two lanes occurs, and it is near centilane 53, then the pilot selects the lane and centilane for the course deviation display (centilane 53 is zero-centered). Thus, locally there is an infinite number of parallel courses parallel to the direction of any LOP with constant spacing. For example, as Figure 13 shows, the pilot crosses lane 51.00 and sets the centilane to 0.53, and then turns into this centilane (51.53) following it to the crossing of lane 105 (of the obliquely crossing lanes), and then sets centilane 105.47 turning into it.

This navigation process is equivalent to VOR radial selections, intercepts, etc., except that it is simpler and easier because of the constant Omega sensitivity and better ability to easily judge intercept distances (turning, say, 20 centilanes before the desired one to allow for the turn radius of aircraft and Omega delay). This was demonstrated during the approximately 1 hour of flying experience that was gained in the McFarland demonstrations (reference 2). Thus, such area flying is much easier

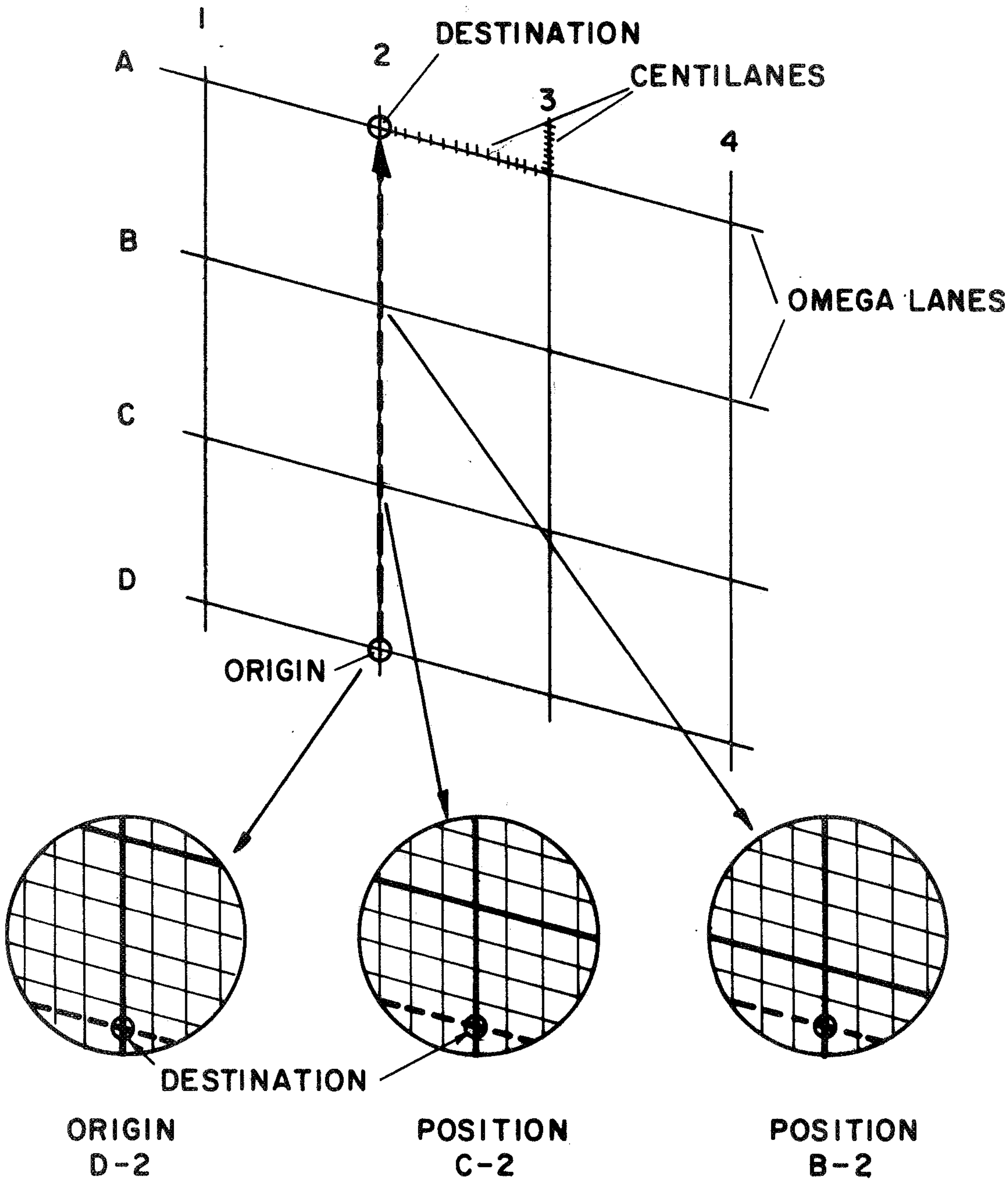


Figure 13.
LOW-COST PILOT'S DISPLAY OF DIRECT OMEGA LINES OF POSITION AVOIDING COURSE LINE COMPUTATION

to teach to new IFR student pilots, and is far less costly than the VOR/DME/Computer display of the VORTAC system.

The locations of the station should, therefore, provide to the maximum degree this simplified use of Omega. Even in the Boston area very near the New York Omega station the LOP's of New York-Trinidad are remarkably straight. Even so, if the station were, say, 500 miles into Canada, this would give good coverage. However, from an ATC viewpoint of serving the dense areas where general aviation actually needs such a system, these areas are in most cases sufficiently within the U.S. borders so that the Omega-A station could be located within the U.S. boundary. To optimize the distances to the Omega stations (signal strength, diurnal effect, etc.), some computer runs on the geometrics of several possible station locations should be made to satisfy the requirements of good LOP crossings and the maximum extent of straight LOP's.

When considering a small geographic area such as the United States (about 4.0 x 10^6 miles) vs the Omega 3-station potential of about 4,000 x 5,000 or 20 x 10^6 miles, it is obvious that several parameters of a 4-station Omega chain for the U.S.-only application can be optimized and improved over world-wide Omega. For general aviation use, considerable improvement over what is experienced today with the U.S. coverage of world-wide Omega is possible.

It is not implied that there is anything wrong with the U.S. coverage by world-wide Omega utilizing sophisticated receivers and processors; instead, we are merely discussing an optimized condition for obtaining simplicity, lowest cost, reduced data delay (4 seconds between samples), and minimum diurnal and other propagation effects. Means of automatically correcting a small area, such as the United States, is possible as it is but 20 percent of the world's surface area. Obviously, theoretical study will be required on this subject, though the 4 stations might emit near the 13.6 kHz of world-wide Omega to obtain the greatest number of electrical (phase angle) degrees per mile of track change. Perhaps a stronger signal and the use of another

VLF frequency (nearby) for heterodyning may be necessary, since the "coarse-fine" ratio would be about the same as that existing with the present 10.2 kHz and 13.6 kHz (3.4 kHz) signals. This new heterodyne signal might be similar to the present signal, creating a non-ambiguous position indication of about 30 miles. Composite processing of the two signals by methods demonstrated by Professor Pierce result in enormous reductions of diurnal effects (reference 9). Thus, with only a dual-frequency Omega receiver (rather than the 6-speed world-wide system), the desired general aviation service can be rendered. Furthermore, some effect on station location and use of optimized geometrics for ambiguity resolution will occur to enhance the 2-speed ambiguity of the largest value.

Once having planned this network, of course, the stations exist for other frequency emissions just as in the Omega world-wide chain, so that ambiguity resolutions could easily be enlarged to, say, 2,000 miles for airline use. Of course, this requires a more sophisticated receiver.

The objective in selecting the Omega-A transmitting sites and the VLF frequencies they will emit is hopefully to provide general aviation with the maximum benefits at the lowest cost on a national, not local, basis. This VLF-Navigation system would be compatible with and synchronized with world-wide Omega. The relationship is summarized in Table I.

It is not, of course, possible in this study to give the design problems in great detail; however, the steps are outlined by which these problems can be identified, resolved, and a decision arrived at on the future of Omega in ATC and general aviation.

1. Conduct a computer modeling of several locations of a 3 or 4 station chain of Omega-A emitting slightly above or below 10.2 and 13.6 kHz with a heterodyne frequency not far different from world-wide Omega optimizing the maximum non-ambiguous range difference.

2. Examine on a U.S.-only basis the signal strengths, the geometrics, and the diurnal effects of several candidate configurations of a 3 to 4 station chain. Test the 6

WORLD-WIDE OMEGA	U.S.-ONLY OMEGA
8 STATIONS	4 STATIONS
10-SECOND SAMPLING	4 TO 5 SECOND SAMPLING
TABLE OR DIFFERENTIAL DIURNAL CORRECTIONS	AUTOMATIC DIURNAL CORRECTIONS WITH CENTRAL STATION 5th
4000 TO 5000 mile BASELINES	1500 TO 3000 mile BASELINES
FREQUENCIES (THREE CARRIERS) F_1, F_2, F_3	FREQUENCIES (THREE CARRIERS) F_4, F_5, F_6
AVERAGE SIGNAL LEVELS	STRONGER SIGNAL LEVELS
ABOUT 3 TO 4 LINES OF POSITION ANYWHERE	ABOUT 5 TO 6 LINES OF POSITION ANYWHERE
10 TO 14 kHz REGION	10 TO 14 kHz NAVIGATION 15 TO 25 kHz DIURNAL
COMPLEMENTS 4-STATION U.S. CONFIGURATION	COMPLEMENTS 8-STATION GLOBAL CONFIGURATION
DIURNAL CORRECTION AREAS ABOUT 5000 (200 nm x 200 nm)	DIURNAL CORRECTION AREAS ABOUT 100 (200nm x 200nm)
COVERAGE AREA (approximately) 200 million sq. miles 60 million - LAND 140 million - WATER	COVERAGE AREA (approximately) 4 million sq. miles 3.5 million - LAND .5 million - PERIPHERAL WATERS

Table I. RELATIONSHIP OF WORLD-WIDE TO U.S.-ONLY OMEGA hyperbolas to optimize crossings and "coarse-fine" lane spacings from selected pairs.

3. Examine cases for the stations within the United States boundaries (48 states) as well as possible sites in Mexico and Canada.

4. Study the integration of the Omega-A (or U.S.-only) with the basic (now committed world-wide) Omega plan (stations in Trinidad and Minnesota) to determine whether some integration of the sites could occur with the Omega-A using these two stations; this would reduce the cost of the U.S.-only installations. Several permutations and combinations exist: use only one of these existing stations; use two of them; use 2 additional (U.S.-only) stations; use 3 (U.S.-only) stations; use only 1 additional (U.S.-only) station.

5. Study transmitting cycle signal formats and choice of frequencies to optimize the use for general aviation and for transcontinental air carriers as a national navigation network "comes for free" even when attention is given to a 2-frequency-only receiver with optimum performance in local areas (say, 200 miles on the side).

6. Study low-cost Omega receiver designs, such as a modular concept where some 8 to 10 basic modules are developed that can be assembled into a 1-frequency, 2-frequency, or 3-frequency receiver with modules for local oscillator, processing, and direct (raw) LOP/CDI indication outputs.

7. Study several configurations for the sealed CDI type map and track following displays and have models built and flight tested in selected areas against existing Omega signals.

8. Test various means of automatic diurnal corrections such as a central station utilizing a continuous channel for data transmission to local areas or a sharing of the VLF navigation frequency.

9. Long-term general aviation testing of the Omega signals is required. The details of the test must be commensurate with the signal strength, proximity to a transmitter, etc., of the U.S.-only chain (say, flying on Trinidad-New York at the baseline mid-point). These tests should be run continuously for one year with an instrumented aircraft to measure static, automatic diurnal correction, accuracy, SID, etc., that may adversely affect the system and require system changes.

10. Study the applications of Omega to ATC at various locations in the United States that now have pressing needs,

such as the Northeast Corridor, Southeast Corridor, and the Chicago-Great Lakes areas. Examine surface signal levels, effects of hangars, use of the signals on an airport surface (registry of position in the cockpit before takeoff). Also examine the use of monitoring locations throughout the United States to assure performance and develop flight-inspection techniques.

11. Use computer analysis on air traffic flowing at prescribed lower altitudes (from jet traffic) that will be mostly general aviation traffic to determine the traffic capacity of the Omega airways that can be generated directly with coordinates from the U.S.-only Omega chain. Since most air traffic is on a parallel basis (all runways in New York airports are either 4-22 or 13-31, for example), a natural, harmonious, geometric condition exists that probably is needed in ATC and is inherent in the Omega coordinates. Determine how far this argument applies throughout dense and low-density air traffic areas of the United States.

12. Examine the integration of the Omega Navigation and air traffic usage with SSR, VORTAC, and existing (ATC) alphanumeric computer display centrals--for example, insertion of Omega data into existing ATC displays, and using Omega as an equivalency of DME with VOR stations or ILS localizers.

13. Flight-test the concept of the air-to-air separation data from Omega signals to determine feasibility and then utilize this data in computer simulation of traffic handling using such dual inputs of proximity warning data (between aircraft and aircraft to surface).

14. Test the BTL triple tone data transmission (selection of 100 codes in 40 milliseconds) as a means of relaying airborne-sensed Omega coordinates to ground facilities.

15. Test the simplified use of Omega coordinates for low-cost ATC displays and low approach with differential correction for thousands of small airports and very low density air traffic areas including low altitude coverage. Simple roll-call techniques may permit three-dimensional data.

16. Examine airline and high-altitude traffic usage of Omega for a "no-channel-change" universal navigation system from coast to coast. Also examine airline-to-airline separation (proximity warning) at high altitudes using the air-to-air mode of Omega roll-call techniques herein described. Also examine the common airspace sharing by general aviation and airlines both using Omega in such common airspace for navigation, PWI, track separation, vertical separation, etc.

17. Test and study the use of the Omega time signals for a national aviation timing source, because many of the functions can benefit by using a simple time standard available in all aircraft and all ground facilities (goal is a $250 general aviation unit accurate to about 1 to 2 milliseconds throughout the Omega 10-second sequence, assuming a 4-station 5-second cycle.

18. Test several of the differential Omega concepts such as (1) use of "dead-time" of Omega receivers for processing of a VHF transmitted signal for diurnal correction, (2) elapsed time between such updates on a national basis, (3) means of automatic voice updates on Omega using VOR or similar voice circuits, and (4) the possibility of a common Unicom frequency. Also test VLF for slow rate digital transmissions addressed to distinct parts of the country. Compare single frequency automatic diurnal corrections to results of dual-frequency "composite-Omega" techniques.

19. Examine the VHF communications load with the national use of Omega-VOR in general aviation use only; then, for all airspace users determine the amount of voice loading that can be reduced with a national grid of navigational coordinates and a national air-to-ground data reporting system of these grid signals. Determine whether this creates the redundancy essential for the SSR data (high-density traffic). Examine the results obtained, assuming that all IFR traffic is under control of both the SSR and the VLF systems. Surveillance SSR data and independent navigational data (VLF-VHF), also reported to the ground, provide the essential safety for high-density mixed traffic because the VLF data corresponds to the actual information utilized by the pilot for track following.

20. Examine the air-to-air and air-to-ground proximity warning features of a simple time slot reporting of height, positions, etc., and the maximum degree of simplicity and minimum cost that can be achieved in combining the barometric sensing, BTL tone data, time slots, and so forth, in an aircraft readout of another aircraft's messages. Determine whether a dual mode of sequential time slots and multi-tone data link is optimum.

21. Conduct a VHF ATC-communications channelization study for establishing a few national open VHF channels such as "Unicom" for time slot or tone data link reporting. Theoretically, such a system should reduce the voice load so extensively as to free several channels for full-time VHF data transmission of VLF Omega coordinates to and from aircraft. These VHF channels could serve about 50 aircraft simultaneously with PWI, air-to-air track separation, altitude reporting, etc.

22. Examine a total national plan where one coordinate system exists on a ½ to ¼ mile accuracy basis. Determine whether this system can carry the full traffic load in, say, 30 years, while in the interim joint VORTAC-Omega coordinates exist, even if this is less efficient in use of airspace. Establish an optimum cost-benefits relationship between a limited future VORTAC environment and a national VLF navigation and position reporting system.

23. Study and flight-test the emission of the time signals, BTL data, and the Omega coordinates over VOR stations since the VHF navigation equipment in most general aviation aircraft could provide a dual function of data on the voice channel and normal VOR navigation.

24. Study and flight-test a "mix" of VOR and Omega LOP signals, since an Omega receiver may be cheaper than a DME receiver. The concept is that the VOR would send the Omega differential signal so that the coordinates could be fully referenced to the VOR the pilot is tuned to (and utilizing for navigation). Test the following of LOP's of Omega using VOR radials as distance along track or destination. Various combinations of: 1 Omega LOP and VOR, 2 LOP's and VOR, 3 LOP's and VOR, 1 LOP and 2 VOR's, 2 LOP's and 2 VOR's, etc., should be considered. Examine the integrations of VOR and Omega LOP flying in the same instrument since they are both CDI type instruments.

25. Test the time of arrival at multiple ground sites of Omega-timed VHF signals from aircraft as an independent surveillance and position correlation technique.

26. Most CDI instruments have but two mutually perpendicular needles. Tests (human factors) and flight validations should, therefore, be made of the use of a double-needle display using color-coded needles for smooth transitioning from one LOP to another, or for showing destination LOP crossings and current position LOP crossings. This is with a gimbal arrangement for presenting true geometric LOP crossings. Such an instrument may aid considerably in the ATC usage of Omega by general aviation.

27. Study and test the concept of a vertical radar signal for in-flight calibration of barometric-sensed height to permit low-cost barometric encoding as in radio-sonde units. This unit is to be integrated with an Omega transmission for differential correction and position and identity reporting, so that the two "differential" concepts of vertical and lateral separation are treated in concert and not in conflict.

28. Obtain permission from the Navy to test a slow digital message transmitted to existing Omega stations during their dead time to test the concept of a national system with automatic continuous diurnal corrections.

V. AUTOMATIC CORRECTION OF VLF NAVIGATION ERRORS

Many references explain the effect on navigation of the variations in propagation that occur in the VLF region. Perhaps the best summation of these and related engineering problems is contained in a recent book by Arthur D. Watt (reference 7). The waveguide modes of the two main frequencies of Omega (10.2 and 13.6 kHz) vary somewhat during the day as the sun path across the earth's surface varies the effective height of the ionosphere. Since the actual position of a given LOP is determined by its geometric relationship to the varying ionosphere, various baseline directions need different correction.

It is possible to predict with a fair amount of accuracy the diurnal variation at any point in the coverage of a pair of Omega stations, and this is done by the Navy using past history and computer simulation of the waveguide VLF transmission modes. These diurnal correction tables are published and used by ships and aircraft that use Omega receivers. Prediction accuracy is improving continuously and will probably result in overall predictions of less than 1 mile of error anywhere in the coverage of the world-wide, 8-station complex.

By comparing the 13.6 kHz and 10.2 kHz in a composite mode, it is possible to utilize the fact that the phase shift of one frequency is in the opposite direction from the other frequency (though at a different amplitude) and, when properly used, creates an effective cancellation of the two shifts. This comes about theoretically from the fact that the waveguide velocity varies for the two frequencies that are separated by about 30 percent.

It is also possible to locate an Omega monitoring receiver at a surveyed point in a local area and transmit the diurnal errors established by comparing its location and the actual received LOP's with an averaged LOP position. These tests have shown that accuracies of about ¼ to ½ mile can be expected (reference 10).

Thus, there are many ways to reduce the diurnal error since it is highly predictable and repeatable. It can be removed for operational purposes just as the variations in surface barometric pressure are transmitted to aircraft to add or subtract to their airborne units (of barometric pressure measurement), which is operationally utilized as altitude data for both air and ground in the national ATC system.

A. UNIFORM NATIONAL MONITORING OF VLF SIGNALS

It is possible to organize the method of correction of the VLF diurnal effects somewhat differently than in the past to improve the forecasting of the differential data and to provide, if desired, a fully automatic diurnal correction in the aircraft receiver. Figure 14 illustrates a concept that uses about 20 Omega receivers that are strategically located throughout the United States. These sites receive at specific, precisely surveyed locations the signals from the four VLF stations. The receiver outputs are converted to low bandwidth data transmission to be suitable for transmission of all their outputs by normal land wire to a central computer in the central part of the United States.

At the computer the instantaneous readings of the phase angle at the various locations are examined on a total-area basis, compared with past history and any possible non-ordinary occurrences (such as solar flares, PCD's, etc.) that may affect the ionosphere. These inputs on a continuous basis from a wide area permit much more precise prediction to be made than is usually experienced. One must recall that the four VLF stations that serve the United States provide navigation for an area only 2 percent of the total area covered by the eight-station world-wide net. Thus, each monitor represents but about 0.1 percent of the earth's surface. Such a scheme is suited to such small areas, but it is probably not suited to a world-wide installation. Furthermore, 90 percent of the U.S. coverage is land, allowing ground monitoring, whereas only 30 percent of the world's surface is land, resulting in enormous unmonitored areas.

The centrally located computer then computes the actual value of the correction signals that should be used anywhere in the total coverage area of the four stations. This output is then

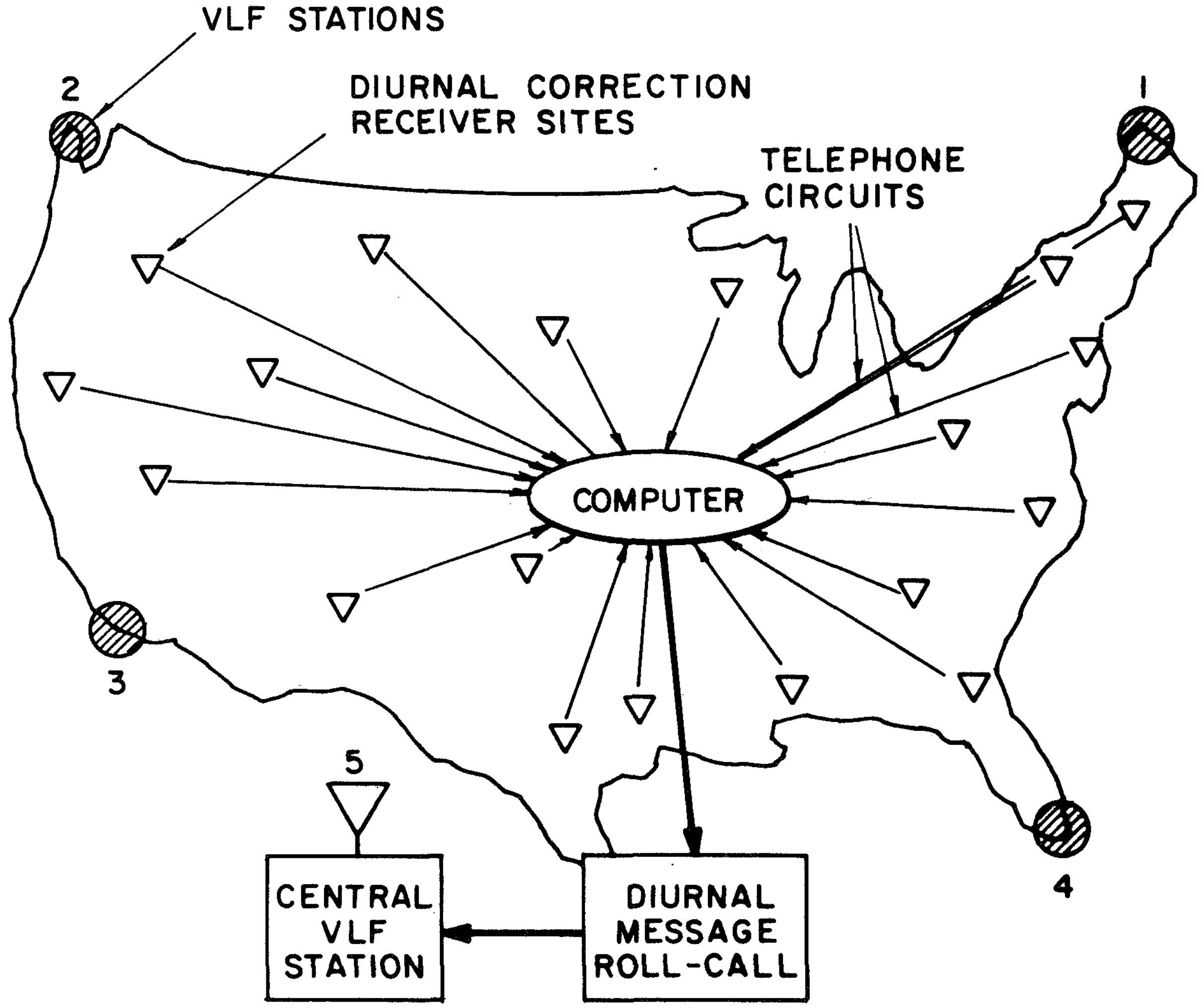


Figure 14.
ABOUT 20 MONITORING SITES FOR COMPUTATION OF NATIONAL DIURNAL CORRECTION MESSAGES AND FOR QUALITY CONTROL OF GUIDANCE DATA

transmitted to airborne receivers over a fifth station (also on VLF) on a continuous basis. The diurnal correction data from the computer can also be transmitted on a national basis, if desired, to individual local areas and placed on the VOR voice channel, VHF Unicom, or special national VHF communication frequencies. Aircraft reception over VHF of diurnal corrections is in voice suited to manual pilot insertion. There are also several possible ways of automatically correcting, through the Omega receiver, the diurnal error using digital data correction transmissions.

One of the most intriguing methods is to use the Omega receiver itself to receive the central message, decode it for the local correction, and automatically insert the corrections into the receiver output.

Prior to discussion of the method of transmitting this centralized transmission, it should be noted that the 20 sites would be typical of the total needed for monitoring a total VLF coverage of the United States. For cost comparisons consider that the VORTAC system requires two major monitors at each site: one monitor for DME and one for VOR. Furthermore, many aircraft are flown on nearly a continuous basis for flight inspection of the VORTAC signals. Thus, to guarantee the safe, continued operation of the national VORTAC network of polar coordinate navigation, 2,000 local station monitors are needed with 2,000 remote indications of the monitor outputs. The massive manpower for installation, maintenance, monitoring, flight inspection, etc., for VORTAC is an enormous, continuous financial drain on the resources of the FAA.

With a national, wide-area, VLF coordinate navigation system, localized monitoring is unnecessary since the generalized propagation characteristics of VLF can be monitored for the whole nation at about 20 critical locations and fed to the central computer for processing and transmission of locally addressed correction signals.

The performance and integrity of VLF signals at a surface receiving site, carefully selected to sense the true, local, Omega flux, is a fair reproduction of the same signal at altitudes up to the highest used in aviation. VOR monitoring on the bottom skirts of the bottom vertical lobe does not offer this same high degree of integrity and correspondence between what data is monitored and what data the pilot uses in flight. Thus, Figure 15 suggests central monitoring, diurnal computations, and other quality control functions that would be required of a national lattice of VLF coordinates created by the 6 LOP's.

B. <u>PHASE-CODED MESSAGE FOR DIURNAL CORRECTION</u>

It is possible to transmit from one centrally located VLF transmitter a slow phase-coded message that should be received without error under any conditions where VLF navigational signals can be received. The automatic diurnal correction signal will be assured in the same manner as the VLF navigation is assured nearly continuously from an adequate number of high-powered pairs selected from the four-station complex. By using a slow transmission cycle that is synchronous with the switching cycle of the VLF navigation net, we can assume that a continuously synchronized means of a roll-call to specific geographic areas can be realized. An example of such a message is shown in Figure 15, where the phase of the VLF signal is shifted in 90-degree steps with some 8 bits in a given frame to create a possible series of coded data messages totaling about 100. As shown in Figure 15, since the message is completed in about 1 second, it is possible in 100 seconds to send messages to a hundred (or so) designated areas of the United States simply by organizing a sequential geographic roll-call. The message having a possibility of conveying 100 quantities would be able to correct to 1 percent of a lane width, or the quantized error corrections would be in steps of about 500 feet, or assume ± 250 feet.

Professor J. A. Pierce of Harvard has successfully tested similar phase-coded messages, and the results indicate that the large steps in phase difference overcome any possibility of phase errors caused by noise. If for signal format economy one would desire a more sophisticated message, say, in steps of

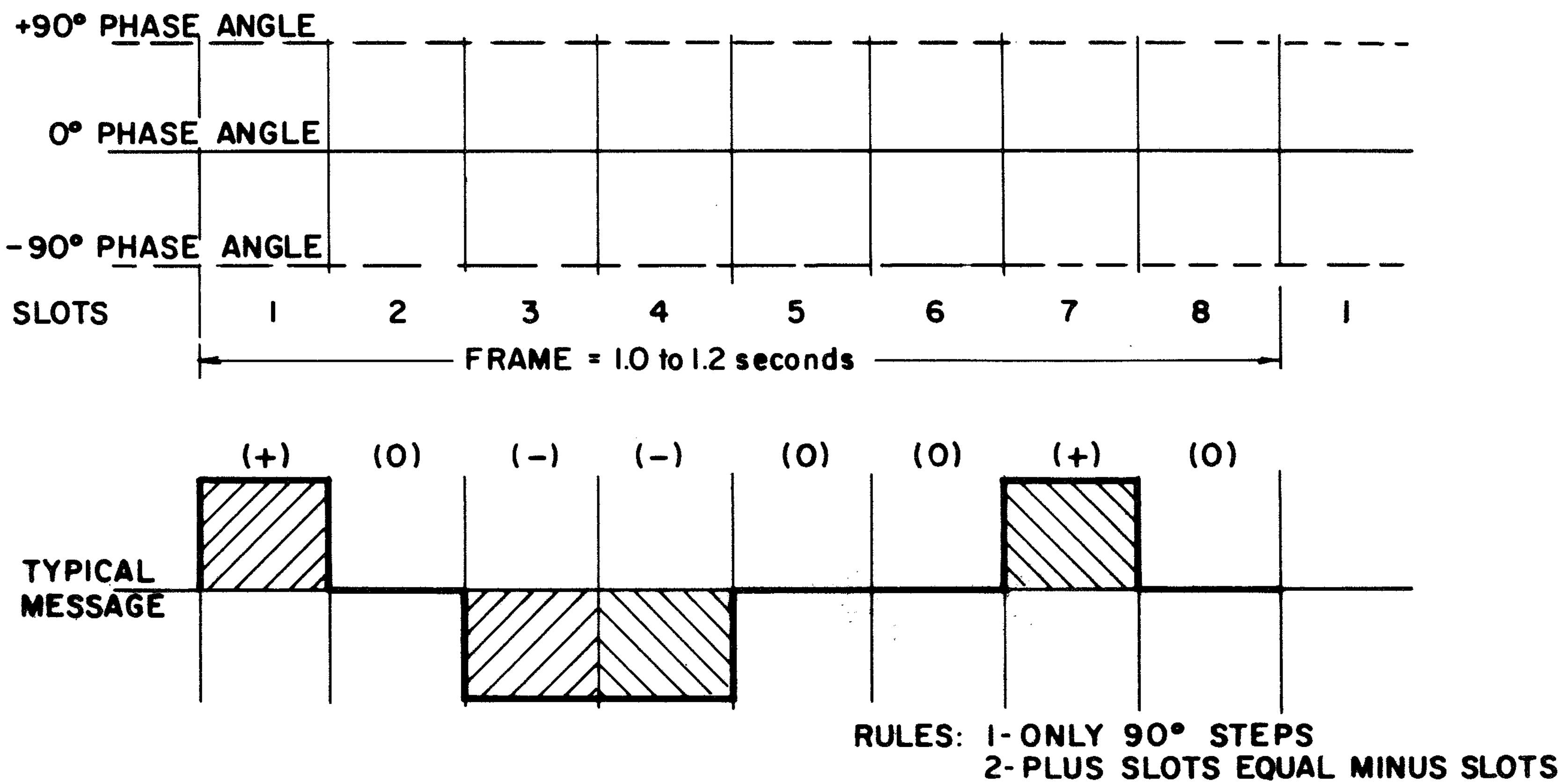


Figure 15. EXAMPLE OF PIERCE TYPE CODING FOR NATIONAL DIURNAL CORRECTION SIGNAL (99 COMBINATIONS)

30 degrees of phase angle change rather than 90-degree phase steps, this would create a greater number of code variations and thus require less time to transmit a given correction signal. However, occasionally the noise bursts may be sufficient in level that the 30-degree phase condition could be shifted or difficult to interpret. Thus, 30 degrees seems inadequate based on past experience. A possible compromise using 60-degree steps in a digital phase-coded message format is noted in Figure 16. It is evident that the optimum code can be determined only by testing under typical propagation conditions (typical of the United States) and by simulating the four stations and the power levels employed. However, since the 90-degree phase-coded digital messages are the most conservative with respect to overriding any interference and require the longest time to transmit, we will examine this signal format to determine its effect on total system planning.

C. ROLL-CALL OF 100 AREAS FOR DIURNAL CORRECTION DATA

Figure 17 illustrates several points. First, the areas that receive specific data and are assigned a given diurnal correction time slot are variable in size with the areas being smaller near the stations and larger in the mid-point between stations. The reason for this is that the VLF wave, once propagated, varies more in phase near the station than at great distances from the station, since the wavelength is so long and the ionosphere effects are greatest. Thus, by using small diurnal correction areas near the stations, the corrections are more valid and the total user error is reduced. It is estimated that some areas would be as small as 100 miles square and others as large as 200 miles square; averaged out about 100 areas could cover the United States.

By numbering the diurnal correction areas in a sequential manner with geographic location, as suggested in Figure 18, it is possible to simply sequentially transmit the error signals designated for a given location. Each bit is about 15 milliseconds so that an 8-bit, 90-degree phase-coded message requires

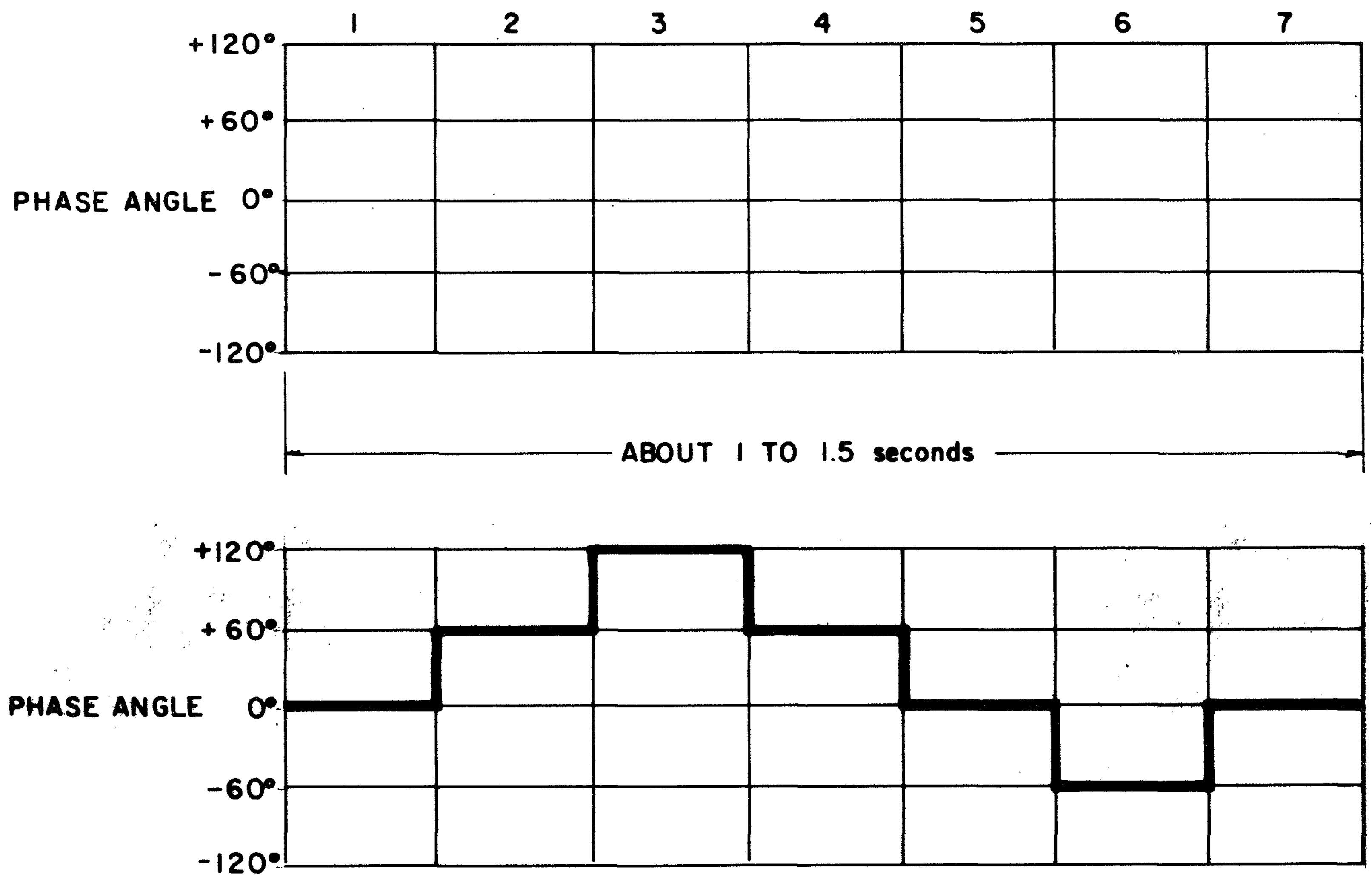


Figure 16. DIURNAL CORRECTION SIGNAL USING 60-degree PHASE STEPS CREATING OVER 100 DISCRETE VALUES

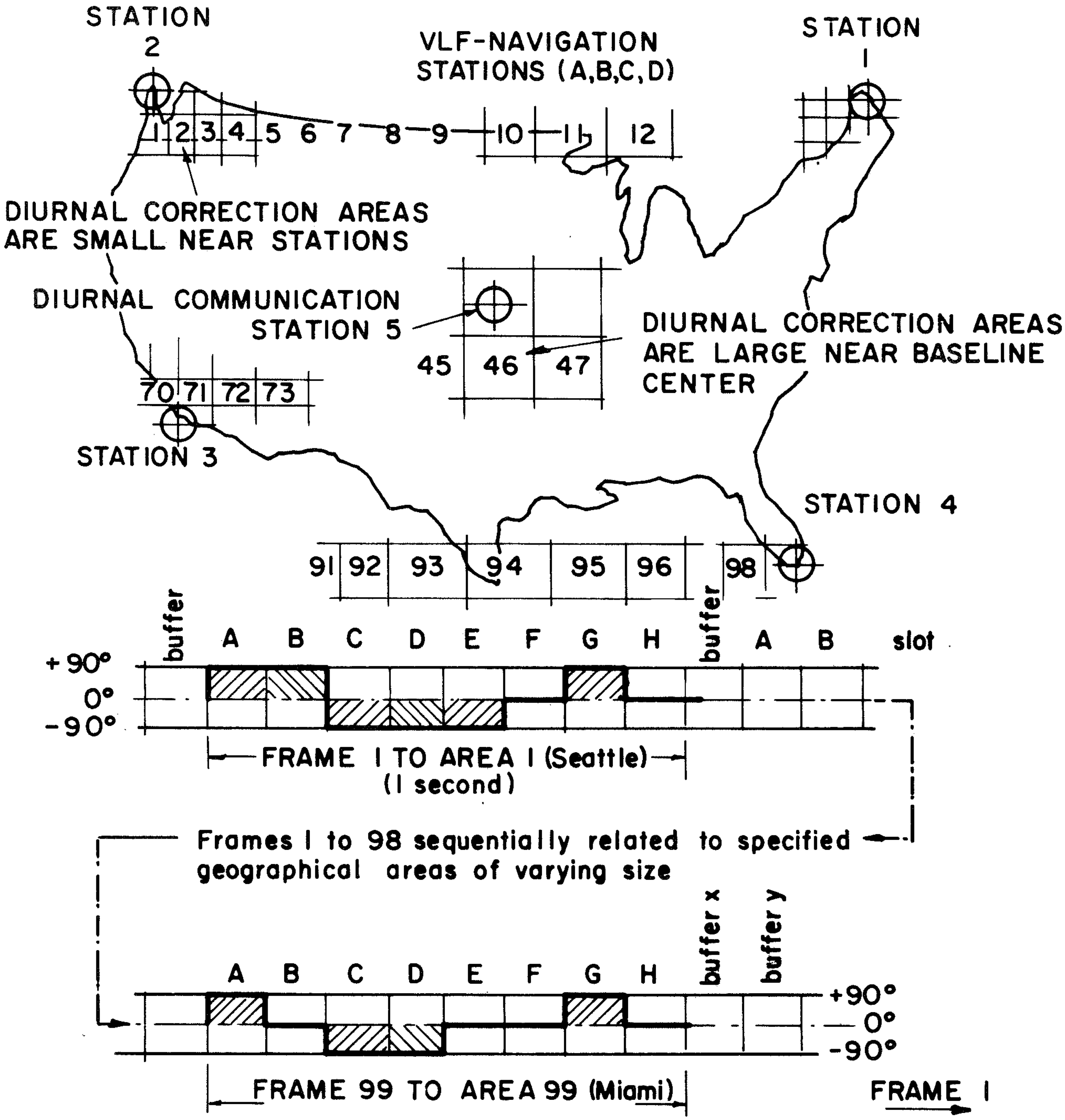
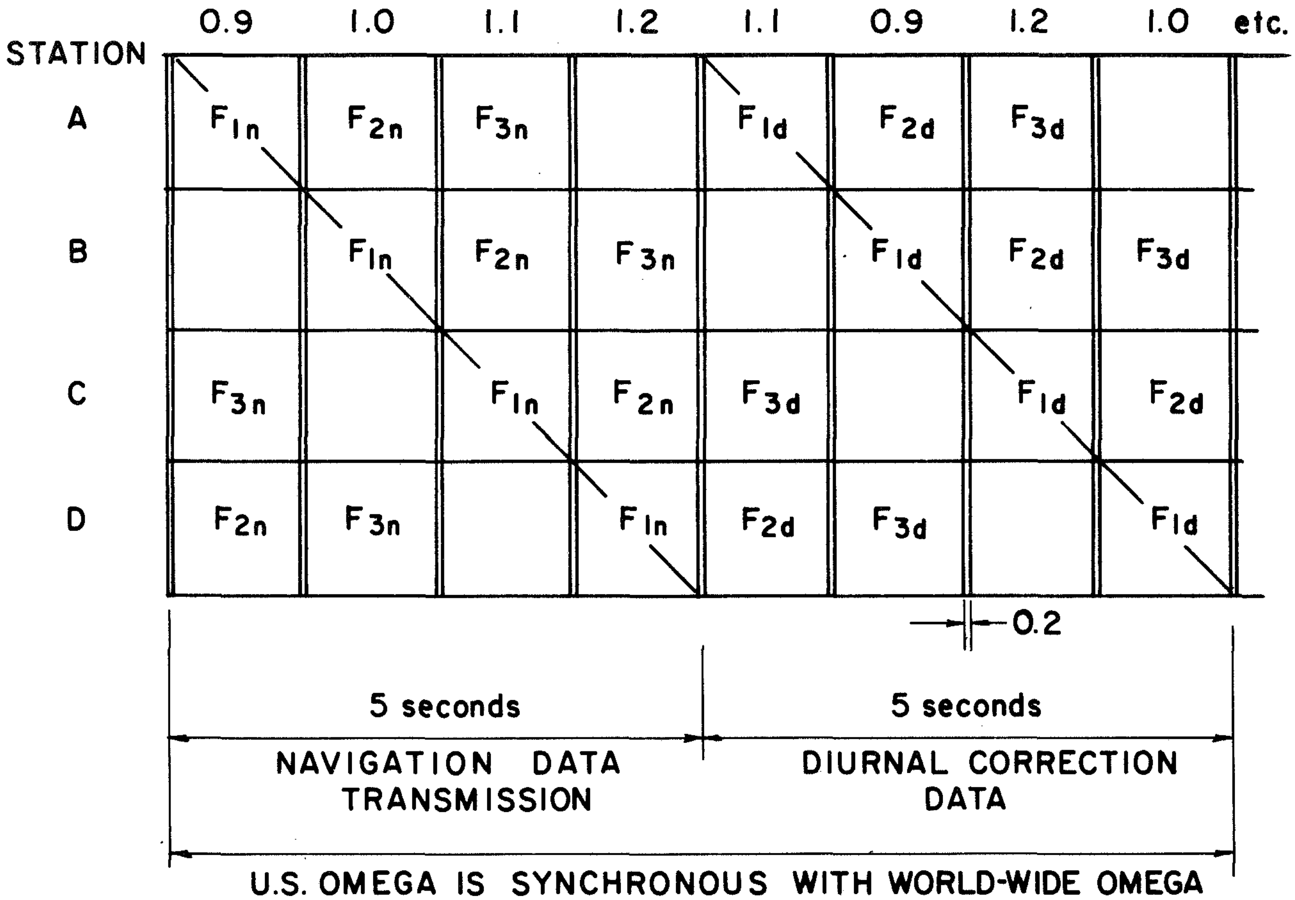


Figure 17.
DATA TRANSMISSION FOR AUTOMATIC DIURNAL CORRECTION OF NATIONAL VLF NAVIGATION FACILITY



F_{1n} (etc.) NAVIGATION FREQUENCY NO. 1

F_{1d} (etc.) DIURNAL TRANSMISSION FREQUENCY (SAME F_1 IS USED FOR NAVIGATION AND DIURNAL DATA)

Figure 18. SIGNAL FORMAT FOR FOUR-STATION U.S. ONLY VLF NAVIGATION WITH AUTOMATIC DIURNAL CORRECTIONS

about 1 second for completion. Since the completed sequence to 100 areas takes but about 100 seconds, or about 20 minutes, synchronization is quickly established in any aircraft. Since all Omega signals can be received on the ground even before the aircraft engines are started, the synchronization problem is not serious. Another feature is that the diurnal corrections for adjacent areas will differ very little with respect to each other because this is characteristic of the propagation phenomena that establishes the diurnal correction. Thus, if a message is lost or an adjacent area message is erroneously received, the errors will be minimal. Also, it is possible to receive the messages for the local area to which they are addressed as well as messages for each adjoining area. If desired, the more sophisticated users who desire the utmost in accuracy, reliability, etc., can interpolate adjacent samples of this signal.

Since the errors are quantized in steps that are ±250 feet of a given value, as determined by a national monitoring and computer facility, adjacent areas can vary by this amount if there is a progressive diurnal change across the nation. The signals from the four stations each vary in transmission times as in the world-wide Omega signal (0.9, 1.1, 1.0, 1.2, etc.). Thus, the station identity code using variable durations is also synchronized every 4 seconds. The central (fifth) station also transmits a synchronous signal at the start of each roll-call of the 100 areas. Since the roll-call can be arranged for correcting each station there would be four roll-calls, lasting a total of about 8 minutes with adequate synchronization signal between each. With the four Omega navigation stations and the central, digital-data VLF station all transmitting synchronous signals, no fear of loss of synchronization is warranted. In fact, the synchronization should be easing within 1 to 2 milliseconds so that each bit of the phase-coded message (lasting for about 15 milliseconds) cannot be erroneously decoded. Furthermore, the 90-degree phase-coded steps themselves will create another second-by-second synchronization signal, so that two to three continuous clock messages are received from the system. With the United States, which is only 2 percent of the world's area, being divided into 100 areas, the average area receiving a diurnal message is only 0.0002 of the earth's surface. In other words, such a scheme is not applicable to world-wide systems because about 5,000 areas would have to receive coded messages.

Since the individual diurnal correction is addressed only by roll-call on a geographical sequential basis, the synchronization must be assured at all times. Figure 18 illustrates this principle and denotes a raster type roll-call sequence across the nation, with area 1 being near Seattle, then sequentially areas across the northern part of the nation are identified. Then centrally the area about slot 50 (say, in Kansas) would be encountered, and finally the last raster would end in the Miami area, with slot 100. Maps would contain the number of the area, and the pilot would simply turn his switch to this number for the automatic reception of the local, automatically decoded correction.

If the pilot were to fly into an adjacent area without turning the switch, the diurnal error would be minimal, possibly adding another 500 feet.

Since the diurnal error can be corrected to about ±250 feet, and the receiver errors should be maintained within about 500 feet, it is likely that such a VLF navigation system, updated for diurnal corrections every 10 minutes, should create a total national error averaging less than 1,250 feet, or about ±¼ mile. The areas of granularity of errors are mostly uniform (rectangles or parallelograms), so that this is an approximate error of ¼ x ¼ mile, or 1/16 of a square mile in aircraft positioning vs the FAA AC 90-45 (reference 4) estimate of VORTAC errors of ±1 mile at best, and ±4 miles as the worst case. This fact alone should offer a granularity of VLF of about 20 to 40 times better than VORTAC and, consequently, add enormous area capacity for flight tracks, airport approaches, etc., not possible with VORTAC.

In other words, the inefficient use of the airspace as shown in reference 4 would be improved greatly with the VLF system using the simple diurnal correction system described in this report. Piloting errors in the FAA estimates must also be added to VLF, but because of several piloting advantages (linearity, constant sensitivity, non-convergence, etc.) the piloting error averages much less.

D. ALTERNATE DIURNAL TRANSMISSION OF SIGNALS

Since the world-wide Omega operates on an eight-station, 10-second cycle, it is possible to operate but four stations on a cycle of half the time, or but 5 seconds. This leaves a 5-second period open for each Omega station to transmit a phase-coded diurnal message. Thus, by time-sharing methods, about half the time could be devoted to automatic diurnal signals. Dual frequencies permit two separate diurnal phase-coded message paths to each aircraft, thus doubling the message capacity, assuming the same 90-degree phase-coding 8-bit message. This scheme has some attractions since the message could be received with the identical receiver, phase circuits, etc., and time-coded so as to add the corrected amount to the receiver output. Using the same phase measurement circuits and receiver could reduce costs. The roll-call method would be similar, and the diurnal corrections might occur on two or three of the Omega transmitting frequencies, each addressed to a different part of the nation, to increase the capacity for message formats. Such a plan still allows a monitoring and central computer for national updating of diurnal errors continuously every 10 minutes.

This raises the question of how frequently the diurnal corrections should be received and inserted in the navigational data. Examination of the rate of change of diurnal errors, to determine the highest rate of change, indicates that with a 10-minute updating of all diurnal errors to quantized amounts of about ±250 feet, the error accumulated since the past update would be less than 500 feet; thus, little added error would occur. Furthermore, this rate of change is predictable every day for each hour of the day, and for each area of the United States, as the daily recordings of these errors repeat to amazing correlation accuracies. Thus, in areas where a rapid diurnal change was momentarily anticipated, some lead in the time of the diurnal correction data could occur to minimize any degradation of the sampling time influence.

Figure 18 suggests one possible signal format that is a derivative of the world-wide Omega signal format so as to be fully compatible and in synchronization. It will be noted that stations A through D transmit navigation data for the first 5 seconds, and then they transmit diurnal correction data for the next 5 seconds, and then back to navigational data for the next sequence. Thus, in 10 minutes a total of 300 seconds can be devoted to diurnal messages, and each message requires about 1 second. The planning of 300 messages on two frequencies can create 600 messages to optimize (1) the time between messages, (2) the area each is assigned, and (3) the complexity of the reception means. The plan can be accomplished only by a trade-off study and analysis based on the validation of experimental equipments. This scheme and the fifth central VLF station scheme each have pros and cons, best resolved by testing.

E. AUTOMATIC DIURNAL VLF LOCAL VHF TRANSMISSIONS ON VOR OR UNICOM

One interesting thought is that all general aviation aircraft will retain a VOR and/or VHF communication receiving capability at all times in the future. Since the VLF diurnal correction signal can be readily received at a VOR station, for example, it can provide the data to all aircraft, established either by direct VLF navigation monitoring or from a centrally computed diurnal correction signal. The local VOR station would transmit the VLF diurnal correction every few minutes. An automated voice message is employed just as the "canned" voice message is now used to provide the station identity. Since the station identity is so overly redundant, it is possible to insert the automation voice correction signal every few minutes without fear of any degradation of the basic VOR signals.

Furthermore, the coverage would be self-controlling since a given VOR signal cannot be received beyond line-of-sight, and the local VLF error signal would correlate fully with the location and actual coverage area in which the VOR signal is receivable. Thus, one would not worry about addressing the VHF emitted diurnal correction because the area of VHF coverage is commensurate with the correction (navigation data) area. Even possibilities of semi-automation occur, since the VOR can easily transmit a phase-coded message using its own 9.96 kHz reference signal--that is, the subcarrier for the 30 Hz VOR reference. Possibly a 10.2 kHz signal could also be sent directly on the VOR station carrier in a periodic manner without affecting a VOR's normal function. Consequently, a local user could receive his VLF correction directly in phase angle (of Omega data) but from the VOR reference signal.

Furthermore, since the VOR is a radial track, locally used system, it can be used with national VLF lines of position so that a crossing lattice of oblique-parallel lanes and VOR radials occur. This provides data that is equivalent to a DME function for the owner of a VOR receiver. He can avoid DME and a costly course line computer as "raw" data is used. Similarly, the synchronization of the diurnal and air-to-ground data messages on the VHF channels suggests a closer relationship between the VLF and VHF methods and airborne equipments. Thus, two receivers can convey all the information needed in the aircraft, and one VHF transmitter will convey all the information needed on the ground concerning the aircraft.

It should be noted that dual frequency "composite" Omega is showing considerable promise and might suggest that an automatic diurnal correction scheme can be avoided. On the other hand, short baselines of the U.S. VLF system and land installations on U.S. soil force use of VLF navigation data much nearer the stations than in a 4,000 to 5,000 mile (baseline) installation where "near-station" usage is easily avoided. Furthermore, composite Omega is not incompatible in any way with automatic diurnal, and both will improve VLF performance and integrity on the side of the very, very low cost user of a single frequency; thus, differential or automatic diurnal data becomes essential.

VI. AMBIGUITY RESOLUTION USING MULTIPLE VLF COORDINATES

As noted previously, the two-speed VLF guidance signal (dual frequencies such as 10.2 and 13.6 kHz) is not ambiguous in an operational sense, since continuous tracking prevents ambiguity. With single-frequency ambiguities about 8 miles apart and about 30 miles apart for dual-frequency, two-speed system receivers, the ambiguities of a given pair of the four-station, U.S.-only Omega (VLF) system can be resolved. Continuous tracking of a single-speed system prevents ambiguities (8 miles is about 3 minutes flying time in small aircraft) simply because the pilot is "coupled" to the data and would immediately recognize any major change, such as 8 miles of position or a 3-minute data gap. Even so, the "U.S.-only" configuration offers other simple means of resolving any single-frequency ambiguities.

Even with the single-speed system one must recall that all four stations can be received anywhere in the United States because of their electrical design, the "geometrics" of the (total system) installation, improved signal levels, and the rapid position and track updating. Thus, even a single-frequency one-speed system can be composed of a series of six hyperbolic lines of position. Each hyperbolic family of LOP's fully overlaps all other families of LOP's. Since any single LOP is essentially straight for about 50 miles, it is possible to simply examine more than two pairs of (single-speed) LOP's, and use the 3rd or 4th LOP as a means of ambiguity resolution.

For example, a specific phase angle difference of a 10.2-kHz signal between the Seattle and Maine stations (30.0°, for example) will not be located at the same position as an equivalent phase condition between the San Diego and Maine stations. This is the case because the baselines are different in both length and direction, and the exact phase control of specific pairs of equaphase lines relative to specific surface points can be controlled. Figure 19 illustrates a "sample" area in the eastern United States, and the four sketches of four typical pairs of LOP's clearly show the wide selection available of

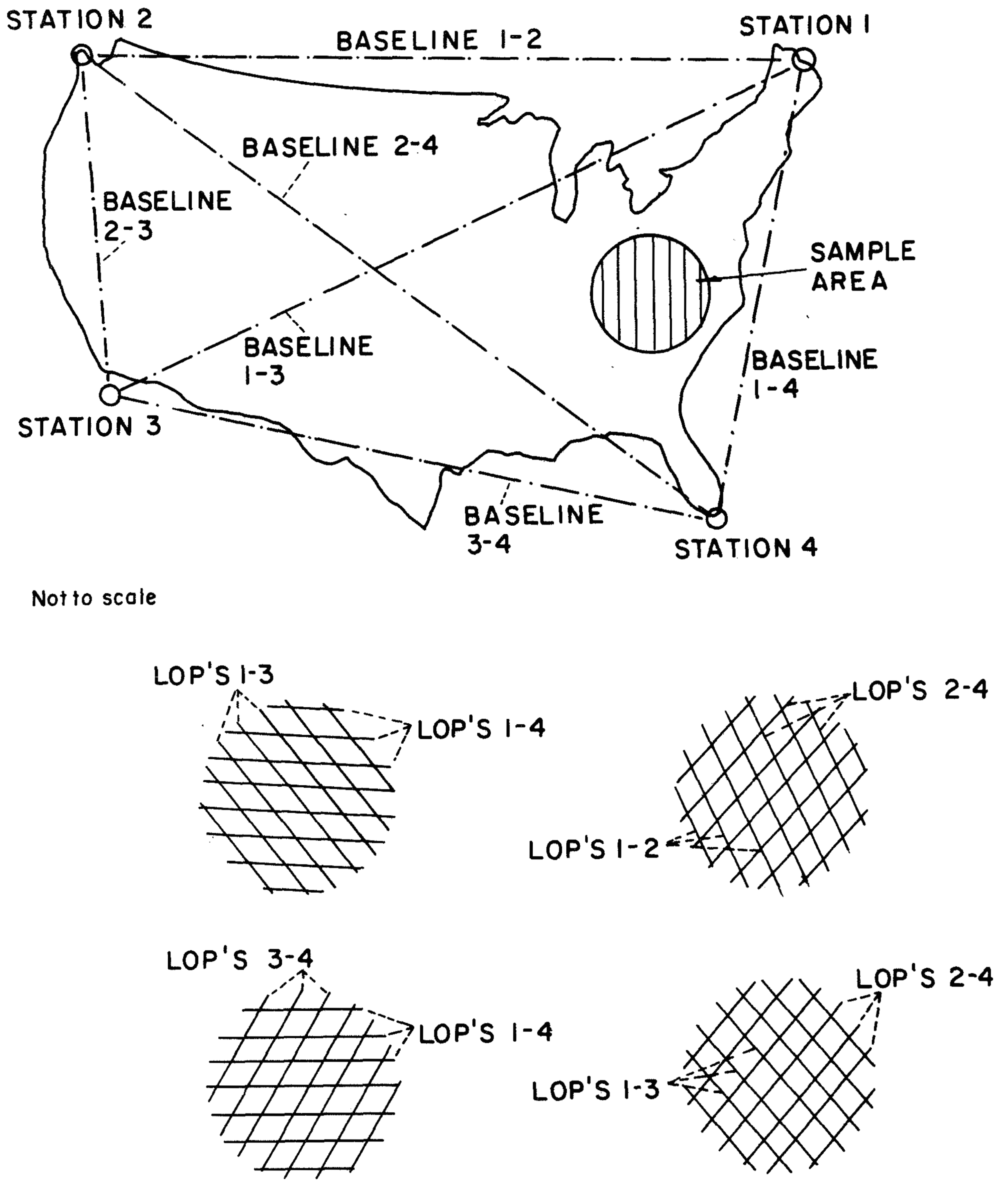
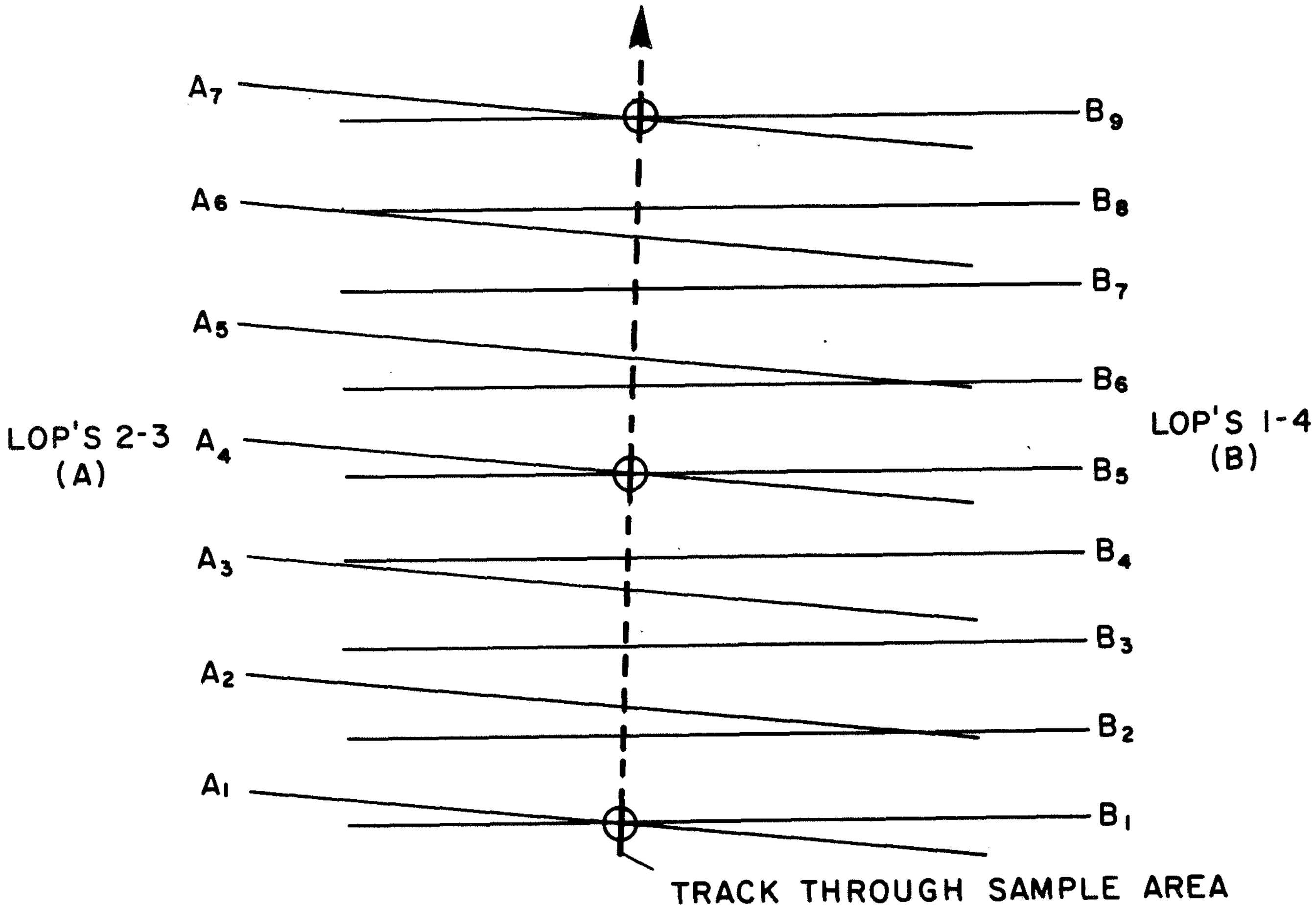


Figure 19. EXAMPLE OF LOP'S IN A SPECIFIC SAMPLE AREA

various geometrics from even a one-speed system. The hyperbolas with long baselines (500 to 3,000 miles), on a curved surface such as the earth's sphere, tend to curve less on such a surface than on a flat plane. Hyperbolas generated with short baselines between stations, such as 100 to 200 miles, curve extensively. It is obvious that the six combinations would not all be optimum in creating LOP's, however, since two LOP's are adequate for guidance and position determination; adequate redundant signals exist, and some are useful for ambiguity resolution.

Two significant aspects of the geometry of the multiple LOP's can provide an ambiguity resolution function. By using the baseline at some distance, there is some spreading of the spacing between the adjacent LOP's compared with a similar baseline pair at a shorter distance. Consequently, in the small sample area noted above (say, 100 miles in diameter) in the eastern United States, LOP's from the West Coast baseline (stations 2 and 3) will be spaced more than is the case in the same area created by the stations 1 and 4 pair. These two sets of LOP's can be aligned phase-wise to give a coarse-fine; such an example is illustrated in Figure 20 which shows coincidence every 3rd LOP (for pair 2 and 3) and every 4th LOP (for pair 1 and 4). It is not necessary that the exact 3/4 ratio exist. In fact, any similar ratio can exist and be most useful simply by showing on the sectional aeronautical charts such VLF coordinate data, much as the VOR data is shown. Thus, any ratio that creates a reasonable change every 30 to 40 miles will suffice.

On a national airspace basis, this technique may prove quite useful, thus avoiding in the very low cost installations the need for a two-frequency VLF receiver and two-speed usage. The airlines may profitably choose the two or three frequency method since it has advantages such as redundancy and differential (heterodynes) corrections are smaller. However, for the light aircraft on shorter missions (say, up to 200 knots of speed on trips up to 500 miles), the single-speed use of the somewhat different spacings of the two LOP's will aid. It is evident that the course shown in the illustration suggests that a third LOP is



In the Sample area LOP's 1-4 are more closely spaced than LOP's 2-3 because of the differing distance from the baselines (about 400 and 2,000 miles)

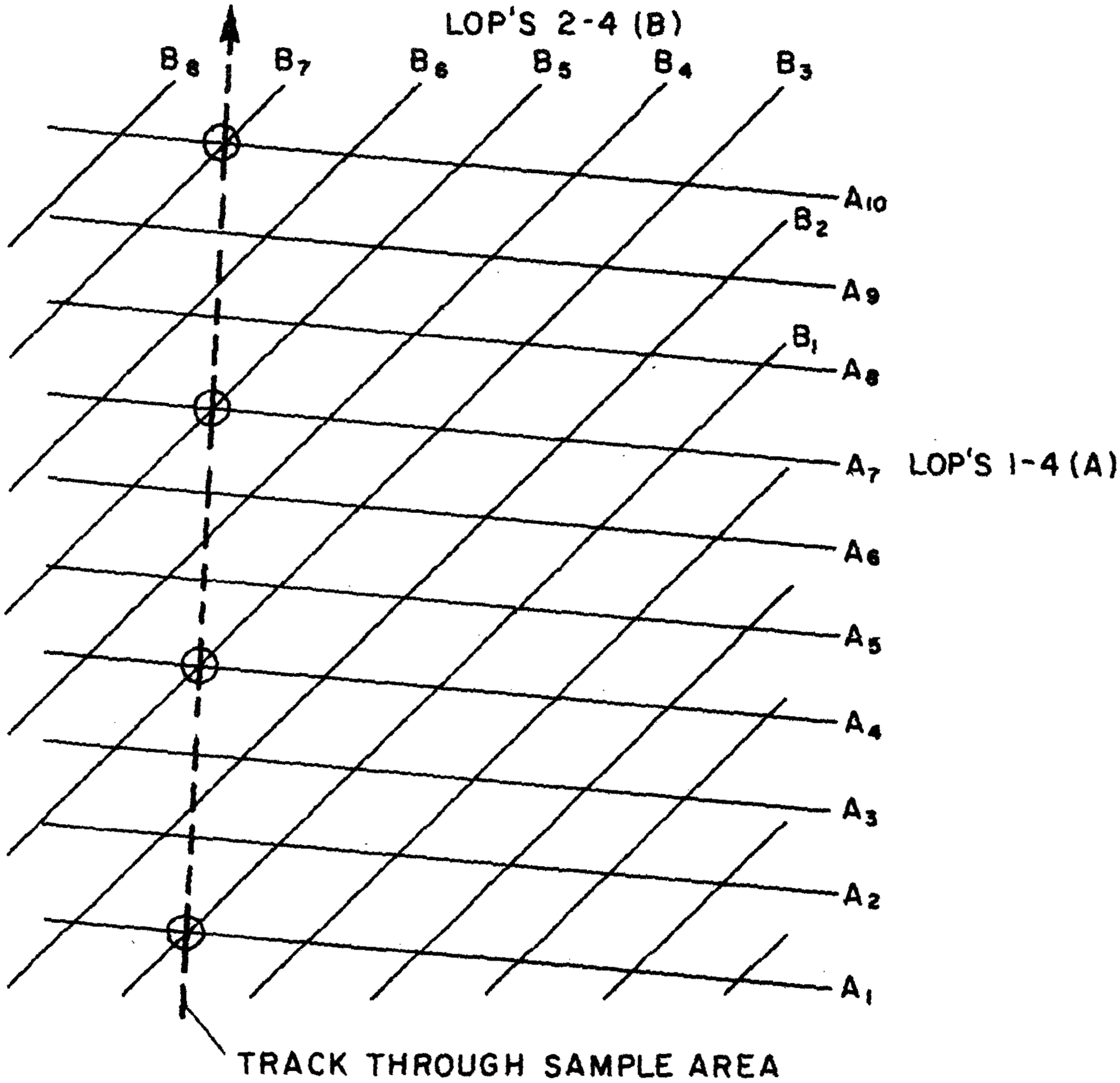
Note the coincidence of A_1 and B_1, A_4 and B_5, and A_7 and B_9 giving a "coarse-fine" with a single VLF frequency.

Figure 20. EXAMPLE OF A SINGLE FREQUENCY RECEIVER PROVIDING A COARSE-FINE AMBIGUITY RESOLUTION BY SELECTION OF APPROPRIATE LOP'S

in use to create the indicated course. The two LOP's being compared are used to illustrate the ambiguity resolving powers of the geometric "spread" of the long-based VLF lines of position.

Another single-frequency geometric "coarse-fine" technique is shown in Figure 21, where, because of the diamond-shaped nature of the LOP's, the crossings of lines B (even when spaced on a normal-line through them, the same as the A lines) create on the track illustrated a greater distance per lane than LOP's of A. This simple parallelogram effect of LOP's that do not cross at 90 degrees, but at some lesser angle such as 70 degrees, provides this coarse-fine relationship. Note that every 4th LOP-A coincides with every 3rd LOP-B. Again, an exact relationship such as ¾ is not essential but aids in illustrating the principle. Since the geometry changes little for large areas, local sectional charts could average a given fixed geometry. Again, it is assumed that a 3rd LOP is used to follow the desired track illustrated, so that the crossings of the A and B lines create in effect a "DME"-type display that has fine-grain and ambiguity resolution by comparing the two other LOP's. Low-cost ambiguity resolution occurs once again since all data from the four stations is on a single frequency.

Testing and validation is required to determine (1) whether it is simpler or lower in cost to design a general aviation receiver for VLF navigation that uses the single frequency and the two "geometric" coarse-fine ambiguity resolution methods, or (2) whether it is indeed lower in cost to receive both frequencies of a dual-frequency system. The use of the automatic, diurnal correction signal will be useful in both cases and can readily be implemented with any method of ambiguity resolution.



Because of the crossing angles, LOP's A and LOP's B have different spacing relative to the track through the sample area. A coarse-fine relationship is provided by a single frequency receiver. Note the coincidence of B_1 and A_1, A_4 and B_3, B_5 and A_7, and B_7 and A_{10} (shown by circles). This exhibits the 3 to 4 ratio---that is, every third B coincides with every fourth A.

Figure 21. EXAMPLE OF SINGLE FREQUENCY RECEIVER PROVIDING A COARSE-FINE AMBIGUITY RESOLUTION

VII. IN-FLIGHT CORRECTION AND CALIBRATION OF ERRORS IN BAROMETRIC ALTITUDE DATA

The vertical dimension of our airspace is probably aviation's most valuable asset at present and for future ATC systems. Because an aircraft's altitude is measured indirectly by first measuring the atmospheric pressure and then relating it to height above an assumed datum point (such as sea level), many errors can accrue and many have been identified (for example, see International Civil Aviation Organization Doc. 7835 AN/863). Airliners can afford to use sophisticated barometric sensing units that reduce many of the instrumentation errors, such as backlash, friction, etc., utilizing servo-aided drive and electrical sensing of the small movement of an aneroid sensing unit. Since such airline units cost several thousand dollars, they have not been installed by many general aviation aircraft owners. These cost-conscious owners are characterized as persons who own and operate single-engine aircraft costing between 10 and 20 thousand dollars.

However, with increased use of SSR transponders, VOR and other ATC/Navigational aids, commensurate increased "mixing" of the simple and sophisticated altitude sensing systems occur in the same airspace as illustrated in Figure 22. Thus, the vertical separation between similar or diverse type aircraft is established by each pilot flying in accordance with his own on-board altitude indication. Obviously, the actual vertical separation is the difference between altitude indications in two aircraft that have been assigned adjacent altitude layers. Consequently, the errors in both barometric sensors must be considered. The actual separation is the difference between two independent non-correlated sensors, and those difference values are controlled more by the unit with the largest errors (than the unit with the small errors). When, say, an airliner and a small general aviation aircraft are separated vertically by assigned altitudes, the safety is dependent on the unit with the largest errors.

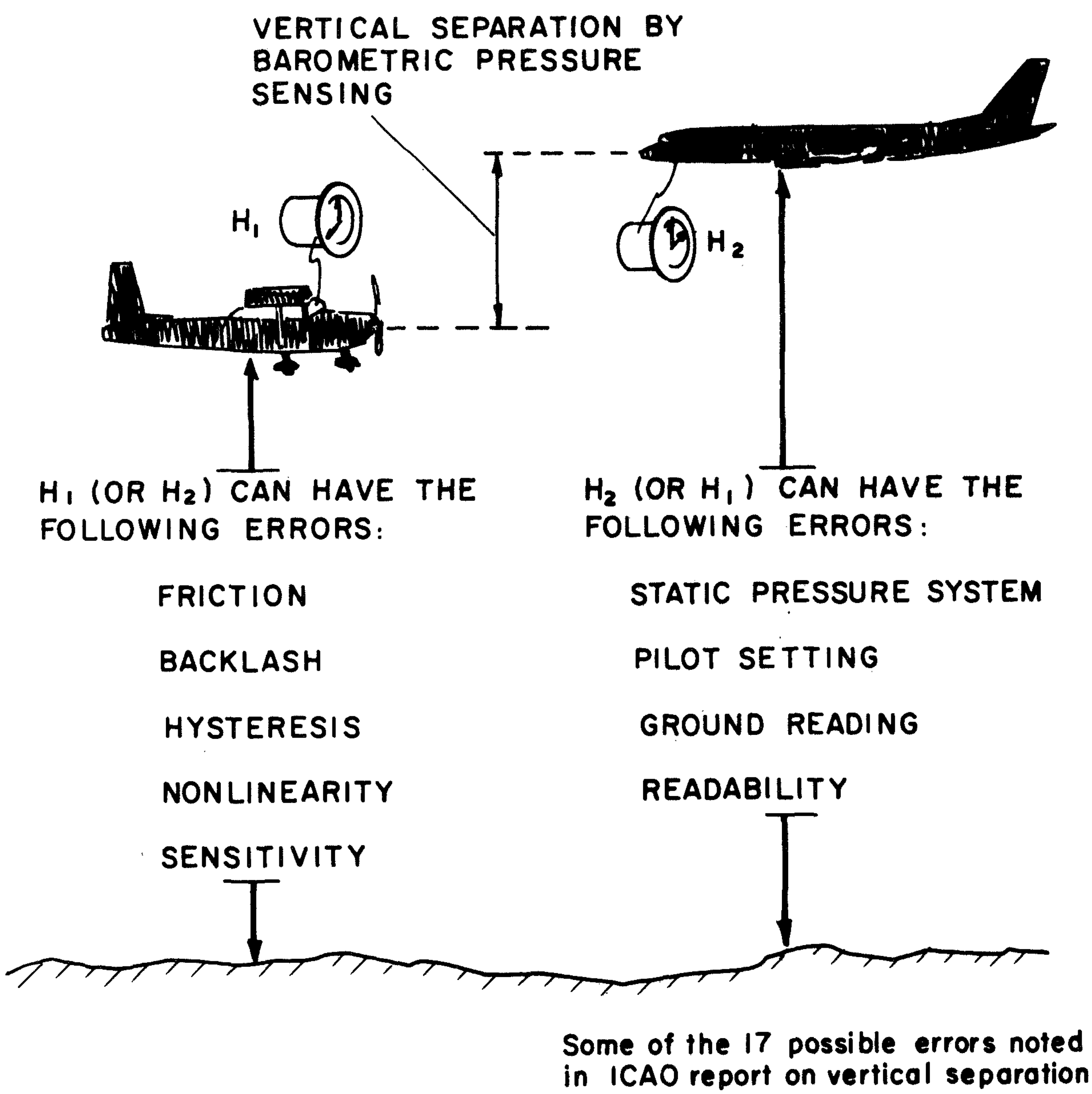


Figure 22.
VERTICAL SEPARATION ERRORS

Some of the many errors are noted in Figure 22. It is impossible in today's ATC environment to routinely determine the in-flight error of any barometric altimeter. Since the calibration occurs at the time of installation or repair, and errors are established by varying pressure in a bell jar under laboratory type conditions, an unrealistic standard can exist quite removed from the real world environment in which the two pilots of adjacent, vertically separated aircraft must actually depend for safe vertical separation. An in-flight capability of calibrating by automatic or semi-automatic means the pilot's barometric altimeter or sensor should aid enormously in assuring that safe vertical separation actually exists. Quick identity of units that are outside of tolerance is possible. An ATC source of certain valuable input data for the forthcoming computerized ATC system utilizing altitude coded SSR data is also available.

A. SURFACE RADAR WITH VERTICAL BEAM FOR BAROMETRIC CALIBRATION

Most of the barometric height measurement errors can be avoided by using a precision, surface radar signal that measures the vertical range of the aircraft. If radar is used from the aircraft, accurate altitude checks can only be made over precisely known, elevated and flat surfaces, such as open, calm sea water. Over land, the aircraft radar altimeter measures only the clearance above the terrain below and, of course, this is a complex, rapidly changing variable not known to sufficient accuracy to warrant this approach.

By planning a new automatic altimeter calibration facility using radar on the ground, several advantages accrue, as for example, (1) the precise establishment of the aircraft's vertical height, (2) precise comparisons of the actual height of the aircraft to other vertical reference datum points, such as airport elevation, sea level elevation, or obstruction clearance. The necessity for all aircraft to carry a costly, sophisticated radar is thus avoided.

Several means exist for reporting the aircraft's barometrically-sensed altitude to the surface; the most advanced and common one is the Secondary Surveillance Radar (SSR) airborne transponder that automatically transmits a coded message that corresponds to the aircraft's barometric height. Over 4,000 codes permit data transmission from air to ground in 100-foot increments. Other means for converting the mechanical motion of the barometric pressure sensor to a related electrical code or change in modulation signal have been tested or proposed many times. A convenient and very-low-cost encoding scheme for general aviation is suggested in the form of using the multi-tone data signaling developed by the Bell System. Data transmission is possible with units costing about $20 that are part of the touch-tone hand-set, where a single message lasting but 40 milliseconds can convey one of 100 quantities on a VHF communications channel.

For general aviation, the automatic reporting of height in 100 or 200 foot steps from sea level to 10,000 to 20,000 feet might be accomplished at very low cost if a means were found to reduce the cost and serious errors of low-cost simple barometric sensors. Currently the lowest-cost SSR altitude transducer unit sells in the region of $3,000 to $4,000, while a price nearer $200 would be more acceptable to the general aviation user we are most concerned about.

Thus, by a VHF or similar relay of the barometric height data to the ground radar, a direct comparison is made, and a calibration signal is then made available to the pilot. One difficulty appears in such schemes if the aircraft is not directly over the height measuring radar. The lower half of Figure 23 indicates that "radar-slant-range" height errors can occur and nullify the value of the measurement if the aircraft is not directly over the height measurement facility.

B. CROSSED-BEAM RADAR CONCEPT

It was noted in Figure 23 that the cosine of the angle "a" between the line connecting the aircraft to the radar and the zenith line must be established. To measure the angle "a," various schemes of scanning radar beams have been considered and usually become complex and costly, minimizing any serious consideration

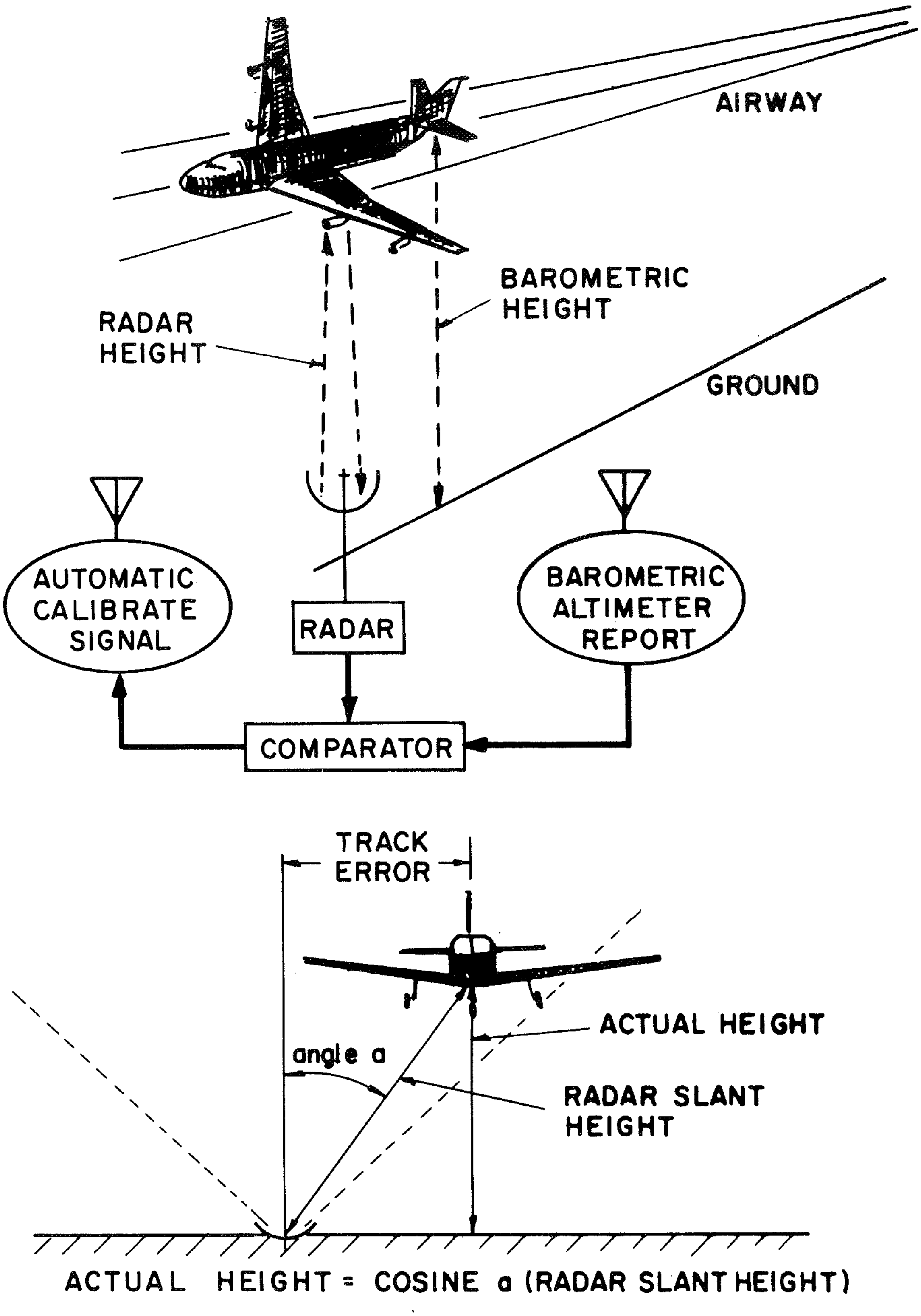


Figure 23. COSINE ERROR CORRECTION

of wide-spread application of the altimeter calibration facility. Sufficiently wide-scale installations of low-cost radars must be used to be of value to all users: airlines, military, and general aviation.

A simple static-beam radar concept consisting of two crossed fan beams is suggested as a low-cost yet effective solution to this problem. A simple static antenna radar mounted at existing sites of navigation facilities, such as markers, VOR, communications, etc., should be low enough in construction and implementation costs as to warrant its consideration for a national facility, much like the marker beacon and VOR facilities. In fact, the altimeter calibrating units would be located at these facilities for convenience because they demark airports and airways.

In nearly all VOR or Area Navigation concepts, it is essential that the direction of the airway be established, and it can be assumed that viewed from the ground the aircraft flying on the airway will be traveling approximately in a known, specific direction as they pass overhead. The two crossed planar beams are oriented so as to cause the aircraft flying the airway to pass through them in a given geometric relationship.

Figure 24 is a plan view showing the time differences of three conditions of track error. The spacing of the radar signals of beams A and B is directly related to the aircraft's cross-track error. Since variables of aircraft speed, cross-track error and height occur, it is essential to find a means of compensating automatically for these variables while still measuring angle "a." This is achieved as illustrated since the radar PRF is constant, and the time within each beam and between beams can be related to the number of pulses received on the ground from each beam. The time "Y" between the interception of each vertical beam is the key to the solution. The number of pulses in the known beamwidth establishes the speed of the aircraft along with the slant radar range. It is possible then to establish angle "a" and correct the slant range data to vertical height data. It is apparent that "Y" increases directly with track error, and that no ambiguities exist. In fact ATC data exists on the (1) presence,

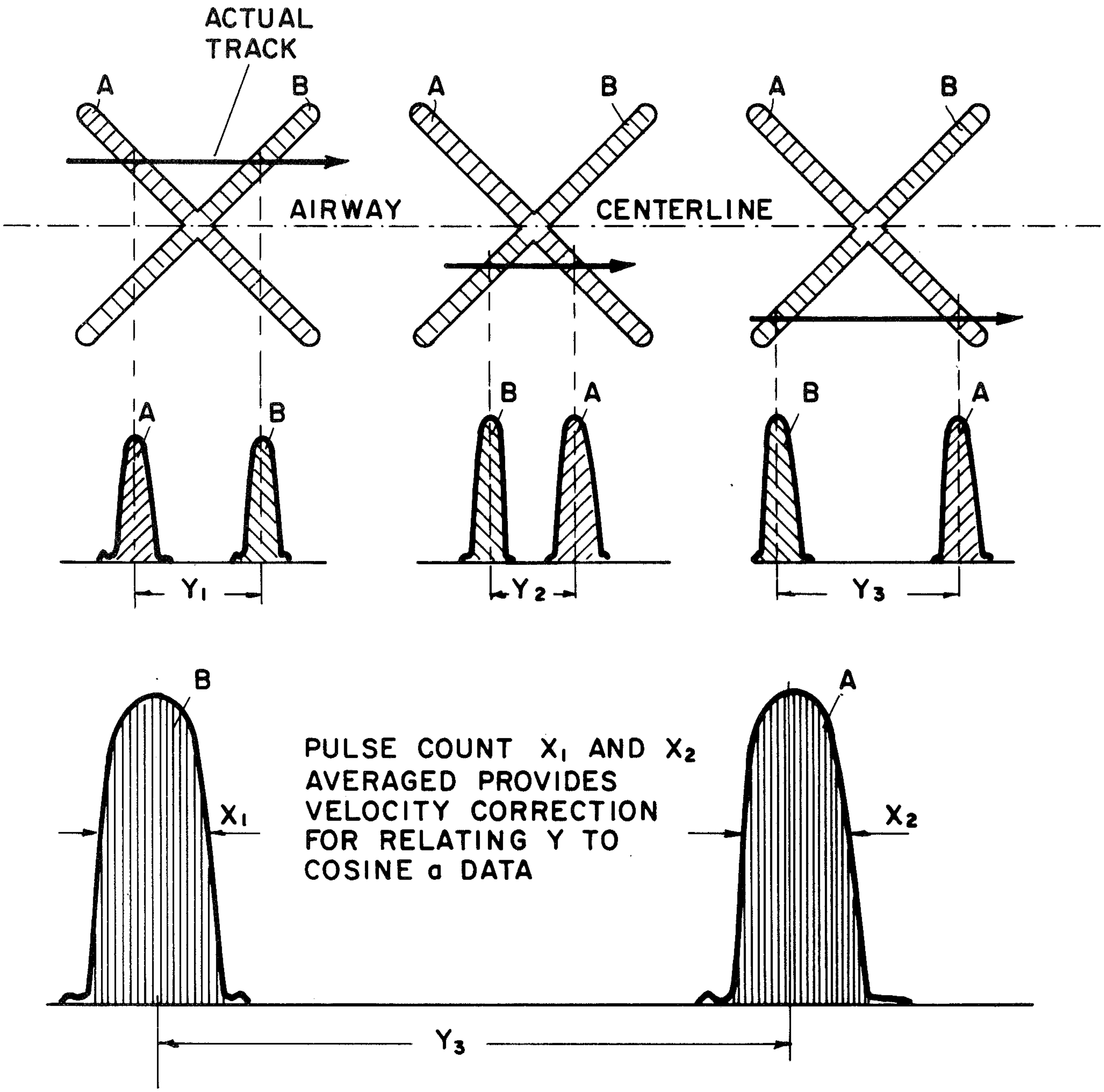


Figure 24. MEASUREMENT OF COSINE a

(2) direction, (3) velocity, (4) height, (5) identity, (6) track error, etc., of each aircraft as it intercepts the beams in passing over or near the facility.

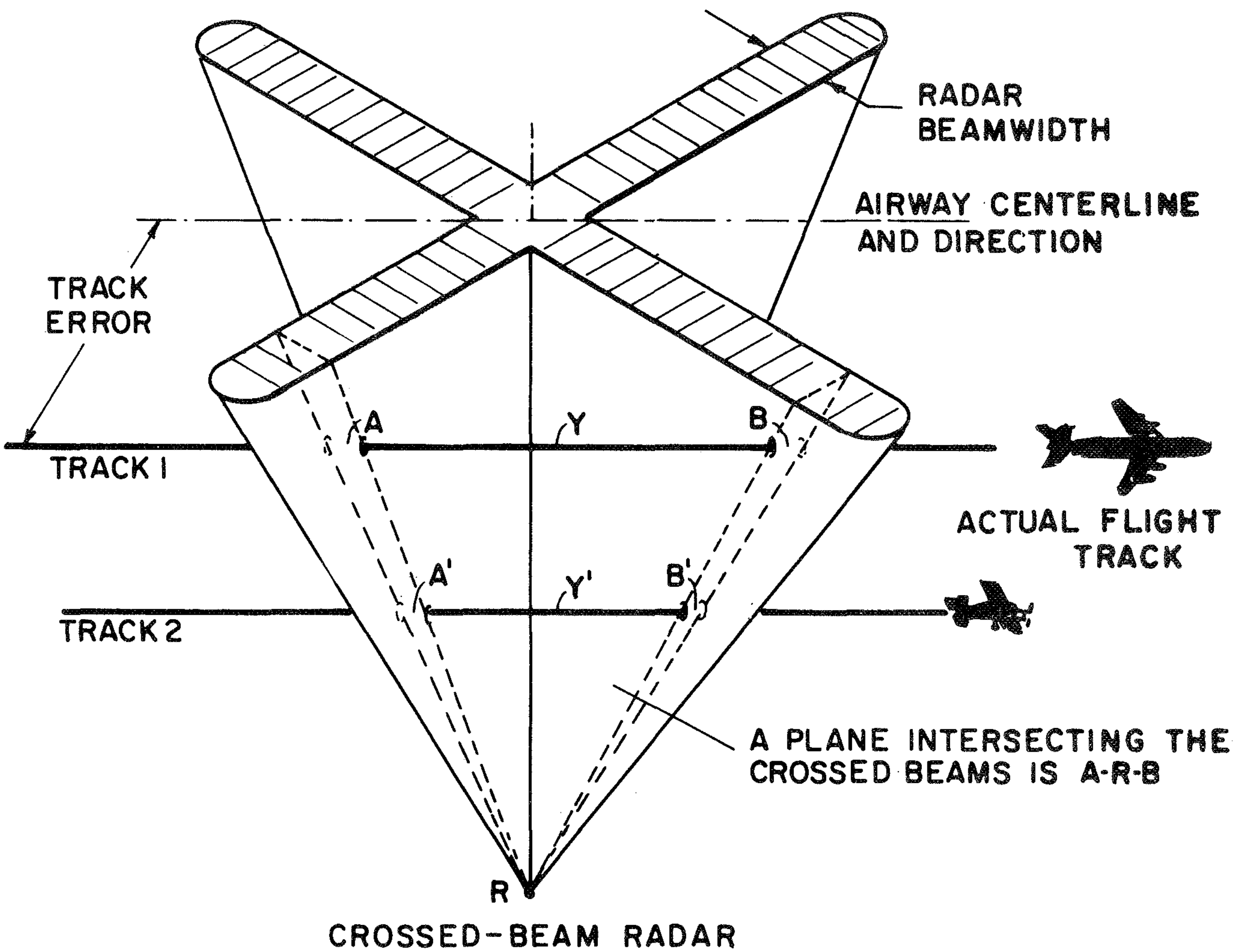
The two radar beams are flat planar beams that are very narrow in one dimension and quite wide in the other. Each antenna can be fed in parallel from the same radar, or the radar can be rapidly switched alternately to each antenna with a slightly different PRF, thus identifying in the return signal in the ground receiver the beam illuminating the target.

C. COSINE CORRECTION OF OFF-ZENITH TRACKS

The crossed-beam radar altimeter calibration facility is further illustrated in Figure 25. An example is shown of two tracks with cross-track errors with respect to the airway centerline but at different altitudes. For explanation purposes it is assumed that they both lie on an intersecting plane RAB. Note that the ratio of the beamwidth and the time duration between the two beams remains constant for both high and low tracks. The beamwidth is angular as is the intersecting area RAB. Of course, the radar will measure the slant range of each of the two aircraft, but the correction of the viewing angle from the facility will be the ratio that is unique to that specific vertical viewing angle and consequently the cosine "a" correction is available.

Thus, it would appear that the measurement of angle "a" is independent of the actual radar altitude measurement itself even though such a measurement is used. By averaging the returned radar pulses in beams A and B (several hundred), an improved quantity is arrived at that is truly representative of the beamwidth. Since the two beams are identical and they are sufficiently close, a straight flight track intercepting both is a reasonable assumption.

Thus, the ratio of Y/A or Y/B can be determined regardless of speed and height of the aircraft and can establish the plane RAB, which in turn creates the angle A with the zenith of the crossed radar beams. Of course, all of this information is read automatically by straightforward radar circuitry avoiding



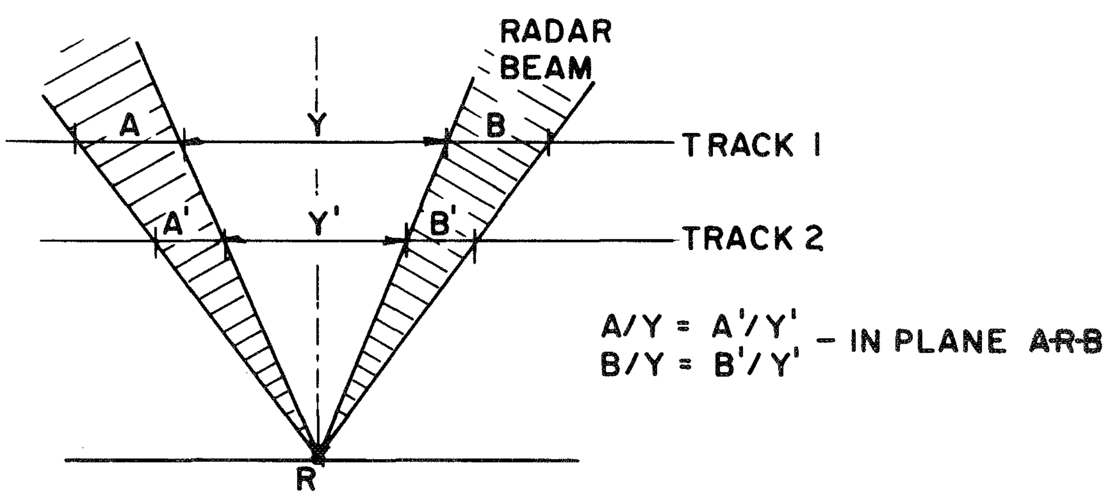


Figure 25.
COSINE a IS THE RATIO OF BEAMWIDTH TO THE ANGLE BETWEEN THE CROSSED BEAMS

any human interpretation. Another example showing the variation in track error and how each track error establishes a new plane RAB is shown next and must be compared to this illustration to envision the three-dimensional aspects of this rather simple concept. Even if two aircraft are in the beam simultaneously (a quite rare occurrence), range-gating can readily separate the two height measurements and provide individually identified calibration data to each aircraft. However, since the vertical planar beam is so narrow, the probability of two aircraft is extremely remote.

Figure 26 illustrates two aircraft at the same height, but with different track errors; of course (because of ATC), these aircraft pass through the beams at separate times. Track 1 establishes plane RAB, and track 2 establishes plane R'A'B'. The angle between each of these planes and the zenith of the crossed vertical beams establishes the respective angles a and a'. It will be noted that angle "M" is formed by plane RAB and is equivalent to the simple electrical radar measurement Y. Similarly, the angle O is established by an equivalent radar measurement of Y'. As noted previously, the track errors E_1 and E_2 are directly related to Y.

Thus we have the relationship:

actual radar height = radar slant-range height (cos a)

or

$$H_a = H_r \cos a$$

$$H_a = H_r \cos \frac{Y}{\frac{1}{2}(A + B)} \times K$$

K is a constant established by the beamwidth of the flat planar beam measured along a line parallel to the airway and intersecting the narrow dimension of the beams. The data processing takes place in simple pulse counting circuits that count the number of pulses received in each beam and the time interval between the averaged center of each beam's pulse returns. This is part of a study now being conducted for NASA's Electronic Research Center.

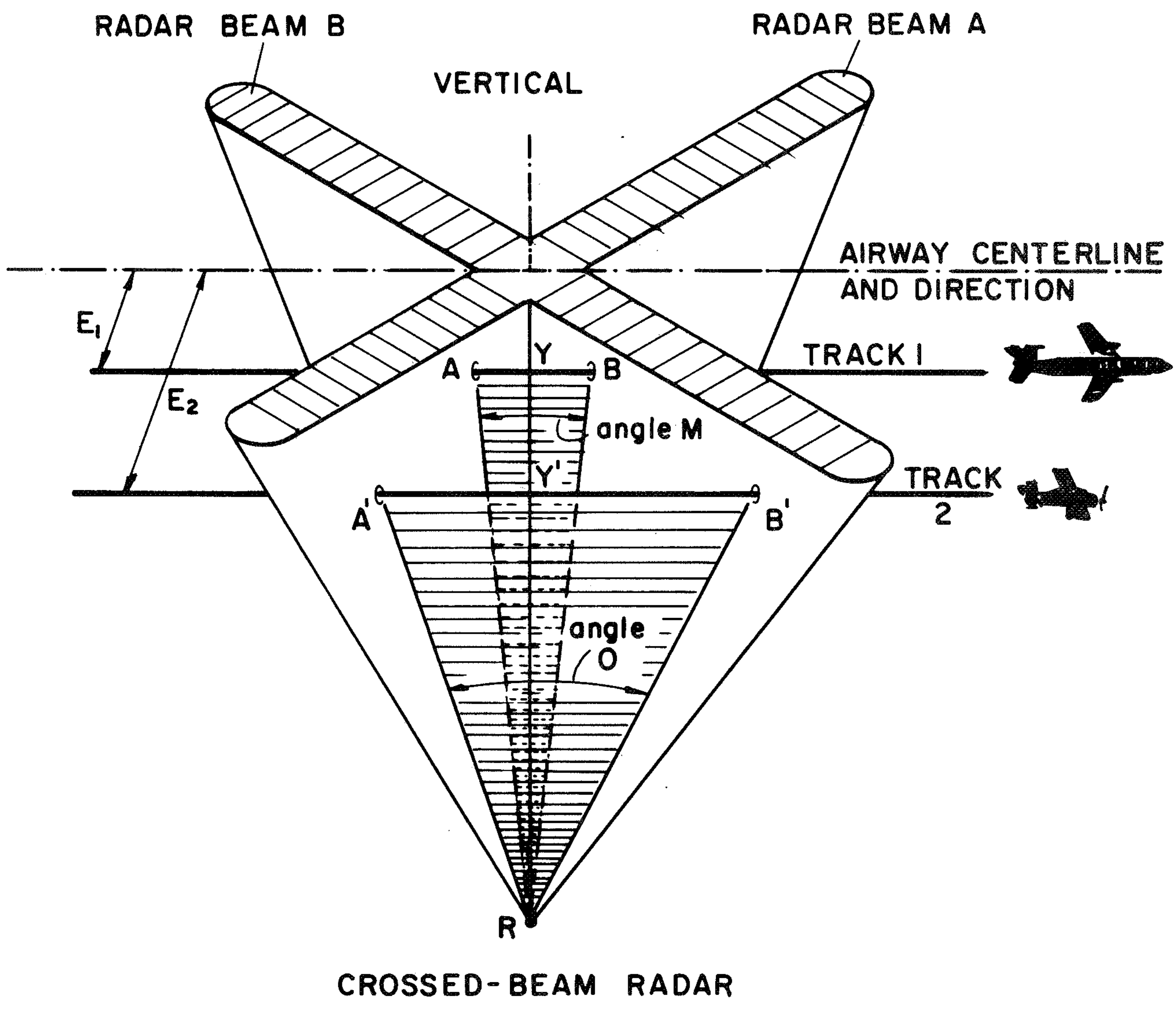


Figure 26. DIMENSION Y IS PROPORTIONAL TO TRACK ERROR

Figure 27 illustrates the relationship between the value of the cosine "a" and the angle from zenith that the aircraft target appears. The angle is shown in beamwidths of the narrow fan beam and a 3-degree beam is assumed for the illustration. It will be noted that the value of Y increases with the distance of centerline while the value of the cosine function varies at a very slow rate initially. Thus, for the most normal angles near the zenith, the correction is minimal (1½ percent) for 10 degrees. However, at angles of 30 degrees and greater, the values change more rapidly. For example, at 40 degrees off zenith, the dimension Y is about 13.3 beamwidths, and the cosine correction is 0.766. Since the beamwidth is measurable to about 1 percent electrically, then the angle is measurable to the same accuracy. This would suggest that the correction factor will be accurate to about 1 percent of the 0.766 or about 0.0076 of the height. At a height of 3,000 feet this is an error of about 30 feet, well within the measurement needs at this altitude, since 100-foot granularity is the finest data used in the ATC system and perhaps 250 feet is the more realistic barometric sensing accuracy on an average of all aircraft using the airways.

D. EFFECT OF SPEED ON ACCURACY OF RADAR HEIGHT MEASUREMENT

As an aircraft off the exact center of the airway or at an angle relative to the zenith of the crossed beams intercepts the two beams, there will be two outputs, one for each beam. It is convenient to express the beamwidth in terms of the number of pulses received between a specified beam level. A convenient point for this measure is the 3-db or 6-db point. Thus, the aircraft, upon entering the coverage of the static beam, returns signals with increasing signal intensity that represent the directivity of the vertical beam. This is often expressed as $\frac{\sin x}{x}$, where the angle x creates a signal output proportional to the sine of the angle. Upon passing through the maximum value (beam peak), the signal decreases again passing through the initial threshold counting point in the form of a decaying signal level.

Although the pulse-to-pulse return within the beam will

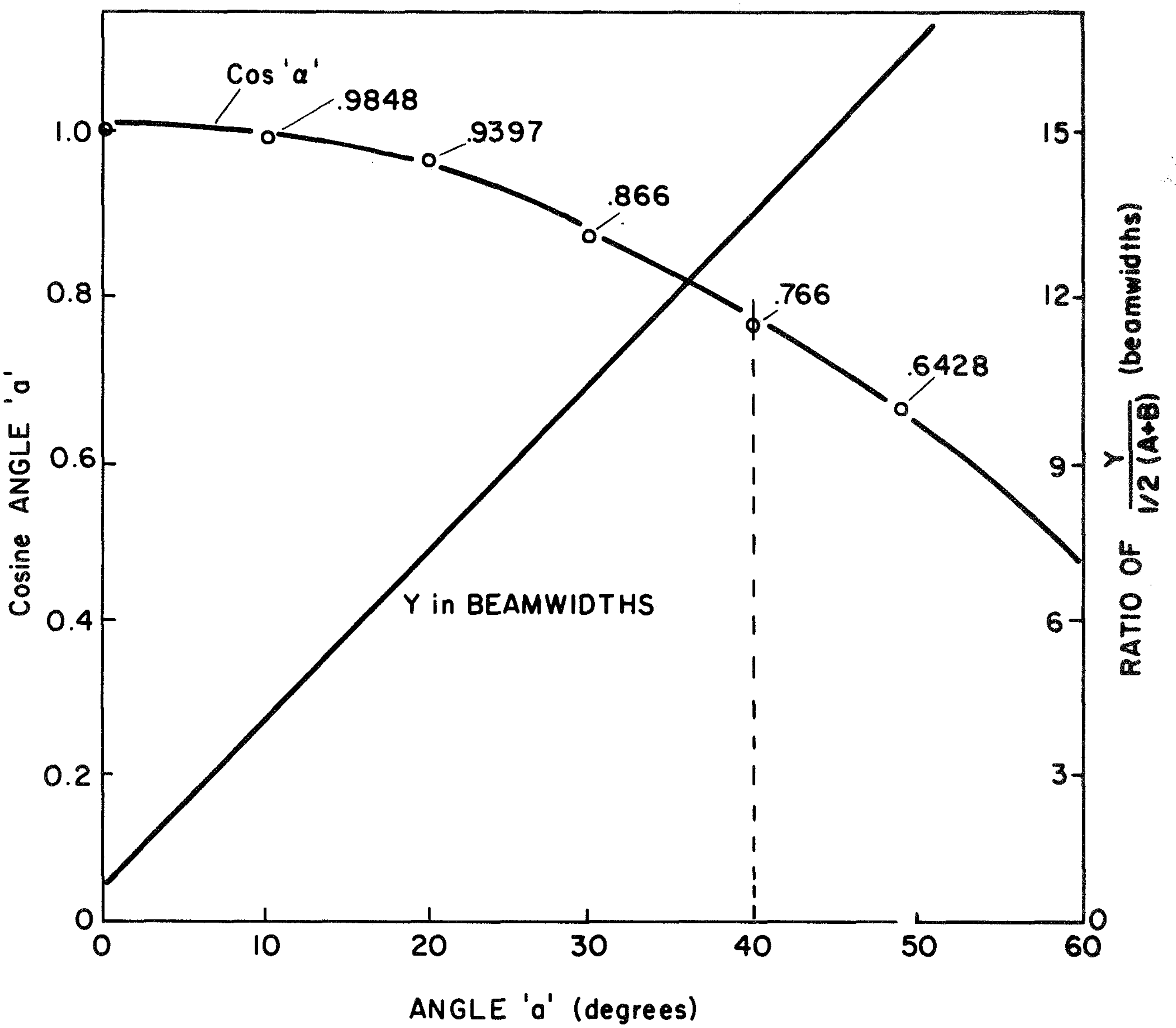


Figure 27. RELATIONSHIPS OF ANGLE 'a' AND DIMENSION 'Y' MEASURED IN TERMS OF A 3-DEGREE FLAT BEAM

vary somewhat in signal level, the typically flat nature of the bottom of aircraft, lack of any ground clutter or moving targets that might confuse the radar receiver, and the large number of pulses creating the amplitude envelope of the return pulses should combine to permit a rather accurate measurement. Consequently, the count of pulses can be well controlled, making the threshold point on the rise curve and the decay curve (representing the signal amplitude) consistent for each beam. Typically, the signal can be stored in a pulse counter that is started when the initial threshold level is reached (say, the 3-db or 6-db points). The counter continues to count the pulses and stores the count until it is terminated by the pulse-to-pulse signal level decaying below the threshold value. The number of pulses counted and stored is then commensurate with the occupancy time of the aircraft in the beam. A fast aircraft will fly between the beam rise and decay threshold points in less time than a slow aircraft on the same path. A smaller pulse count occurs with a fast aircraft than with a slow aircraft.

As noted previously, the two beams are identical in their shapes and sensitivities so that the beamwidth values can be averaged between the two beams aiding in the accurate establishment of the beamwidth value. An example will illustrate this point. Assume an aircraft passing over the outer marker wanting to check the altimeter with the vertical ground radar before ILS descent. Typically, the aircraft altitude is about 1,000 feet. Assume that the beam is about 3 degrees between the rise and decay threshold points, and that the aircraft is on final approach flying at about 200 to 250 feet per second. The aircraft will be illuminated by the beam and the pulses counted between the threshold points for the time it takes to traverse the horizontal distance between the points. This distance is about 50 feet for the example (tan 3° x 1,000 feet). At a velocity of 200 feet per second (120 knots), this infers that the aircraft is within the above limits for a time of ¼ second or 0.250 second.

The typical pulse repetition rate for such a radar is 1,000 pulses per second. This then indicates that the radar receiver will have at its output 250 pulses to average (or otherwise process) between the two threshold points. To determine beam center, it is possible by counting to half the total value or the exact center of the beam is the 125th pulse. Similarly, the passage through the next beam creates the same situation, and the center of that beam is also subsequently found. With this pulse granularity it is obvious that there is no lack of an adequate number of pulses for averaging. If, on the other hand, only 3 pulses came back, it is hard to "split a beam" with any accuracy using such a small number, and particularly with the pulse-to-pulse signal variations typical of radar return.

However, with the large number of pulses that are representative of the beamwidth, theoretically the beam can be divided into at least 100 parts and create an angular datum line, for our example accurate electrically to about 0.03 degree. Also, the angle subtended between the two beam centers should be measurable to about the same amount of accuracy.

Figure 28 illustrates the point that if aircraft with speed differences of two to one traversed the two beams on the same path, the count of the beam would vary proportionately (two to one) with the speeds. Thus, we have a means of speed determination that may be of value in final approach traffic control. However, the purpose here is to note that the measurement of height and the angle off-zenith is not degraded by speed variations. First, Y illustrates the point that the pulse count will show half the number of pulses in each beam created by the passage of the high-speed aircraft relative to those created by the passage of the slow-speed aircraft. Furthermore, the time Y between the peaks of the two beams (beam centers electrically speaking) also has a 2 to 1 ratio. Thus, in the processing of the data, the ratio between the beamwidth angle and the beam center separation angle remains the same regardless of the speed.

This same result can be realized with two aircraft at the same speed but one aircraft at twice the height (radar range) of the other aircraft (and on a plane through the radar containing the other aircraft and the two tracks). This was illustrated

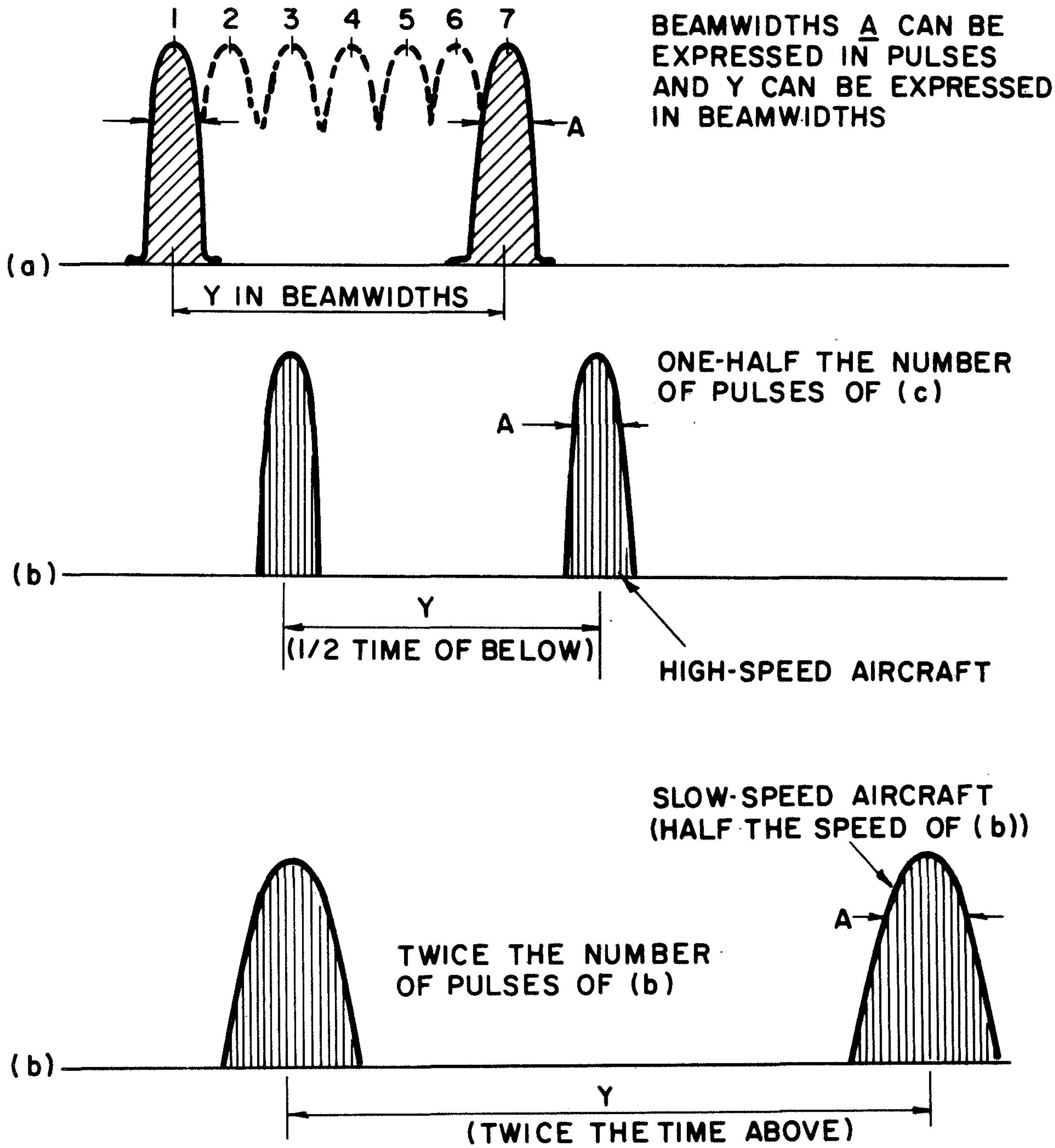


Figure 28.
EFFECT OF SPEED ON Y AND A DIMENSIONS

previously but is recalled here because that situation creates the same 2 to 1 relationship of beamwidths, pulse counts, and separation between beam centers. Thus, it appears that it is only the ratio of the beamwidth to the beam separation that is significant, and other factors cancel in the determination of the cosine of the off-zenith angle.

One way to represent this ratio is to express the separation angle in beamwidths. Beamwidths are expressed in terms of pulse counts between the rise and decay threshold points. The simplest of instrumentation is then suggested, since the radar creates its own pulse rate and can be controlled accurately. The pulse can be generated at a given rate so that pulse-to-pulse spacing is accurate to one part in a million by using a crystal. A count of up to a few hundred thousand pulses may be involved occasionally. Thus, the counter at the output of the receiver counts when any target signal rises above the threshold level. The threshold level can be varied in design and will vary with the size and range of the aircraft, yet, as noted, this level is not critical so long as the same threshold level is used on the rise and decay levels of both beams. Side lobes must be avoided so as not to be counted, but these can be kept well below 20 db so that an ample range of threshold levels exists. Thus, the pulse counter continues to count and stores first the number of pulses between the first rise threshold and the first decay threshold points. The count is continued, storing the accumulated count from the first rise threshold in a second storage means.

The pulses are then counted between the rise and decay of the same threshold points of the second beam, and this value is stored in a third storage unit. The second counter is stopped at the time of threshold decay of the second beam. Thus, the number of pulses counted in each beam are then averaged, the center of each beam is determined by center of gravity or simply dividing the sum of the two stored numbers by two. The separation between the beam centers is then determined by taking the total pulse count (No. 2 counter) and subtracting the averaged, beamwidth pulse count. The two remaining values then are (1) the average beamwidth of two identical beams (averaging improves this value over a single beam which could be used alone), and (2) the value of the count that occurred between the beam centers.

Thus, as shown in Figure 28, the angle is measured in beamwidths finally, and this simple term is directly related to the cosine of the off-zenith angle. Thus, variations of speed, height, target size, etc., all cancel out in the determination of the dimension Y in terms of beamwidths. This value is then related to the off-zenith angle directly as a linear function.

VIII. A TEST PROGRAM TO DEMONSTRATE CONCEPTS OF ALTIMETER CALIBRATION

Figure 29 illustrates the principles of the altimeter calibration concept. The aircraft flies over a normal Marker Beacon signal and, in so doing, a relay is closed to activate the cockpit light or tone indication of the marker signals to the pilot. Similarly, a test using a low-power SSR interrogator, on a narrow vertically directed beam, would automatically request height reports from the SSR altitude-coded transponder. These transponders provide standard outputs for soliciting altitude data reports from existing 75-MHz marker beacon receivers or SSR. Essentially, the ground facility automatically initiates a short series of measurements of actual aircraft height during the time the aircraft is in the coverage of the SSR or marker beams.

For example, the marker beacon receiver relay activates the aircraft's VHF transmitter for a short time, and a tone-data signal representing the height as established by the barometric sensor unit is transmitted to the ground. The barometric sensor is quantized to perhaps 100-, 200-, 300-, or maybe even 500-foot heights, so that height reporting from sea level to, say, a maximum of 15,000 or 20,000 feet is contained in a simple code structure, holding down the cost of the sensor and tone encoder to a few dollars. Several details of this code (100 quantized elements vs 256 quantized elements) have been discussed before. In the case of the SSR, the altimeter encoding already exists.

At the time the aircraft passes over the height calibration facility, the signal is received on the ground from the aircraft on the VHF "Unicom" frequency, and decoded with a BTL tone-decoding unit to represent the height sensed by the airborne baro-sensor. The SSR code is similarly decoded using the ICAO pulse codes. Often the aircraft's baro-sensor, and particularly a very, very low cost unit suited to general aviation, may be in error, needing adjustment just as the pilot adjusts his baro-sensor manually today.

This auto-calibration function of barometric height

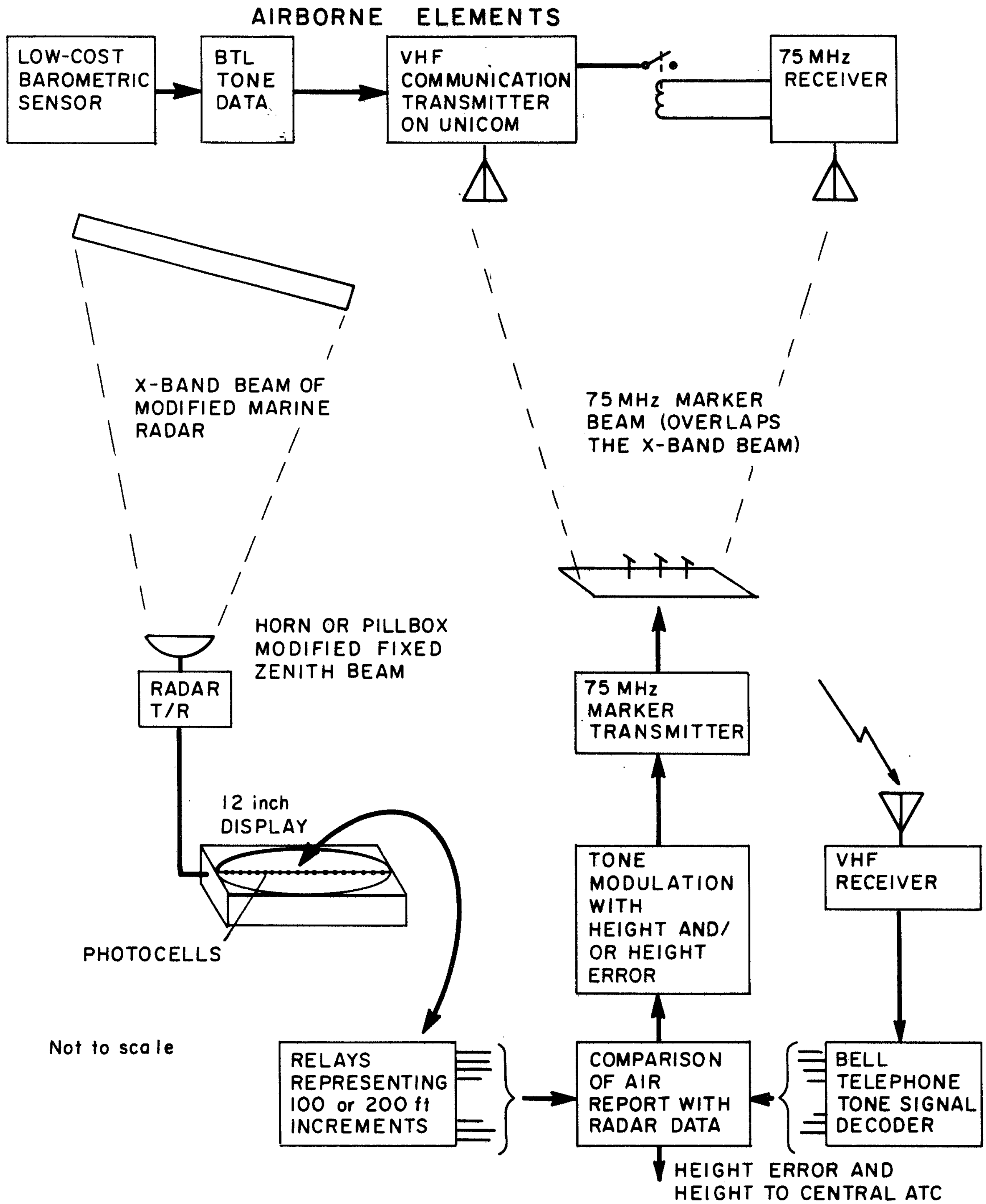


Figure 29. PRINCIPLES OF ALTIMETER CALIBRATION CONCEPT

data is analyzed in a proposed "proof-of-concept" test by use of a direct radar height measurement using a ground radar unit. For an example of the test, an X band (modified marine) radar looks at the underside of the aircraft. With a 50-kw pulse only 0.1-microsecond wide (repeated 1,000 times a second), it is expected that more than adequate signal can be obtained by reflections from even the smallest aircraft. This strong signal return is expected since the radar beam will be a narrow, zenith beam with no ground reflections or other disturbing radar targets. This permits the use of high-gain receivers and voids complex target discrimination such as MTI when large, fixed targets must be filtered from the aircraft targets. The zenith beam seems ideal for a simple, low-cost radar design.

The marine radar's usual rotating antenna is replaced by a microwave horn or "pillbox" antenna pointed at the zenith. The beam is shaped into a fan shape to match or improve the 75-MHz marker beam shape. By use of two orthogonal, vertical fan beams, an automatically derived correction for slant range errors is provided.

The radar cathode-ray display with special retentivity characteristics (of the phosphor) is offset so that the ¾-mile (range) scale, or 4,500 feet, represents the full 12 inches across the display. A series of photocells are placed in series on a line positioned over the PPI static line. Each photocell monitors discrete distances (now, of course, heights). Marine radar* has at least two ranges of interest to the test: ¾ mile and 1½ mile, and, by means of available range switching, the photocell signals can represent twice the height values for instrumenting simple flight tests. One inch of the (12-inch) display consequently can represent about 400 feet of height. It is possible to utilize small photocells so that at least 5 to 10 can be located per inch. These photocells would be placed directly over the cathode-ray beam (line) established by the offset of zero range to the edge of the 12-inch radar display.

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* Three to four manufacturers produce similar units that will satisfy the experimental program.

Remember the radar is not rotating but is being used as an "inverse radio altimeter;" thus, the cathode-ray sweep of the screen will be a stationary straight line offset so that "0" represents "0" height and 12 inches represents a height of 4,500 feet, or a height of 9,000 feet as determined by the range switch. Large photoelectric signals suitable for selected units will be obtained from the bright emissions. The high PRF allows many radar sample "hits," so that the phosphor integrates and correlates perhaps 500 samples.

Figure 29 represents the test of the overall system and shows the electrical outputs of the photocells going to a set of relays (or solid-state switches) that represent quantized heights. Since there are normally no air or ground targets in the radar beam area, the output of the radar can be ignored (or gated out) except when a VHF or SSR reply signal comes from an overhead aircraft indicating it is in the vertical beam coverage. This also assures the fact that the aircraft is in the radar height measurement (crossed) beams. Consequently, the relay outputs are only electrically activated at the time of the measurement. No signals need exist unless they are activated by the "presence" of an aircraft in the 75-MHz marker beam or the vertical SSR beam, thus eliminating many problems of channelization, interference, etc.

If, for example, 4 photocells per inch are used (this could possibly be more, say, 5 to 10 if need be), then there will be a maximum height quantization into 48 units. At the ¾-mile range (4,500 feet maximum range) this is every 100 feet approximately, and at the 1½-mile range (9,000 feet maximum range) this is every 200 feet, and at the 3-mile range (18,000 feet maximum range) this is every 400 feet. These values can obviously be changed once the "proof-of-concept" is established. However, they obviously are very adequate for such a test. Thus, coming from the radar are the 48 electrical contacts representing the 48 quantized height elements.

Similarly, the VHF "Comm" receiver on the ground receives the BTL tone data signal and can also read out quantized height data from the aircraft. By use of a typical SSR decoder (say, a 10 or 20 channel decoder) a similar source of quantized, barometrically sensed data is available from the aircraft for the test. About a 40-millisecond burst can provide any one out of 100 possible height codes, using the triple tone data equipment of BTL via the VHF channel. Alternatively, two (16 x 16 = 256) bursts of 40 milliseconds each can achieve this with simple dual-tone (4 x 4 =16) equipments. Either will probably do for testing purposes. Both means (SSR and VHF-BTL) will repeat the baro-sensor encoded data many times while overhead the facility.

Now we have a similar number of wires available from the air-to-ground signal source representing quantized data to be compared with the radar-sensed height. The comparison circuits merely examine the quantized data and determine whether the heights agree. For simplicity, assume the radar and aircraft data are each quantized exactly the same. Then, say, wire 21 (of each source) represents 2,100 feet (at the 4,500-foot maximum height range) of the radar. If, however, a signal appears on wire 21 of the radar data processor and wire 24 of the BTL-tone or SSR transponder data output processors, then the "comparator" recognized that a height reporting error of 3 quantized elements, or 300 feet, exists. This is accomplished by simple relay logic and is inexpensive to build for experimental tests.

The difference* signal, provided by the comparator circuit, is now transmitted to the aircraft. By use of similar VHF tone signaling to the aircraft (ground-to-air), this can be realized so that a plus and minus value in 100-foot steps can be transmitted for the error data. For example, if 16 codes were used in the (low-cost) commercially available BTL tone (4 x 4 tones) system, we could have a +800 and -800 foot range of error corrections in 100-foot increments, or, say, ±1,600 feet in 200-foot increments. The pilot can now be provided a readout directly in height error. Several methods of relaying altitude error to

* Quantity and polarity--for example, the error above is +300 feet and the corrective difference signal would be -300 feet, causing the 2,400-foot report to now read 2,400-300 or the correct 2,100 feet.

the pilot are suggested in Figure 30. He can reset his baro-sensor from the ground data so that it is corrected. Similarly, this error can be used to automatically correct the output of the baro-sensor in one of many ways. Both servo-driven units or electrical "code-shifting" units can be used so as to "auto-calibrate" the data of the sophisticated user.

Since all of this occurs in a second or two, the airborne readout would be in a stored circuit so that error data is stored.* Error could be transmitted by a tone message such as the morse code, which is still used in many aviation facilities, so that 26 to 30 steps would be available. For example, the aircraft is in 75-MHz signal coverage for about 30 seconds. Error data could be used to automatically correct the altimeter by a closed-loop circuit (merely shifting the encoder contacts or the code itself).

A. SOME NEEDED LABORATORY DATA FOR PLANNING THE EXPERIMENTS

It would be useful to measure some data on photocells to determine their sensitivity to cathode-ray tube phosphor emissions (retentivity, spectrum response, etc.) typically employed in radar displays. Also, it may be necessary to use some circuit gain after the photocell pickup of the phosphor signal to provide power to actuate relays or logic circuits. It is also possible that the photo-sensitive device's output itself will be an adequate switching signal. The reason for this assumption is that the radar is really working at fairly close range, by its usual standards, against a rather large target (aircraft underside cross-sections are much larger than head-on profiles of aircraft), and there are no other targets to cause noise or other electro-luminescence of the phosphor of the radar cathode-ray tube.

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* This permits the pilot to correct at his convenience and to note the amount of error for replacement of the low-cost baro-sensor unit ($20.00) if its errors exceed the specified limits. The stored data would be deactivated, say, in 2 to 3 minutes, permitting the system to be automatically initiated again by flying over another height sensor.

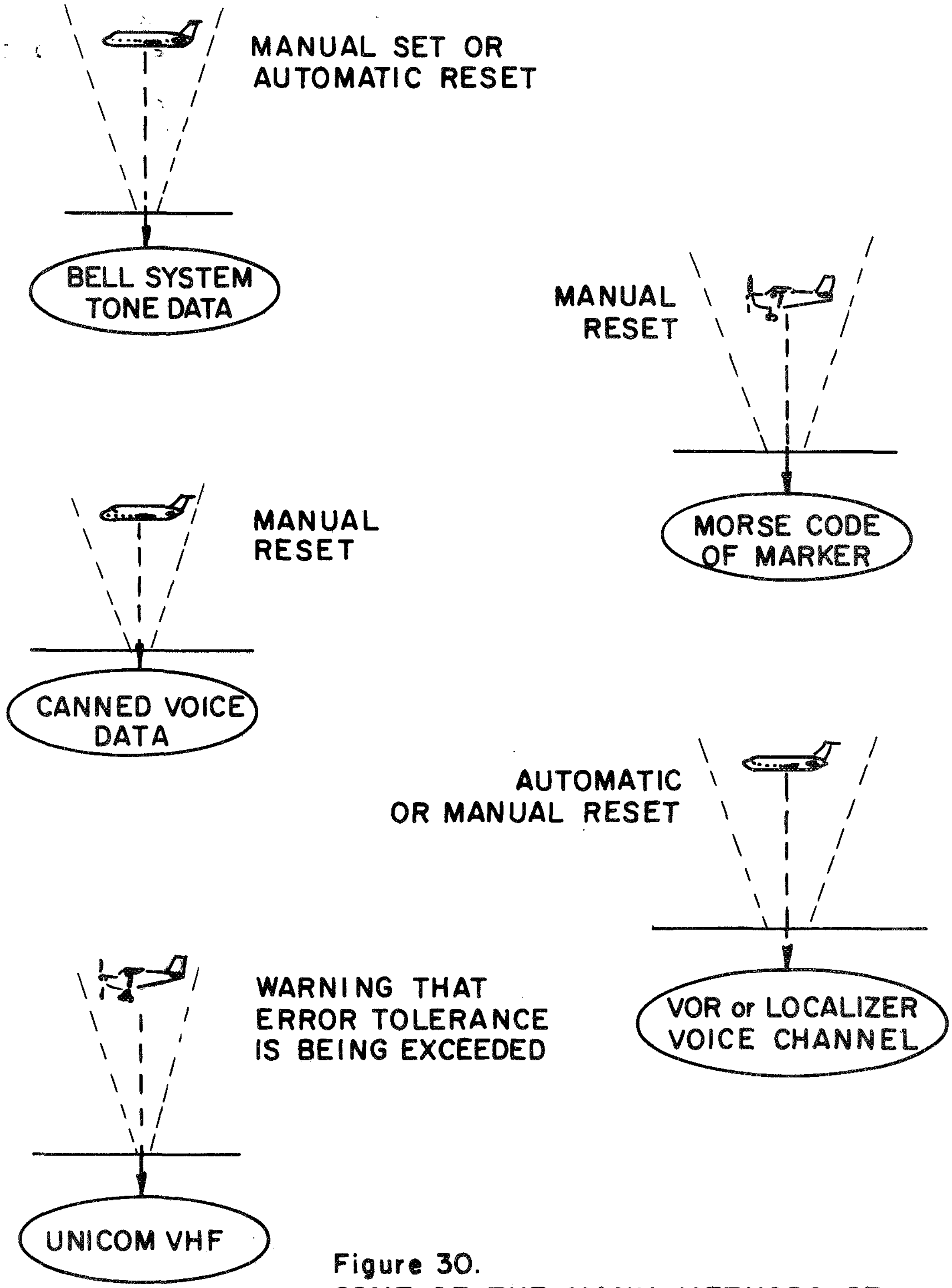

Figure 30.
SOME OF THE MANY METHODS OF
RELAYING ALTITUDE HEIGHT ERROR
BACK TO THE AIRCRAFT

Furthermore, some 500 to 1,000 radar hits exist during the brief time the aircraft is in the radar beam. The tube phosphor integrates and stores this repetitive signal, enhancing signal to noise enormously.* Thus, the signal-to-noise ratio should be very good, and the target is only sensed when it is known by reports that the target is in the beam (via the interrogator SSR or marker beam signals causing the aircraft to emit its tone height data).

If the photocell system does not work for some reason, then a direct use of delay lines and typical range decoders would be indicated. The latter is a more direct type of engineering but can be more complicated with the number of range or height outputs desired. It is desirable (at least initially) not to cut into the X-band radar circuitry or to modify it, thus avoiding radar engineering problems until a later stage when validated tests will justify such engineering.

Furthermore, there is a visible display of the height of the target (with the cathode-ray photocell readout) available to the ground observers. This would be a good visual data source for observing and monitoring the tests. Each photocell would be mounted in its own light shield box so that it is exposed only to the light source of the radar strobe line directly beneath it. Adjacent areas would be similarly shielded as they would be separated by an amount such as ¼ inch. The smallness of the photocells is important but many exist that can do this job. Perhaps literature research will turn up some photo-sensitive solid-state devices that will give direct, current switching, replacing mechanical relay functions.

The basic elements for this significant experiment are the low-cost radio-sonde baro-sensor with modified baro-switch plates, BTL tone-data equipment, and a commercial marine radar. The special experimental equipment needs would be the zenith-

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* Special storage tubes exist with a memory designed into the phosphors and electrical means to read out such data. Tests of these special storage tubes are suggested after the initial proof of concept stage where a multiple photo-cell unit is used for economy and expedition.

pointing X band antenna, photocells, and the comparator of the radar height outputs with the BTL outputs. The equipments suggested should permit a low-cost flight test and evaluation of the proof-of-concept type. Since the items are all commercial items, and utilized well within their performance limits, there should be little stretching of any engineering. Admittedly the $10 barometric sensor such as the well known "VIZ" sensor may be low-cost, but it can be corrected to within about 100 feet if data for this correction is available in the cockpit during flight. Automatic recordings taken with VIZ units indicate that, with automatic in-flight calibration, results equivalent to those obtained with a $1,000 baro-sensor should be obtainable. Furthermore, the vertical (ground) radar would report automatically the presence of the aircraft, its identity, and establish by automatic means whether excessive (hazardous*) height errors actually exist in the airborne baro-sensor installation.

This latter function is now a national necessity even with current SSR baro-sensor units utilizing the 4,096 codes of SSR. As noted, the identical ideas and equipments herein described would work with the SSR and should be tested as such, since the floating height references between aircraft without any in-flight monitoring or ability to correct height errors can be fatal in dense air traffic. Furthermore, the ability to conduct in-flight calibration makes a very, very low cost sensor practical, since it can be corrected at the exact time of its use, in the exact environment of its use, and at the exact height at the time of the reporting (not with a bell-jar test every 9 months in a remote, sea level, ground laboratory environment.

B. RADIATION PATTERNS

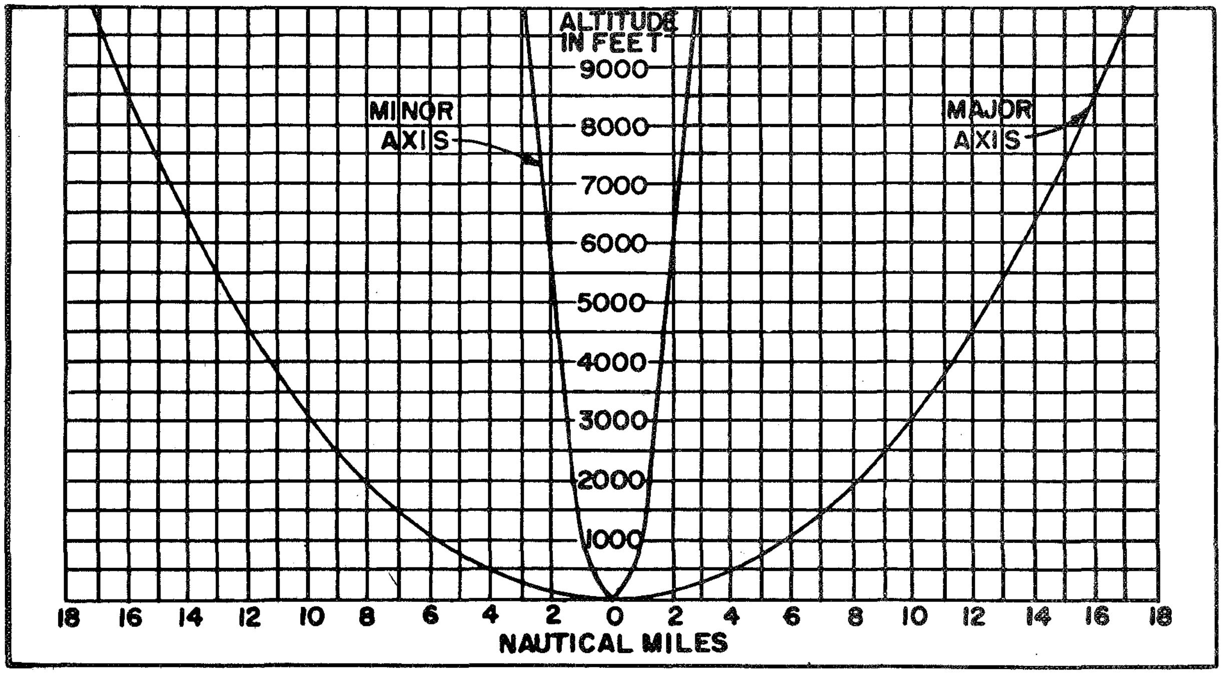
Although the foregoing material explains the principle of the auto-calibration of baro-sensed height information, several

* All the elements for automatic reporting of large errors to a central point (via land wire) exist, so that a fully monitored system is possible, thus permitting full use of vertical separation criteria for all users of the airspace.

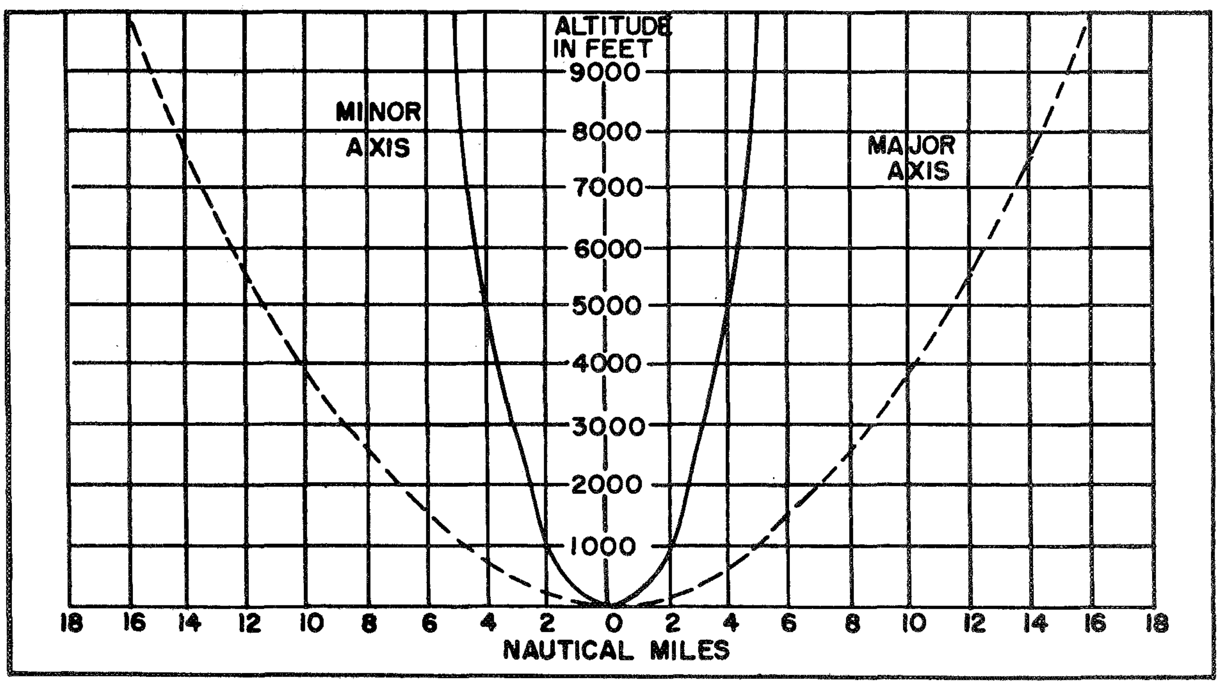
questions arise as to the exact width of the beams (75 MHz and SSR-interrogate), whether the aircraft is in the beam long enough for data exchange, the likelihood of two aircraft being in the beam, the serious fact that the aircraft may not pass through the actual zenith line from the beam emitter because of flight errors (off the VOR track slightly, deviation from Area Navigation display, or localizer CDI display).

The best way to approach this matter is to first examine the coverage diagrams of the 75-MHz markers. Most 75-MHz beams are basically the same, but have some variations in the minor and major axis dimensions depending upon their application. The attached diagrams (Figure 31) from the FAA Flight Inspection Manual illustrate these dimensions and some tone identity and tone code signals combinations now in use. Typically, if an aircraft is 5,000 feet in altitude, it will pass through the minor axis (normal to the airway direction) in ±2 NM of flight, or 4 miles duration (see Figure 31A). At 120 knots, this is a time duration of almost 2 minutes depending upon the sensitivity of the receiver. Since this duration varies (probably on the low side), the time of reception of the 75-MHz signal will probably be between 1½ and 2 minutes at this height. If the speed is 240 knots, this is cut in half (45 to 60 seconds), and at 480 knots, this is about 23 to 30 seconds of time.

In any case, the marker signal is present long enough to attract the pilot's attention so that he can hear the tone signals and tone codes several times. An identical or improved vertical beam at 1030 MHz can be created for a low-power SSR interrogator signal. Thus, there is more than adequate time for the exchange of height data as described previously. With increased height, the time for measurements is greater. However, typically, the lower altitudes have lower speeds so that some compensation takes place. For example, at 1,000 feet the signal is 2 miles in width, or 1 minute at 120 knots, and 30 seconds at 240 knots (the latter being the typical, low-altitude, terminal-area speed of jets). Thus, it is concluded that at least 30 seconds, or at worst perhaps 20 seconds, of signal is available on the normal

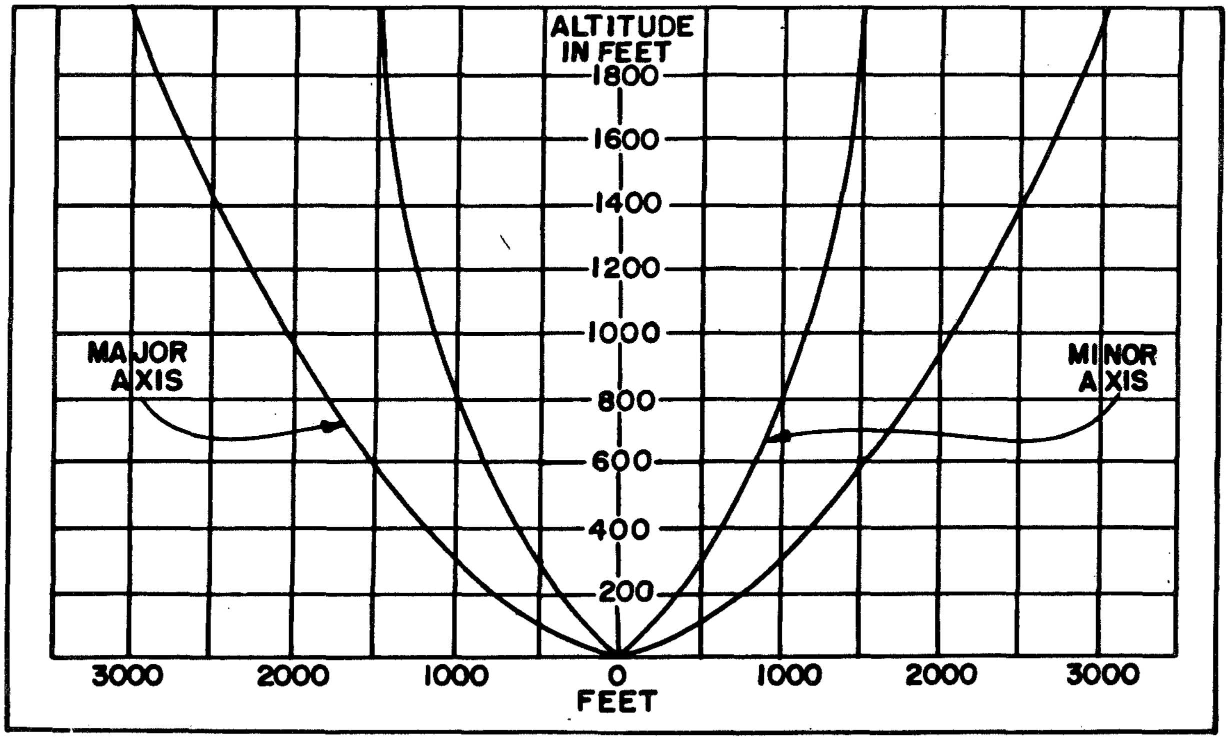


(a) Vertical patterns obtained from a Class FM fan marker having an impoved type antenna array, receiver sensitivity "High".



(b) Vertical field patterns obtained from a Class FM fan marker having a standard type antenna array, receiver sensitivity "High".

Figure 31. TYPICAL VERTICAL FIELD PATTERNS



(c) Vertical field patterns obtained from an ILS marker beacon. Receiver sensitivity "Low".

Figure 31 (continued). TYPICAL VERTICAL FIELD PATTERNS airway marker. This is more than adequate to alert the height measuring equipments and to assure that the radar will measure the most accurate height and minimize or eliminate "slant-height" measurement errors.

If the aircraft is not over the zenith of the marker beam emitter (passing through the vertical beam axis), then some means must be used to assure that a height error is not incurred by the radar measuring that range (as noted in Figure 23). This general error is less than 2 percent if the aircraft passes within 11 degrees or less of zenith. At 5,000 feet this is a track error of about 1,000 feet. In most cases the flights will be within the track error, if the pilot has maintained the standard (two sigma) ±4.5 degree total VOR system error just prior to passing over the station and if he is near a VOR at the time of height measurement. However, at greater distances this (±4½ degrees) can be more than 1,000 feet, and, in fact, can be 3,000 to 4,000 feet, so that some consideration must be given in the tests to ways and means of correcting for slant-height range measurements.

C. CROSSED-BEAM CONCEPT

Since the radar microwave beam is readily controlled and shaped at X or C band, and directed in any manner we desire, we can cause it to provide data not possible with the wide, poorly controlled patterns of a 75-MHz marker beacon emission. The wide width of the 75-MHz marker is advantageous to this concept because it assures that the tone (data) transmission of height from the aircraft always occurs. However, we must assure ourselves that the radar reads the actual, correct height of the aircraft, not merely the slant-height of the aircraft. By crossing the two flat planar beams, each generated by a simple "pill-box" or microwave horn (see pages 459-464 of reference 11), we can achieve interesting and most useful results.

The geometric principles of the crossed beams are shown in Figures 25 and 26. Two planar beams are crossed at 90 degrees (maybe 60° is better). Each beam is quite narrow in one direction and quite wide in the other, creating a vertical fan-shaped beam.

Typically, a beam 3 x 90 degrees, as measured at the 3-db points, would be a good first experiment. At 5,000 feet, 3 degrees is 250 to 500 feet in radar (beamwidth) coverage, providing about 1,000 "hits" (pulses) as the aircraft traverses (flies through) this fixed beam. It will be noted that if the aircraft is to either side of the airway, two distinct beam returns exist since the antennas are merely in parallel, both fed from the single radar. The width (duration) of each beam return (count of the pulses) is determined primarily by speed. The separation between the two returns (dimension Y) is related to the amount of off-course piloting error.

This off-course error has a track that is parallel to the airway direction at this point, and the crossed beams are oriented according to Figures 25 and 26. Thus, if the aircraft is a goodly distance off the airway at the time of height measurements, then dimension (time units) Y will be large. A simple clock running at the radar PRF (1,000 pulses/second) counts the times X, Y and Z in units of "hits" and time between "hits." This output is a simple digital signal readily processed to obtain the correction factor. This factor is used to correct the actual slant-range height measurement.* Since in most cases we will be dealing with a cosine function (of angle a), the corrections will be small percentages of the slant range height (10 degrees is 1½ percent, 20 degrees is 6 percent, and 30 degrees is 14 percent). Thus, the dimension Y, if measured to an accuracy of 5 percent, creates a final geometric error of height of only 1/20 x 6 percent or 0.3 percent, well within our design objectives. Typically, 0.3 percent at 5,000 feet is but a 15-foot error due to the slant range measurement, well within the nationally standardized 100-foot quantized system (SSR of 4,096 codes, each representing 100 feet of quantized height).

Without a crude means of slant-height corrections, some

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* It is shown in Figures 25 and 26 that the airway or a track parallel to it is a vertical plane intersecting the two crossed microwave planes and that a constant ratio of beamwidth and beam separation (x/y or z/y, Figure 25) represents angle a as viewed from the ground.

serious off-course errors would create false height errors. Further geometric analysis of the crossed-beam concept will show that near the center of the cross the errors due to slant-range or off-track flight errors decrease markedly because of the cosine-function influence. It is likely that a vast majority of the air traffic will be on course or close enough that slant range errors would be minimal. Initial tests of this concept can assume aircraft directly over the vertical radar because it is known that a simple slant correction will be tested during a second phase. However, even in the adverse case of airway traffic being off-course sufficiently that, when viewed vertically from the measuring site, the aircraft is 30 degrees from the zenith. The dimension Y is readily measurable to 1 part in 20, and thus the computation using Y corrects the 14 percent error to 1/20 of that error, so that the geometric error is down to about 0.7 percent. Even in this highly exaggerated case, height monitoring data used for vertical separation, "flagging" altimeters beyond standardized tolerances, etc., is still within the quantized values of our national standard. The higher the aircraft, the less the slant correction for a given airway track error, another compensation aiding the baro-correction above 10,000 feet.

Technically, the crossed-beam concept is easily installed by merely using two horns or pill-box antennas fed with a microwave "T" from the radar. Crossed-beam tests occur after some single-antenna flight tests to determine beamwidths, radar sensitivity, ground target returns, etc. The flight tests would record with tape, scope-cameras, etc., the shapes of beams A and B, their widths, number of pulse "hits," and the dimension Y. Simple electronic geometric correction can be applied to correct the radar range (height data) so that effectively the data is a vertical line equivalent to a zenith altitude measurement directly beneath the aircraft, even if the aircraft is not over the facility. Flight tests of this data will establish the best beamwidths, angles, and likely errors; however, all these values seem well within desired engineering tolerances.

D. OUTLINE OF EXPERIMENTAL PROGRAM LEADING TO THE DESIGN OF A FACILITY FOR IN-FLIGHT CALIBRATION OF BARO-SENSORS

I. Vertical looking ground radar for height measurement

  a. Experimental "crossed-beam" microwave antennas

  b. Modifications to commercial X-band marine radar

  c. Modification of radar display to measure height data (using typically ½, ¾, or 1½ mile ranges with 20 yards discrimination)

  d. Range decoding with digital conversion to land-wire inputs for ARTS I and ARTS III alpha-numeric computer displays

  e. Flight testing using photo-theodolite recording techniques

  f. Data reduction (accuracy, error computations, cosine corrections)

  g. Modifications of test units

  h. Confirmatory flight tests

  i. Tentative design specifications

II. Bell Telephone data-transmission systems (4 x 4 and 4 x 4 x 5 multitones)

  a. Simplified telephone handset push-buttons on VHF voice channel

  b. Variable burst lengths on VHF (normally 40 milliseconds)

  c. Interval timer variation of multitone codes in flight-test environment

  d. Ground, multitone decoding and processing equipment

  e. Ground recording equipment to establish integrity of multitone data transmitted from test aircraft

  f. Test of modulation levels of dual and triple tones on VHF voice equipment

  g. Sequential burst messages of dual or triple tones, giving 1/256 or 1/8,000 code structure (16 x 16 or 90 x 90)

  h. Test VHF lobing, multipath, turning aircraft, air and ground patterns of antennas to establish reliability of transmission paths

  i. Test tone transmission with partial voice jamming on circuit (BTL selection of tones was to eliminate such jamming)

  j. Consult with Bell Laboratories on usage of multitones in air-to-ground and ground-to-air data transmission for general aviation and airlines

  k. Study ground net for sending data to control towers, centers, small airports, synchronous with Omega VLF timing, etc.

1. Establish typical standards on modulation, VHF transmitter characteristics, costs, airborne encoding, air and ground decoding, etc.

III. Low-Cost Barometric Sensor-Encoder Tests

a. Modify "baro-switch" of radio-sonde units (such as VIZ units)

b. Laboratory testing of baro units for repeatability, life, and encoding accuracy

c. Test baro-switch for coarse altitude encoding of every 500 feet utilizing the SSR-ICAO transponder codes

d. Breadboard "inter-face" units between low-cost baro-sensor and existing low-cost SSR transponders.

e. Test baro-sensors and experimental electronics to use multitone data link for altitude transmission using BTL data transmission noted above in step II

f. Flight tests of SSR transponder and BTL (tone-VHF) reporting of barometric height in 500-foot ICAO code and 300-foot BTL code

g. Record flight test data and analyze

h. Modify 75-MHz marker beacon for automatic solicitation of VHF airborne multitone signals.

i. Test low-power, low-cost, vertically directed SSR interrogator signals

IV. System integration tests

a. Locate vertical radar at ILS marker site, and test automatic recording on the ground of aircraft height by BTL tone data

b. Same as (a) but record SSR transponder reports to low-power vertical interrogator located with radar on airway or landing approach flight track

c. Land-wire transmission of large discrepancies between baro-sensed data and radar height data using datum reference of ground radar elevation

d. Automatic reporting of errors to pilots by 2 to 3 methods (voice, data link, error only, 75-MHz tone data, SSR interrogate codes)

e. Automatic calibration of airborne units by electronic shifting of altitude codes or by servo changes in barometric referencing datum

f. "In-service" testing on final ILS approach or VORTAC airway utilizing a few instrumented aircraft

IX. ABBREVIATIONS

1. ATC - Air Traffic Control
2. BTL - Bell Telephone Laboratories
3. CAS - Collision Avoidance System
4. CDI - Course Deviation Indicator
5. CLC - Course Line Computer
6. DME - Distance Measuring Equipment
7. ICW - Intermittent Continuous Wave
8. LOP - Line of Position
9. OBI - Omni-Bearing Indicator
10. PCD - Polar Cap Disturbance
11. PPI - Plan Position Indicator
12. PVOR - Precision VOR
13. PWI - Proximity Warning Indicator
14. SID - Sudden Ionospheric Disturbance
15. SSR - Secondary Surveillance Radar
16. TACAN - Tactical Air Navigation
17. TERPS - Terminal Instrument Procedures
18. VAC - Vector Analog Computer
19. VHF - Very High Frequency
20. VLF - Very Low Frequency
21. VOR - VHF Omnirange
22. VORTAC - Combined VOR and TACAN systems

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APPENDIX A

SUMMARY OF THE CONCEPTS OF A NEW VLF LOW-COST GENERAL AVIATION NAVIGATIONAL FACILITY

This appendix was prepared for a presentation to a professional meeting discussion of Air Traffic Control, chaired by William O'Keefe, the NASA/ERC project engineer managing this effort. The discussion was a part of the technical sessions at the 1969 NEREM meeting.

Since it summarizes the subject of VLF navigation somewhat differently from the text and is relatively brief, it is included for the benefit of those who do not have the time to read through the entire report.

To accommodate the large growth in aircraft and airports by the year 1990, it will be necessary to modernize and expand the present VORTAC system extensively. Many of the current facilities must be modernized with precision (multi-lobe or doppler) VOR techniques. Relocation or complex vertical directivity antennas may be necessary to prevent azimuthal course distortions. To supply total Area Navigation coverage with VORTAC and for low altitude flight coverage down to approach heights of about 300 feet, perhaps as many as 2,000 VORTAC stations will be needed by 1990 (Figure A-1). Each station is complex with two basic subsystems: the VOR (doppler or multi-lobe) and the DME (L band pulse, multiplexed system). Each unit must operate with automatic monitors, dual transmitters and receivers, and automatic change-over equipment. Continuous ground maintenance and flight inspection by dozens of FAA and military aircraft throughout the nation causes this to be a very costly approach for national expansion. AC 90-45 (reference 4) points out that the accuracy of VOR airways for Area Navigation will be about ±1.5 miles for terminal operations, about ±4.0 miles for enroute, and about ±0.9 mile for final approach.

The lower half of Figure A-1 indicates that a total, national navigation system could be achieved with only 4 VLF transmitters operating on the principles and vast experience of the Omega system. These four stations would provide a contiguous, interrelated set of coordinates across the entire nation instead of the randomly spaced, unrelated coordinates of VORTAC. VLF accuracies can be kept to about 0.5 mile using a central diurnal measurement and monitoring system. The propagation characteristics of the 10 to 50 kHz region offers excellent coverage on the surface and behind mountains at all altitudes. Monitoring on the surface is adequate for large regions. VLF flight inspection is minimal.

Obviously, installation, maintenance, and operating costs of four stations will be vastly less than that for 2,000 VORTAC stations. Such a detailed cost comparison and operational VLF tests should be made before a commitment to full-scale VORTAC modification, modernization, and re-engineering program occurs. Perhaps a mixture is needed of, ultimately, about 400 VORTAC stations and 4 Omega stations giving (1) redundancy, (2) vast increase in capacity, and (3) what appears as a very low-cost "total" system of VLF timing, ATC, proximity warning, navigation, etc. A several time improvement in service may be gained with a several time reduction in cost of air and ground VLF units.

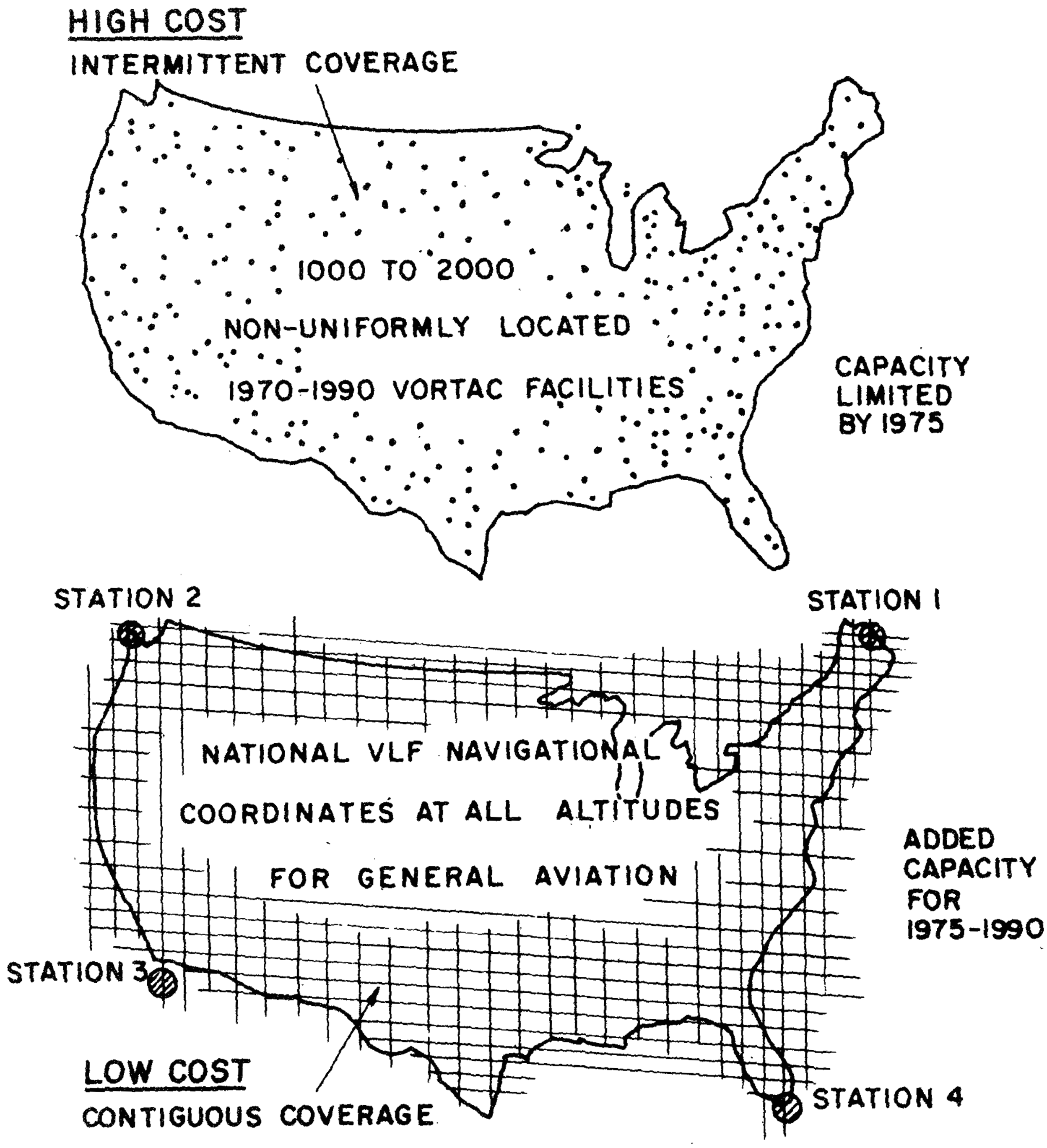

Figure A-1. COMPARISON OF 1000 TO 2000 VORTAC STATIONS WITH BUT 4 VLF STATIONS FOR A NATIONAL NAVIGATION SYSTEM

Although the Omega coordinates are hyperbolic when considered on a 3,000-mile basis, they are essentially parallel straight lines for distances of about 100 to 200 miles. Thus, we have one set of evenly spaced, parallel coordinates crossing a second set of evenly spaced, parallel coordinates. This provides an ideal coordinate system for navigation and ATC as we shall see. Many ATC, piloting and proximity problems are automatically solved with basic, parallel coordinates vs the converging coordinates and random origin coordinates of the VORTAC system.

The simplest means of following the coordinates is to simply use a "crossed-pointer" meter that has two needles that cross, representing the local angle of crossing of the VLF coordinates. Similar instruments are used in normal cockpit usage for ILS and VOR, and flight track following. They are low-cost, yet can give "area-coverage" and are truly an analog or "picture" of the local area.

By using two meter movements, one in a gimbal, it is possible for the pilot to simply set the crossing angle of the needles to represent the angle between the VLF navigational lattice lines. Note in the left sketch (Figure A-2) that the pilot's display is set so that angle a represents angle a shown on the pilot's navigation charts. The pilot would follow the vertical needle and note the movement of the horizontal needle as the aircraft traversed the VLF lanes.

In the center example the lines cross each other at right angles, and in the left example the angle is noted as c which is pictorially presented to the pilots in their displays. Only a single, time-shared receiver is needed to provide this full positioning system and navigation service, and only a simple display equivalent to the present Course Deviation Indicators is required, avoiding hyperbolic or other computations. VORTAC requires 4 elements: (1) VOR receiver, (2) DME, (3) course-line computer, (4) display and controls. VLF Omega requires but two units as there is no coordinate data processing (converting hyperbola or circles to straight lines). Simply "raw" VLF position data is fed to the two crossed needles.

For further details and test results of this simple concept refer to a paper in the IEEE EASCON 1969 Conference Record (reference 2).

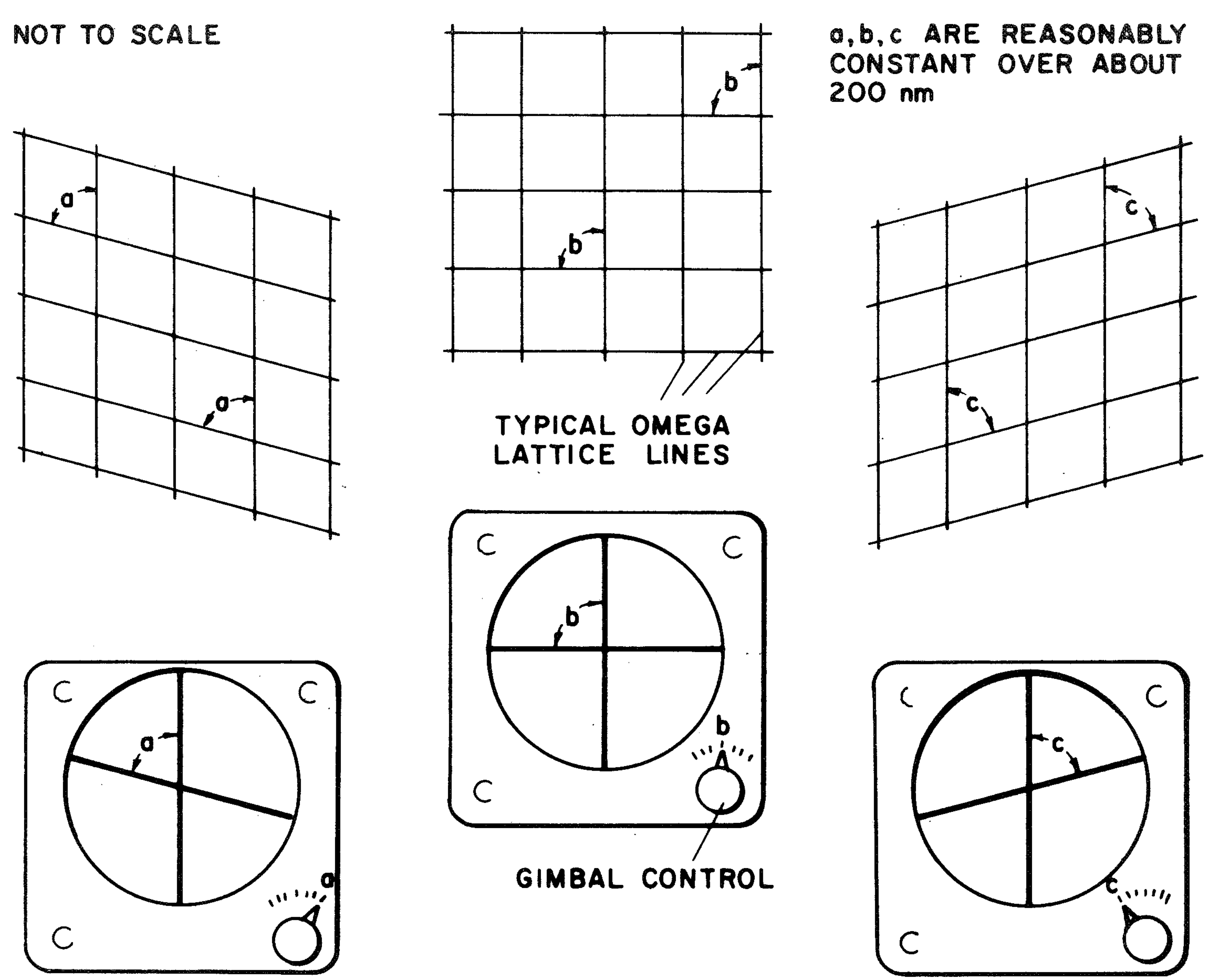

Figure A-2. USE OF GIMBALED COURSE DEVIATION INDICATOR (CDI) FOR VERY-LOW-COST AREA-NAVIGATION PILOT DISPLAY

Figure A-3 typifies a more sophisticated use of the VLF "Wide-Area-Navigation" concepts. At the "start" point the display shows the destination, heading and present position. In five progressive steps we see the pilot fly toward the intended track, intersecting it automatically, and then following the desired track to the destination. All geometric relationships are in real angles and in linear coordinates so that piloting is greatly simplified.

Since Omega is a single-channel, time-shared system, there is no channel changing. The coverage is fully as useful on the surface (and as accurate) so that the pilot can check his display and VLF receiver before takeoff into overcast or dense, controlled ATC conditions. He can even see the display move as he taxies on the airport surface. These features are something not provided by the "line-of-sight" limitations of the VOR and DME that prevent checkable signals to be received on the airport surface from the actual navigation source that will be used in flight. (Both VOR and DME are essential for VORTAC Area Navigation.) The fact remains that no simple means of displaying two coordinates (such as two VOR signals) can be reasonably provided. VORTAC Area Navigation displays provide an equivalence, but are not useful at low altitudes, say, on a let-down under a low ceiling condition to an airfield (remote from VORTAC) that cannot afford an ILS. VLF equally serves what can be thousands of such small airports and their approaches as well as hundreds of major airports anticipated in 1980-1990.

The Omega VLF Navigation display as shown will work "as-is" in Seattle, New York, or Texas; it will be useful at 70,000 feet and on the airport surface; it is fully available in valleys or behind mountains. No RF channel changing is required, and the coordinates are so simple and logical that student pilots should quickly learn to fly and can afford to fly on instruments. Furthermore, the basic cost to general aviation should be less than half that of the VORTAC/CLC Area Navigation concepts.

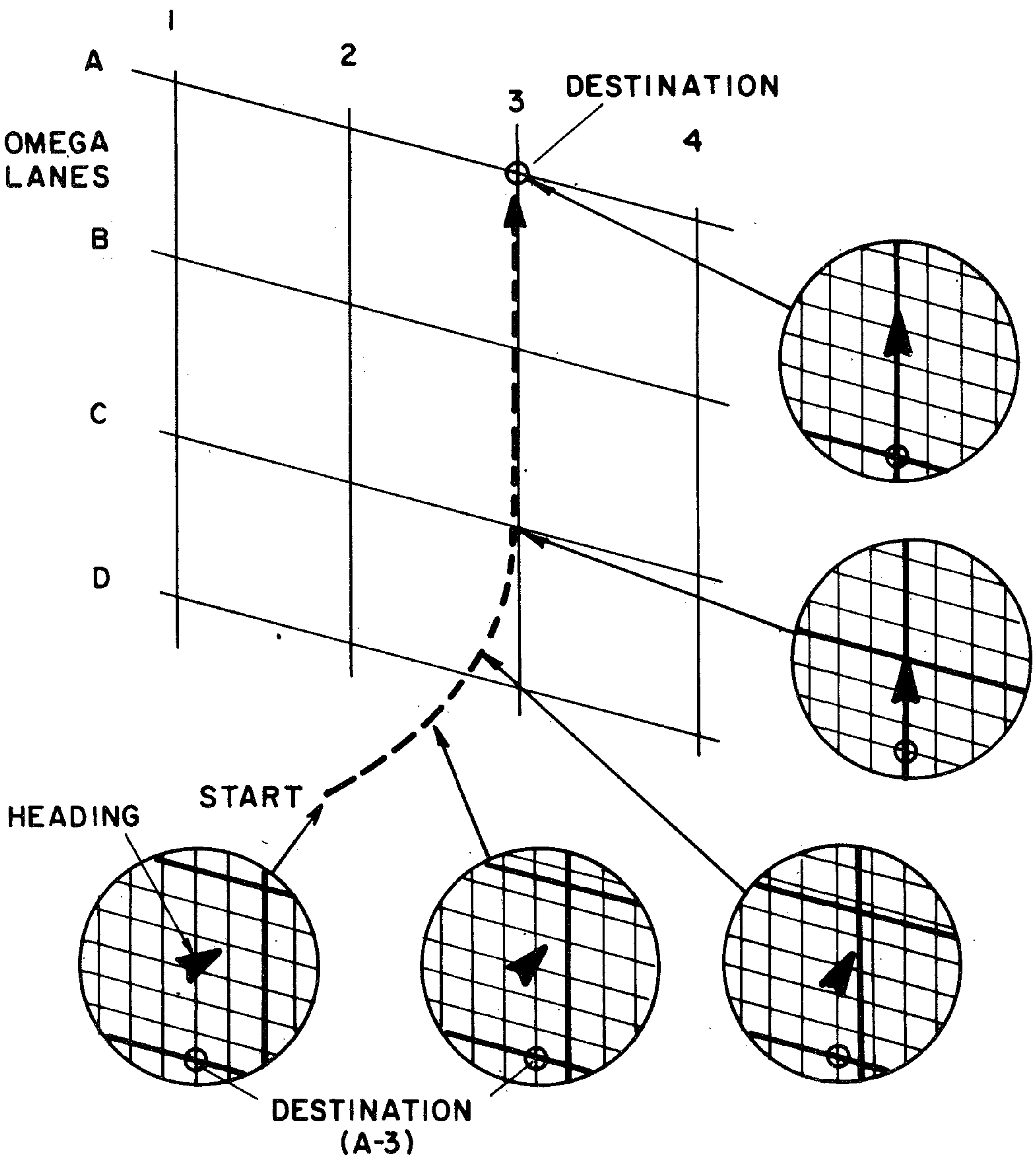

Figure A-3.
EXAMPLE OF INTERCEPT WITH LOW COST DIRECT DISPLAY OF OMEGA LINES OF POSITION AND HEADING WITH FLIGHT FOLLOWING TO DESTINATION

We must mention one of the problems of the VLF transmission phenomena. As the paths are very long and are conveyed in a region between the ionosphere and the earth's surface, some variations in the exact time-of-arrival of a given signal at a given point occurs on a daily or diurnal basis. The amount of variation is well known, very repeatable, and has been recorded and studied for some 20 years by scientists at Harvard, NBS, the Navy, and in Europe. Thus, one can predict the exact amount of diurnal shift that occurs, and computed tables are used to correct the exact amount. Also, by means of a local receiver, the electric coordinates are related to a known geographical reference, and the pilot is told to add or subtract a "differential" correction just as he now adds or subtracts barometric pressure changes.

This "differential-Omega" concept reduces what might be errors of 3 to 4 miles to errors of less than ½ mile. Thousands of tests have verified this concept. Such a concept is readily automated by several means, such as simply transmitting periodically (every 10 minutes is adequate) the local differential correction along with the barometric correction. The ATC tower or center would simply read by automatic voice, units of altimeter settings, such as 29.31, and the navigation settings are +14 centilanes X and -11 centilanes Y--all in a single short broadcast.

However, even a better solution is evident when a small geographical area (compared to Omega's normal world-wide coverage), such as the United States, is considered. By installing some 20 or so monitoring receivers strategically located throughout the country, and feeding their readings by telephone lines to a central computer (Figure A-4), it is possible to have at one point all the data needed to instantly provide the corrections needed at any locale to any user. History of daily shifts and interpolation should permit this correction to be made to accuracies of about 500 to 1,000 feet, based on a wide-area computation using known propagation constants. These can be automatically received by VLF at each receiver, automatically modifying its output to correct readings and reflect the diurnal correction.

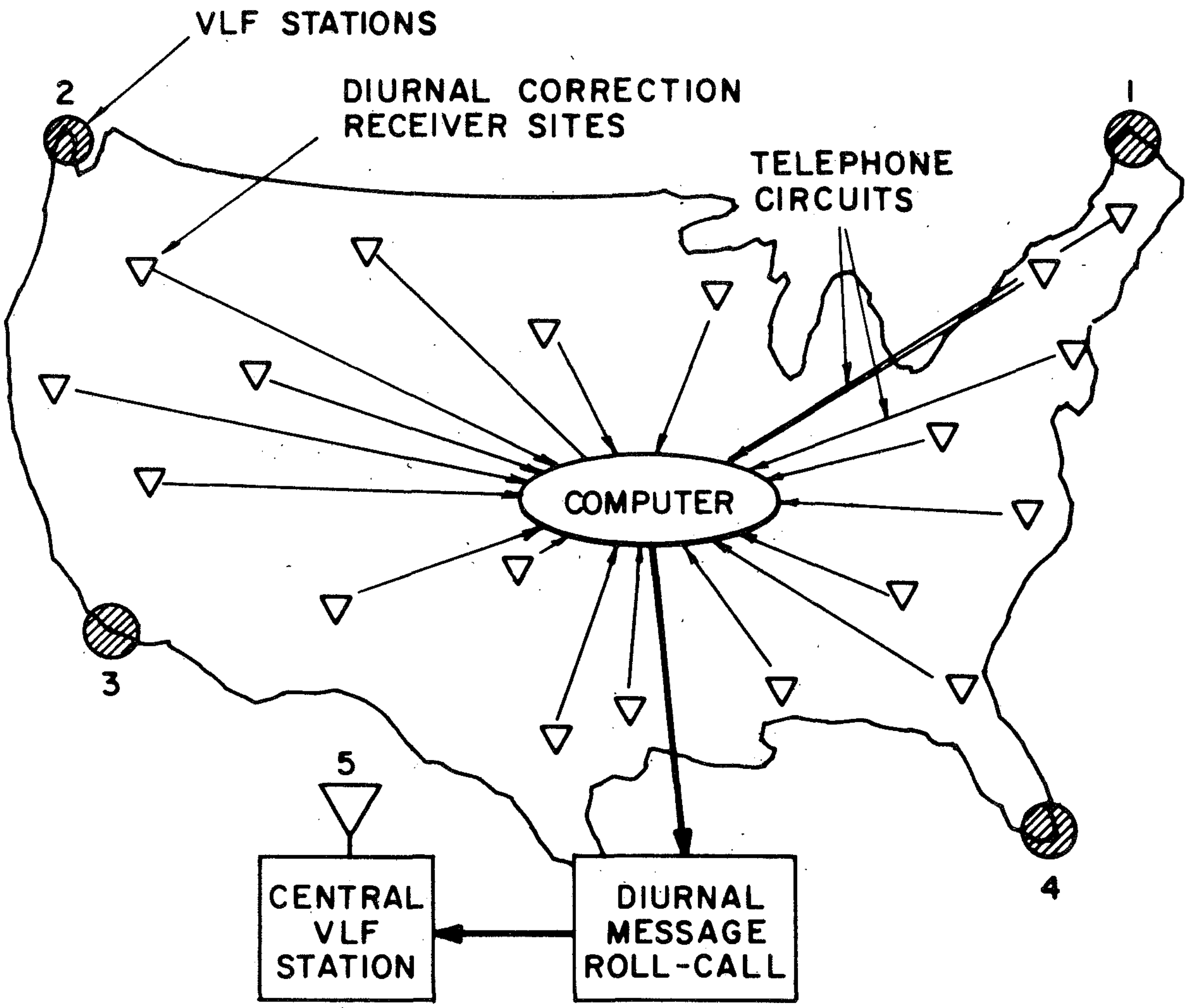

Figure A-4.
ABOUT 20 MONITORING SITES FOR COMPUTATION OF NATIONAL DIURNAL CORRECTION MESSAGES AND FOR QUALITY CONTROL OF GUIDANCE DATA

As noted in Figure A-4, the central computer senses the total VLF "flux" across the nation, and from about 20 sensors a computer examines current readings of all LOP's and the rate of change of diurnal (it repeats day to day to within a few centilanes), according to Swanson of NEL (reference 10). Thus, the computer merely examines the current readings, history and any special conditions, such as CPA's or SID's, and provides a real-time computation of the correction necessary everywhere in the United States for automatically providing a differential VLF navigational correction. Although this can be provided on a teletype circuit to all localities, like the weather service, and be added as an extra message on the weather teletype network already in existence in the FAA and military fields, there is also an intriguing possibility that this can be done fully automatically within each user's receiver.

The Omega VLF receiver receives a phase-coded message that automatically corrects its output. This is done by using the precision 10 seconds of the Omega format cycle (or any multiple of it such as 5, 15, 20 seconds). This format cycle can be synchronously followed by a receiver so that it is "tracking" in a time-sequential manner the 10-second format to about a 1 to 2 millisecond accuracy (navigation is to about 3 microseconds of reading accuracy and should not be confused with the format time-frame signals).

Thus, each diurnal correction message is addressed by roll-call to each geographic area in the United States, so that about 100 areas are "roll-called" in about 2 minutes for a given station. With 4 VLF stations providing national coverage (5 to 6 lines of position everywhere), this would require a total of only about 8 minutes to transmit a full diurnal correction for computing position from any of the 6 possible hyperbolas (Figure A-5).

A possible phase-coded message is illustrated using a "Pierce"* type phase code wherein the 3 steps are: +90 degrees, 0 degrees, and -90 degrees. This code offers the necessary message capacity to fulfill a 1 percent accuracy requirement (one centilane, or about 500 feet correction accuracy).

The lower half of Figure A-5 shows the message and the roll-call addressed sequentially by time from Seattle across the nation to Maine, continuation in a raster-type scan, with varying areas depending on distance to each transmitter, and ending in the Miami, Florida area. A total of 100 areas are thus corrected to the latest diurnal monitoring situation. This automatic correction with the typical errors of equipments and piloting should result in a total user error of about ½ mile to 1 mile, depending on the complexity of the user's receiver and how the differential is inserted.

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*Professor J. A. Pierce of Harvard must receive the major credit for his vision and skill in bringing VLF navigation to its successful stage and world-wide implementation and usage. Many of his comments have been most helpful in the study of the broad aspects of a similar U.S.-only VLF Navigation service.

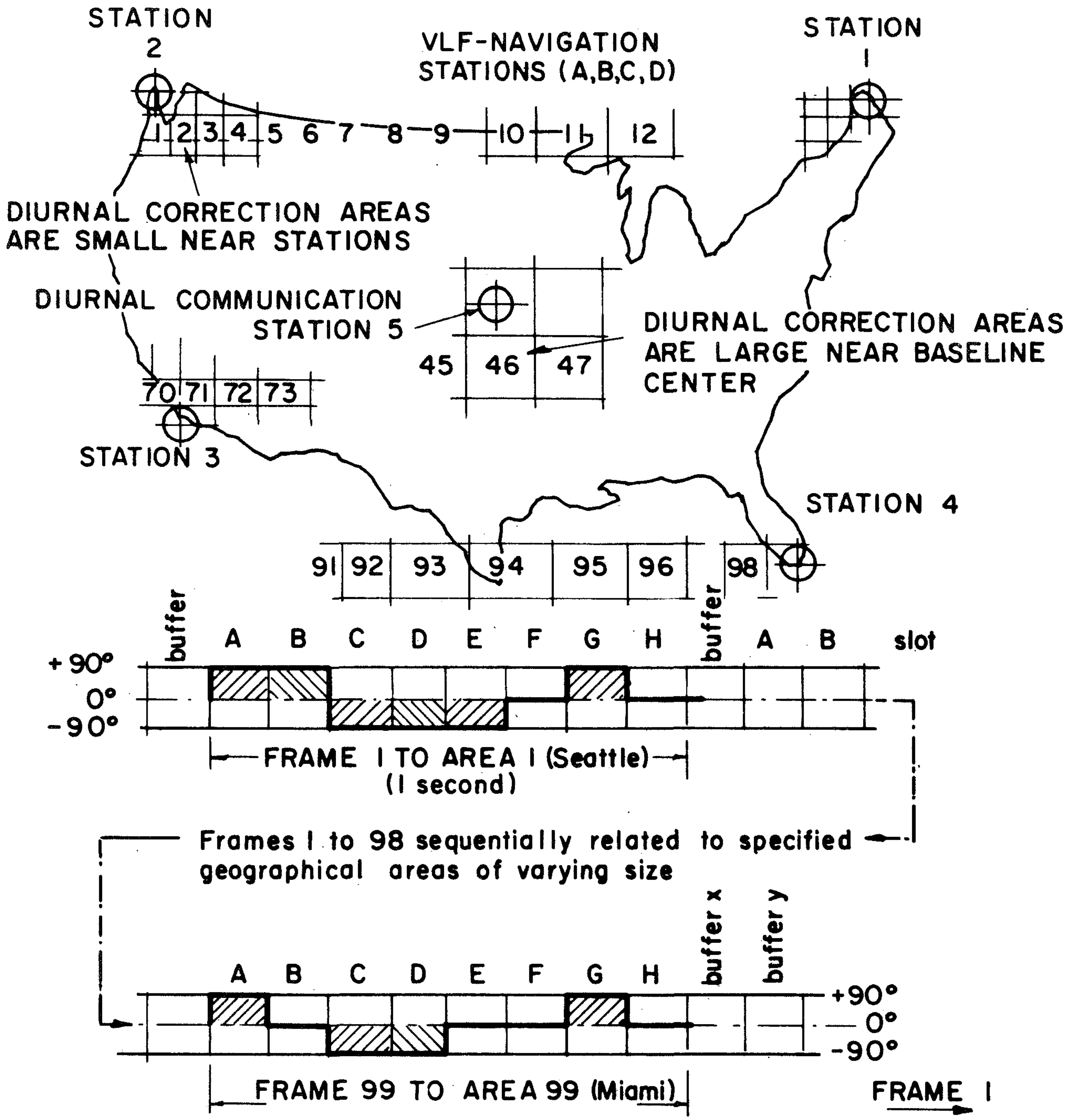

Figure A-5

DATA TRANSMISSION FOR AUTOMATIC DIURNAL CORRECTION OF NATIONAL VLF NAVIGATION FACILITY

Figure A-6 summarizes some of the aspects of pilot usage of VLF (such as modified Omega for the "U.S.-only") and VORTAC (the current system); VORTAC may finally require billions to expand and modernize by 1990 to (1) meet the growing threat of collisions by better ATC and track following and (2) the expanded airspace needs of general aviation and VSTOL. Under "ERRORS" we refer to the fact that the errors of VLF navigation are nearly constant throughout the coverage and are somewhere in the ½ to 1 mile region depending on the user's receiver. In the VORTAC this varies from about 1 mile to about 4 miles or more, depending upon the user's distance to the nearest VORTAC facility (see reference 4, which describes the use of VORTAC with errors of 2 to 4 miles as an Area Navigation system).

With respect to INTERCEPT we see that (depending upon the distance from a VOR) the flight track intercepting the ±10-degree coverage each side of the selected course requires a different intercept angle with differing ranges of intercept. Since the track error is linear and constant for at least 300 miles, the VLF track can be intercepted with a single, standardized intercept angle and meter (CDI) sensitivity. Professor McFarland has demonstrated (reference 2) in a low cost application of Omega that a sensitivity of ±2½ miles is typical with such a standard. This infers that the learning of Area Navigation could be greatly simplified and possibly taught so that every private pilot upon receiving his license can navigate.

Similarly, Figure A-6 indicates that the course varies with distance in sensitivity and that the overall "gain" of the control loop varies by over 10 times on normal flights using VOR radials. This sensitivity change is disturbing to a pilot, since his on-course heading corrections for a given indicator (CDI) error must vary throughout the flight. In the constant sensitivity case of VLF-Omega, a given heading for a given cross-wind or other track disturbance achieves a standardized, repeatable result. Even though VLF/CDI displays are slower to react than VOR, these aspects give the final piloting advantage to VLF.

The coverage portion of Figure A-6 illustrates that the line-of-sight constraints of VHF propagation limit the low-altitude use of VORTAC. Thus, VORTAC is not useful in the cones above the stations nor below the radio horizon, limiting the operational utility of VORTAC, say, for a 300 to 400 foot approach-altitude to remote fields, considerably and forcing new VORTAC station installations for new airports. U.S.-Omega-VLF can satisfy any large number of new general aviation airports (even thousands) regardless of their locations. Furthermore, VLF offers superior service in terms of low-altitude coverage and in terms of accuracy.

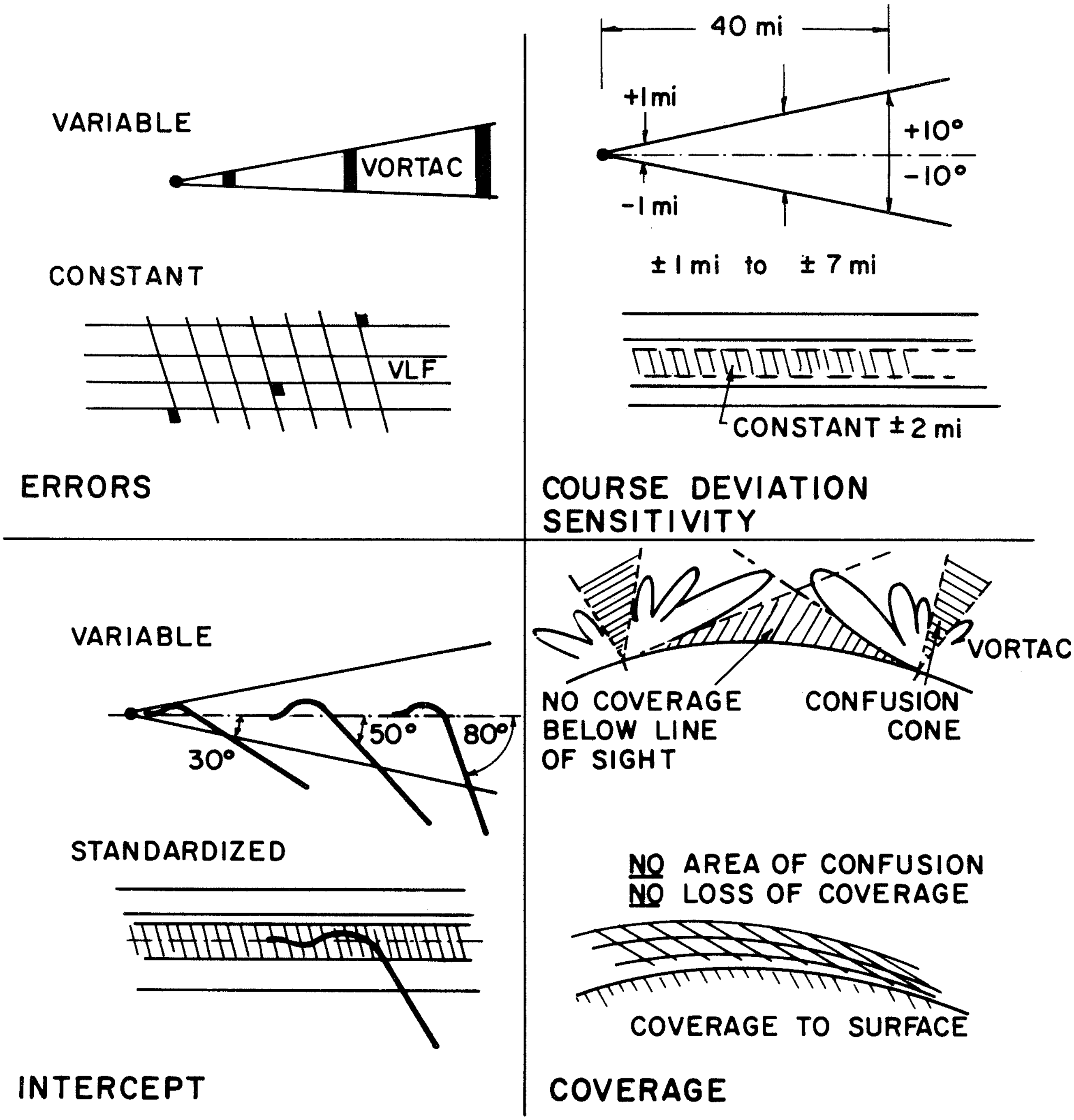

Figure A-6. PILOTING ASPECTS OF VORTAC VS VLF

In the portion of Figure A-7 that shows the number of airborne units, we see that a comparison is made of the VORTAC equipments required in the simplest Area Navigation configuration to comply with the new FAA criteria. The four elements total in cost about $8,000 to $10,000 (for a future expanded and modernized environment of VORTAC that may include more closely spaced RF channels and precision VOR techniques, cutting angular errors to a third seems essential for VORTAC Area Navigation success). When the cost (about $3,000) of a CLC such as the one recently announced for general aviation by NARCO (reference 12) is added to the cost of a VOR-DME and a display, we arrive at a minimum cost of about $8,000.

Although the airline VORTAC Area Navigation units may cost as much as $40,000 to $75,000 for the 4 elements and some redundancy, the lowest general aviation cost, when the VORTAC expansion and modifications occur to really provide true Area Navigation, will still be about half the cost of a good, single-engine aircraft. This does not include the other electronics needed--instruments such as SSR, gyros, communications, etc.--so that the electronics could finally equal the cost of the aircraft itself if we do not find means to greatly reduce costs while adding general aviation service.

The cost of the VLF navigation receiver is low because there is no need for a CLC computer unit, and the single receiver obtains the equivalency of crossing coordinates in the time sharing of 4 stations. Thus, it is estimated that the general aviation user's VLF navigation costs will be probably no higher than that of a good VOR receiver and display or about $1,000 for a total, national, local, "wide-Area-Navigation" capability that is far more useful in additional ways than VORTAC.

In the sketch of Figure A-7 that shows multiple airport ATC, we see that the VLF coordinates fit the approach tracks with better geometric harmony than the many polar diagrams needed for VORTAC. In the comparison on frequency changes, we see that the pilot is forced to repeatedly change channels while navigating with VORTAC, but when using VLF wide-Area-Navigation, there is no channel changing. One channel selection exists in VLF and never changes throughout the nation, so that only track changes are inserted into the display (as seen in Figures A-2 and A-3).

This fact alone results in a large reduction in the cost of VLF receivers, since in VORTAC the many channels must be carefully selected, since it requires the complexity of a hundred or thousand channel unit.

In the sketch of Figure A-7 that shows irregular and mountain terrain, we see that the shadowing of VORTAC prevents its use behind a mountain. However, VLF in the same environments is unaffected by mountains (no multipath errors) and provides coverage behind them and to the surface everywhere so that little airports in valleys have the same good service as those in the open areas. This aspect alone is an enormous national savings as hundreds, if not thousands, of general aviation airports will spring up throughout the nation with the growth to some 200,000 users.

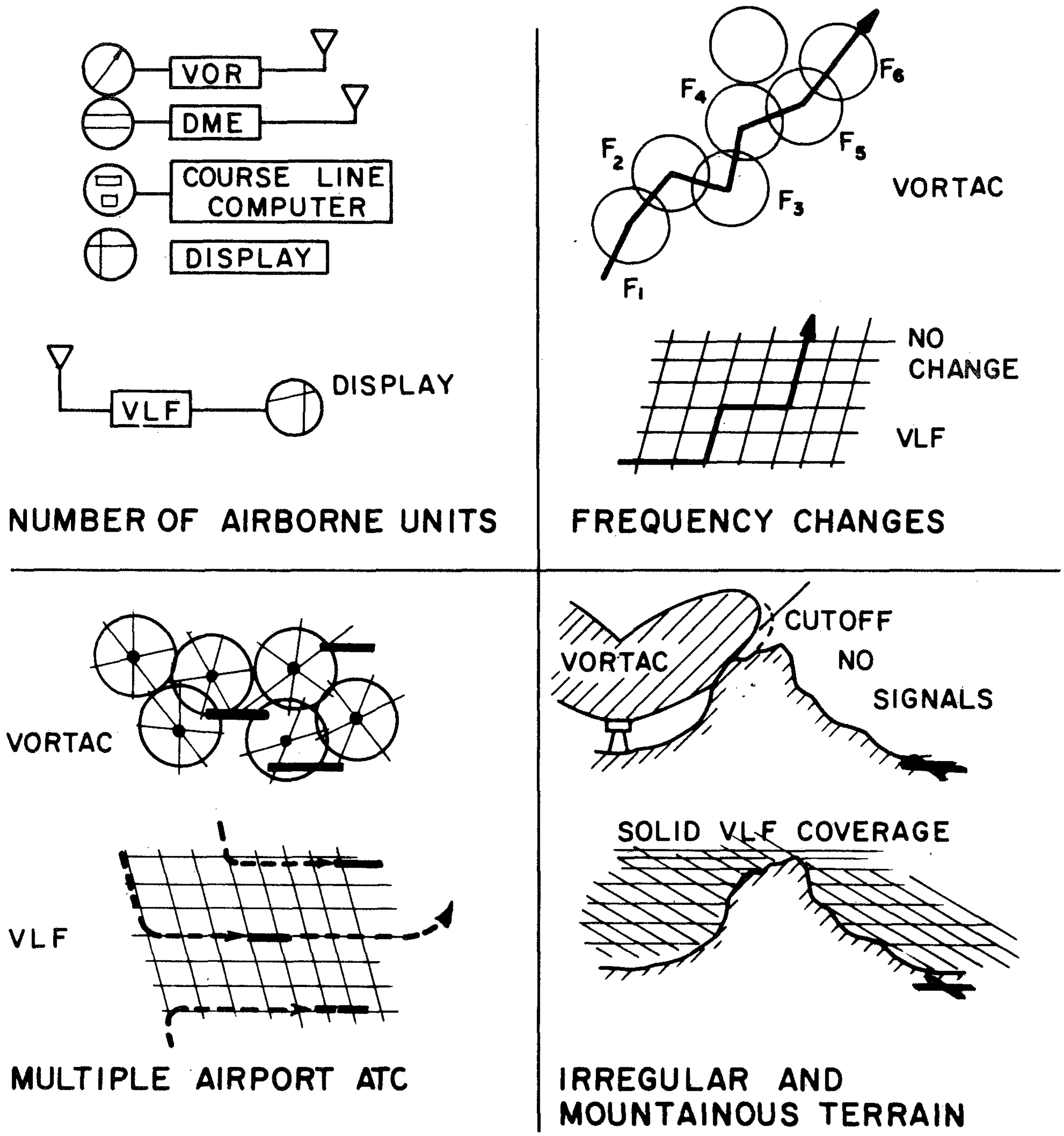

Figure A-7. AIR TRAFFIC COMPARISONS OF VORTAC VS VLF

Table A-I recaps the foregoing discussion about a new 4-station chain of VLF stations that optimizes all we know now about VLF navigation and is similar to, and based on, Omega. The current Omega program is planned to be operational on a world-wide basis in about 3 years so that the 4,000 to 5,000 mile baselines will offer a much needed global service. Although this will also be available in the United States, the extremely low "total" VLF system cost is so attractive that it is proposed that a parallel cooperative net covering only the United States should be installed. The many advantages to be gained are listed in Table A-I.

The main advantages include the sampling rate which is cut at least in half so that the track errors are minimized and the computing and display costs for aircraft can be reduced. Secondly, the VLF signals can be made stronger for this given area by increased power and shorter transmission ranges--again lowering receiver costs and improving performance. Thirdly, we can automatically correct diurnal over a small area (such as the 48 contiguous United States) since it is but a small fraction of the total earth's surface. The 4 million square miles is divided into areas about 40,000 square miles each, or about 200 X 200 for diurnal correction from one single central VLF broadcast, something not suited to a world-wide system. Thus, the automatic diurnal correction offers much gain for users of the limited U.S.-only Omega chain over the world-wide system. Such a measurement and transmission means (as shown in Figures A-5 and A-6) is practical in the U.S. case, simply eliminating one of the admitted limitations of VLF navigation. Thus, we gain many advantages in the parallel, cooperative and fully synchronized, U.S.-only VLF-Navigation system. It will back up the world-wide system, it will be aided by the world-wide system (Trinidad is near Florida and may serve as a station), and the U.S. Omega will aid world-wide Omega.

Basically, the world-wide system is in itself a remarkable achievement, yet some of the urgent general aviation needs cannot be fully met by it alone or by VORTAC. The costs are relatively so low (megabucks per mega-square miles) that for perhaps 10 percent of the cost of expanding and modernizing VORTAC over the next 20 years (more stations, closer channel spacing, increased vertical gain, multi-lobes, doppler, etc., and still not bringing the cost to general aviation below about $6,000 to $8,000) we can offer more coverage and higher quality service to more users (airlines, military, and particularly the 200,000 general aviation aircraft that will probably be forced legally to carry some form of Area Navigation of this nature in a few years).

Thus, for a fraction of the cost we gain an increased number of services: a double gain. The costs of the minimum airborne unit after R & D should be below $1,000, possibly down to that of a good VOR receiver of around $700. Then, we would have a mix of both VORTAC and VLF-Navigation for the 1980-1990 era with about 4 VLF stations and reducing VORTAC to about 500 stations. The two coordinates and transmissions will complement each other (Omega can be a DME-equivalency), and all users have backups, choices, and redundancy.

WORLD-WIDE OMEGA	U.S.-ONLY OMEGA
8 STATIONS	4 STATIONS
10-SECOND SAMPLING	4 TO 5 SECOND SAMPLING
TABLE OR DIFFERENTIAL DIURNAL CORRECTIONS	AUTOMATIC DIURNAL CORRECTIONS WITH CENTRAL STATION 5th
4000 TO 5000 mile BASELINES	1500 TO 3000 mile BASELINES
FREQUENCIES (THREE CARRIERS) F_1, F_2, F_3	FREQUENCIES (THREE CARRIERS) F_4, F_5, F_6
AVERAGE SIGNAL LEVELS	STRONGER SIGNAL LEVELS
ABOUT 3 TO 4 LINES OF POSITION ANYWHERE	ABOUT 5 TO 6 LINES OF POSITION ANYWHERE
10 TO 14 kHz REGION	10 TO 14 kHz NAVIGATION 15 TO 25 kHz DIURNAL
COMPLEMENTS 4-STATION U.S. CONFIGURATION	COMPLEMENTS 8-STATION GLOBAL CONFIGURATION
DIURNAL CORRECTION AREAS ABOUT 5000 (200 nm x 200 nm)	DIURNAL CORRECTION AREAS ABOUT 100 (200nm x 200nm)
COVERAGE AREA (approximately) 200 million sq. miles 60 million - LAND 140 million - WATER	COVERAGE AREA (approximately) 4 million sq. miles 3.5 million - LAND .5 million - PERIPHERAL WATERS

Table A-I. RELATIONSHIP OF WORLD-WIDE TO U.S.-ONLY OMEGA

APPENDIX B

SUMMARY OF THE GENERAL AVIATION PROBLEM OF 1970-1980

The situation faced by the general aviation pilot or aircraft owner (of aircraft costing less than $20,000, probably about 50 to 75 percent of the general aviation population) is the following:

1. The purchase now (1970) of the SSR transponder gives him radar surveillance, services, and a coded message for identifying and acknowledging ATC instructions, but no direct cockpit assistance for track keeping and schedule maintenance for separating his aircraft from others on common tracks. Nevertheless, SSR transponders are so popular that some 1,500 transponders per month are being sold. Use of synchronized air-to-air reception can aid capacity and safety of SSR-ATC concepts.

2. Having acquired the transponder and already possessing VOR and VHF communications under certain circumstances, IFR flight is possible. No ILS is needed except in low visibility conditions at the destination, nor are DME, Area Navigation, computers, or Area Navigation displays.

3. IFR and controlled VFR traffic loads will increase markedly, and the SSR channel will become severely loaded (electrically, operationally, and otherwise). The close-control (or tactical control) concept of ATC is forced onto the controller, since the ground controller is now the best informed of all ATC participants. Often a VOR-airway (radials only to a few points but usually now where the ATC or pilot wants the aircraft to go) cannot be used, and the pilot is then "open-loop" in the sense he is not following a cockpit displayed airway. When a cockpit displayed air route is displayed, the pilot does the navigation and the ATC the separation and surveillance. Surveillance only (without cockpit navigation) places a heavy load on both the pilot and controller, since voice communications is the only means of a minute-by-minute "close-control" by heading, speed, and altitude changes, since this concept must assume that the direct pilot guidance information is lacking or is inadequate. Here, a VLF receiver suited to multiple LOP's and a synchronous system can economically aid by giving an equivalence of DME, CLC, PWI, CAS, Area Navigation, air-to-air track separation, data to central displays, etc., all with one addition rather than a dozen additions.

4. The inevitable results of steps 1 and 2 are then operationally avoided. For ATC to close the loop as it should, by requiring Area Navigation consisting of a DME, range-angle CLC computer, Area Navigation display, dual VOR, etc., something about 5 times or so as expensive as that called for in step 3 is involved.