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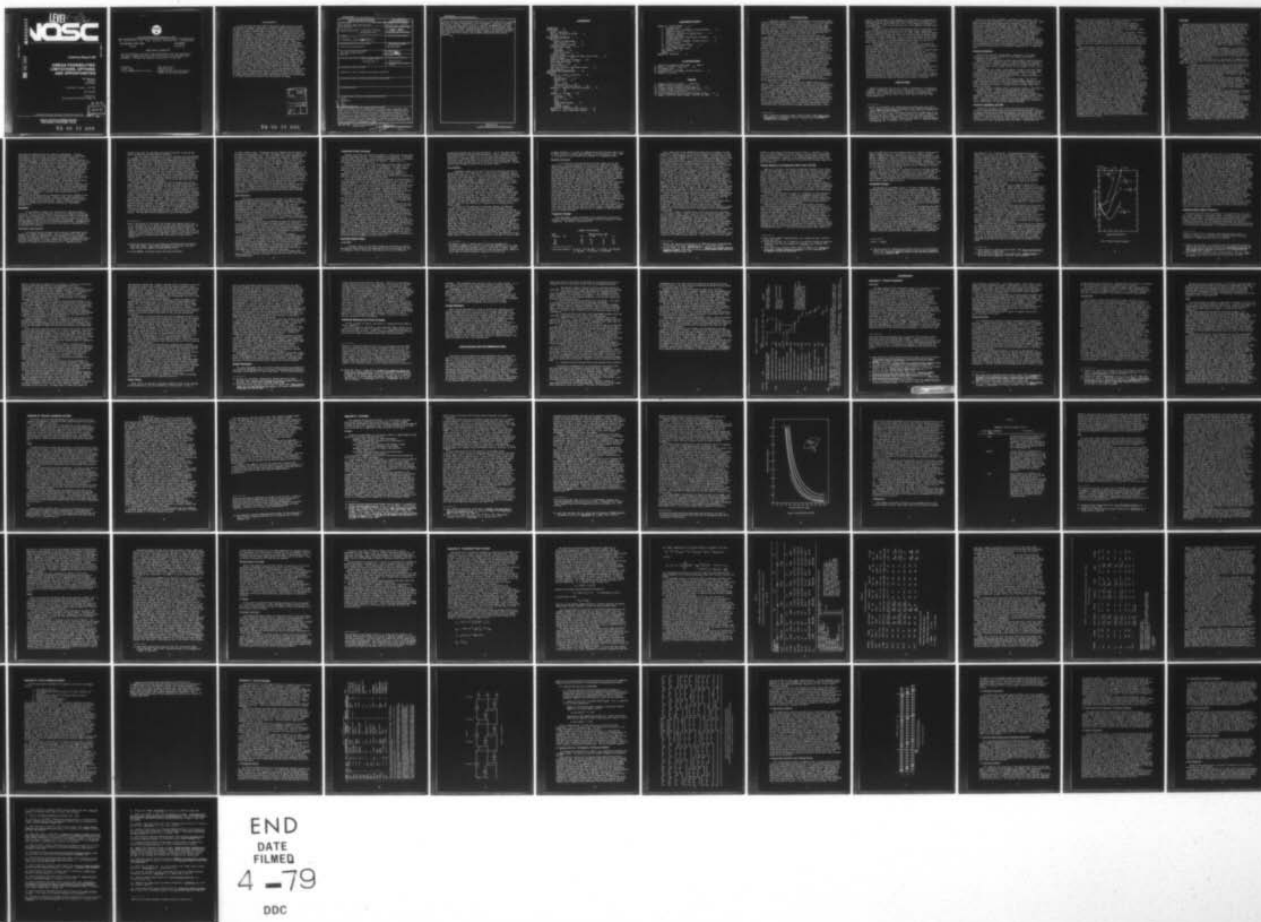
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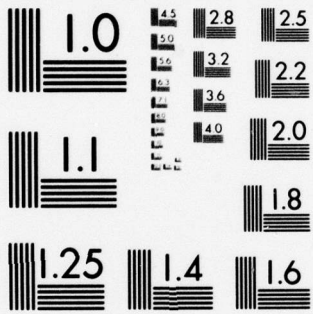
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Technical Report 283

OMEGA POSSIBILITIES: LIMITATIONS, OPTIONS, AND OPPORTUNITIES

ER Swanson
JE Britt
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Final Report: January - July 1978

23 June 1978

Prepared for
Navy Omega Project Office -PME-119

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Potential coverage limitations were identified in several areas while a coverage deficiency in central North America is to be expected. Significant reception difficulties have been noted in aircraft. Specific recommendations are made for investigations leading to improved receiver design and to mitigate reception problems in aircraft. Despite system maturity, a considerable and perhaps surprising latitude exists for modifications. Methods are presented by which one or more additional stations can be added without obsoleting existing equipments.

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INTRODUCTION

It has been 12 years since four developmental cesium controlled Omega stations commenced transmissions on a 24-hour schedule. It has been almost 10 years since the developmental net was declared interim operational. More important, it has been several years since transmissions from eight Omega stations, seven of them in final configuration and at nearly design power, have been available. Thus, although the system is not yet fully constructed, there has developed a considerable body of theoretical, engineering, and operational experience with the system in nearly final form.

It is thus appropriate to pause and review present status and accomplishments. In particular, it is appropriate to search for shortcomings or deficiencies and re-examine some of the system design parameters with a view to determining possible investigations, modifications, or changes which might mitigate or lead to elimination of difficulties. Such a review and re-examination can take at least three major forms: (1) Status review in the sense of station construction dates, review of availability of supporting products such as charts and tables, and review of operational reliability in the sense of station outages and propagation disturbances; (2) review of user experience; and (3) re-examination of basic system design parameters in hindsight using modern theory and considering modern engineering options to determine weaknesses and areas susceptible to improvement. This study falls nearly exclusively in the third category of theoretical reassessment although manufacturer experience was surveyed to assess the influence of platform generated noise or electromagnetic interference (EMI). This study is not exhaustive. Rather, two areas of weakness have been identified and major features of approaches likely to lead to solutions are discussed. For example, coverage weakness particularly in central North America can be corrected by addition of a ninth station. Format modifications necessary to accommodate such an addition are discussed with emphasis on the few options which are deemed presently feasible. For completeness, less inviting options are noted and principal disadvantages mentioned without detailed development of all associated implications. Degradation due to platform noise, particularly in aircraft, is discussed together with possible alternative design approaches to mitigate the problem.

This study is in many ways a survey and somewhat superficial in specific areas. For example, the length of this report may be compared with a previous report on format optimization which addressed only the assignment of frequencies to already defined segments within an eight-station commutation pattern.¹ Although a number of diverse aspects are discussed herein, this is not a system redesign. No doubt many people can (and many others think they can) design a better "Omega" system in 1978 than was in fact designed in the early 1960s. Such speculation is not useful. Omega is designed and is now serving many navigators. Transmitting stations and some 10 000 receivers exist. It is considered administratively essential to maintain continuity of service to the using community. Hence, a large number of constraints have evolved which would not be present in a new design. Nevertheless, there is considerably more latitude within the present system design than is often

1. Naval Electronics Laboratory Center Technical Report 1966, Omega Format Optimization, by ER Swanson, JE Britt, JJ Wilson, and JC Hanselman, 8 October 1975, AD A019364.

realized. Station powers can be changed, pulse envelopes can be sharpened or shaped, modulation can be added, additional frequencies can be added, or even additional stations can be added with little if any impact on the present using community. There are also many ways the using community can make better use of the system.

A report of this length and scope could not possibly constitute a full design review and sensitivity analysis of the Omega system. Nonetheless, there is no denying the desirability of such a tome. Where convenient without excessive additional length, the report has been structured to address design sensitivity to various parameters. This is a necessary adjunct to some areas of inquiry. Further, it has been recognized that a sensitivity analysis may prove useful in other as yet unanticipated areas of inquiry as well as in those areas providing the primary impetus for this study.

Heavy emphasis in this study on formal, technical, and theoretical review in hindsight should not be construed as any predilection by the authors for this particular method of inquiry. Up-to-date statements on administrative intent and operational status are needed by all. System status has recently been reviewed by Herbert and Noland and by Scull and Haislip.^{2,3} There is no substitute for operational experience in assessing the performance of any system. The literature is replete with discussions of operational experience. References will be found in the US and other Journals of Navigation and in proceedings of the International Omega Association. A particularly recent survey is an anthology "Operational Experience in the Use of Omega" including papers by Broughton, Bradley, Reynolds and Riley.⁴ Particularly notable was Reynolds' observation after extensive flight evaluation that "From 1976 onward, ie, after all transmitters except Australia were operational, not one of the evaluated systems was ever without the essential minimum of three adequately configured transmitters. Three-station operation was in fact encountered on only two occasions...." Thus, it is certainly possible to do much navigating without serious difficulty. However, the present method of review indicates that the system is undesirably weak in certain areas and that reception problems can be severe in aircraft.

LIMITATIONS

Whether system characteristics are viewed as advantages or disadvantages, strengths or weaknesses, applications or limitations is primarily a matter of viewpoint. This section has been titled "Limitations" to connote areas warranting special attention, particularly those where further work might expand capabilities.

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2. Noland, TP, and Herbert, NF, "Omega Navigation System Status and Figure Plans," Report of the Technical Conference, Tokyo, Japan 12-14 October 1977 (Japanese Maritime Safety Agency)
 3. Haislip, TT, and Scull, DC, "The Omega Radionavigation System Comes to the Pacific Ocean Area," OCEAN '77 Conference Record, Los Angeles, October 1977
 4. Broughton, DW, Bradley, RHN, Reynolds, PRJ, and Riley, AP, "Operational Experience in the Use of Omega" (A group of four papers), (British) Journal of Navigation, 30, 3, September 1977 p 339-365

Accuracy is the single parameter of navigation systems which is most quoted and considered although it is rarely if ever the most important. Other factors include coverage, responsiveness, ambiguities if any, ease of installation, potential EMI problems, cost, human interface, and most particularly reliability and freedom from blunders. Emphasis within this section is in consideration of (1) coverage and (2) installation in the sense of problems associated with EMI from the host platform. This emphasis has been given since it is these areas which are perhaps the least understood limitations. Further, correction of coverage limitations could lead to substantial system changes or augmentations while correction of EMI installation problems could yield a substantial and rapid improvement in performance for a large segment of the using community. General limitations are not necessarily of lesser importance but are sufficiently well understood as to be mentioned briefly only for completeness. Discussion of the various limitations has been primarily incorporated in appendices but is summarized here.

General Limitations

Discussion of accuracy, responsiveness, ambiguities, cost, human interface, reliability and availability, and freedom from blunders is incorporated into appendix A.

Appendices A and C note that the advertised system/fix accuracy has been 1-2-nmi circular error probable (cep) or a 95% fix probability of between about 2 and 4 miles. Present accuracy may be worse in some locations but it is speculated that eventual system accuracy will be between 0.5 and 1 nmi in most locations.

Responsiveness for a global fixing system is viewed as only that needed for nominal fixing and not that which might be desired for providing rapid sensing of positional change during rapid maneuver. That is, minimum responsiveness is only that needed to obtain a fix of nominal accuracy of 1 mile at ship speeds of 60 knots or less.

Ambiguities are inherent in most navigation systems. The "8-mile" ambiguity associated with 10.2-kHz single frequency Omega operation is well known. Ambiguity resolution is characterized by a certain probability of error which should be viewed as a system failure or blunder rather than a nominal inaccuracy.

The wide adoption of Omega clearly indicates the system is affordable to a large number of users. Continued operating expenses should be low.

Human interface is primarily a consideration of receiver design.

Reliability, availability, and freedom from blunders are discussed in appendix A. Redundancy is an inherent strength of the Omega system. Indeed, Omega is the first navigation system ever to offer redundancy on a wide scale. Nonetheless, future studies of system requirements and coverage may lead to modifications to even further improve redundancy.

Receiver Installation and EMI

Installation of Omega is not a particular problem except insofar as isolation from platform generated noise and EMI may pose problems. There are no special problems such as steerable antennas, very high weight, high power requirements, or excessive size. Maintenance experience has been good so there are no special problems for access except for operator controls and readout. In the case of receivers used with manual fix reduction, room should be provided for use of appropriate charts and tables. EMI problems are,

however, usually critical on aircraft. Results of a survey of installation experience are given in appendix B and are summarized here.

The usual marine installation does not present special problems. Installations on ships with fiber-glass or wood hulls can present more difficulties than installations on ships with steel hulls. However, difficulties tend to be in the nature of installation inconveniences rather than the cause of eventual operational limitations.

Aircraft installations present substantial practical problems. Magnetic field antennas have a reputation for comparative insensitivity to precipitation static which occasionally limits airborne signal reception; electric field antennas are easier to install without excessive EMI. It seems universal to choose one type of installation although the authors see little reason for not installing both types and allowing the receiver to make use of whichever antenna is providing the best signals at any particular instant in time.

EMI harming Omega reception emanates from a wide variety of aircraft equipment but special mention should be given contamination due to power harmonics. 13.6 kHz is the 34th harmonic of 400 Hz. Usually aircraft power is sufficiently unstable that the harmonic interference may drift in and out of the reception band. However, there are now efforts to stabilize 400 Hz power to crystal standards. This could render reception of Omega impossible.

The usual aircraft antenna installation uses a loop antenna which is installed after some skin mapping. Even with this procedure the resulting installation is practically never "clean." EMI will typically limit reception. Effort is ordinarily expended until the installation works "satisfactorily" in the sense that the system will usually navigate well in most areas where reasonably strong signals are available. In areas where poor signals must be used, operation may become inadequate. Installed airborne receiver systems may thus not be able to use the full Omega coverage that would be available to a mariner. It is impossible to obtain quantitative data on the effects of EMI on typical installations but one might speculate that typical degradation was equivalent to about 10 dB in signal. That is, whereas great efforts are made to obtain an additional 1 dB or so at transmitters, the signals are then jammed by about 10 dB in many airborne installations.

Installation details so routinely degrade airborne reception that further work in the area is clearly warranted. A major effort to investigate possible modifications to Omega receivers and/or aircraft to further their integration is needed. The attitude seems to be that Omega can be installed after noise sources have been mysteriously quieted by some undefined engineering gnome. This thinking is unrealistic. Omega receivers can be designed with organic EMI cancellation circuits. Contaminating signals can be measured in the blank intervals between bursts within the Omega commutation pattern. Short term behavior can be modeled as it is linked in phase and amplitude to power harmonics and other measurable sources. The filtering can be arranged to operate automatically by incorporating various adaptive features. Although noise cancellation circuitry cannot yield better operation than would be obtained by quieting the noise sources, it can operate much better in the presence of unquieted noise sources than present processing schemes. A companion investigation would be conducted to identify noise sources and should be extended to include development of engineering procedures to mitigate EMI sources or stabilize the contaminating emissions out of the frequency bands of interest. These ideas are also noted as an opportunity for new improved receiver design.

Coverage

Adequate coverage requires reception of signals from three stations each of which possesses adequate field strength and structural regularity and which collectively arrive from diverse directions. Appendix C discusses signal requirements and develops accuracy criteria. The appendix further includes a rather laborious analysis of possible regions where nominal system accuracy specifications of 1 to 2 nmi rms (2 to 4 nmi at 95% probability) may not be satisfied. Results from the appendix should be compared with a recent analysis by Morris and Tolstoy using fundamental predictive modifications rather than a perturbational approach (Morris, PB, personal communication, May 1978). Both methods have some merit and results from both should be interpreted only as suggestions for direct monitoring rather than firm conclusions warranting remedial action. Results are, however, sufficiently definite to warrant contingency planning.

Various accuracy criteria are discussed in appendix C. In particular, error budgets are adapted for both "present" and future system calibrations. The "present" budget is perhaps conservative for daytime conditions but is perhaps optimistic for nighttime conditions or during transitions and will not apply in areas where gross prediction biases may exist as may presently occur over some equatorial paths at night.

Appendix C considers signal availability, quality and fix geometry and shows that there are several regions where system coverage specifications may never be satisfied:

A small region near the Antarctic coast in the South Weddell Sea near Gould and Halley Bays may not have adequate signal availability to support three-station fixing during the day; or, with more favorable station availability, may provide fixing which will be outside system specifications presently but become within system specifications with improved calibration. The region is small and may be conjectured to be of limited interest.

A small region near the Antarctic coast south of Australia at about 120° east longitude is not expected to provide adequate fixing either now or in the future either during the day or at night. Three stations will be available but the indicated 24-hour fix accuracy is presently estimated at 3.4 nmi rms and would not be expected to improve to better than 2 miles. The region is small and may be conjectured to be of limited interest.

A small region in the Denmark Strait near Greenland at the Arctic Circle during the day; ample coverage is expected at night. Only two stations may be available but measurements are necessary.

The Gulf of Mannar is a region in which only relatively inaccurate navigation may be available at night. Stations providing coverage at night are expected to support fixing to a 24-hour rms error of 2½ nmi using present error budgets but may barely satisfy system specifications with future improvements in system calibration.

Tahiti is the center of a small to moderately sized region (10^6 to 10^7 km²) where available fix accuracy may be adequate during the day but not at night. Stations available at night will support 24-hour fix accuracy of slightly worse than 3 nmi rms using present error budgets and are unlikely to support fixing within specified system accuracy without special attention to calibration in the area.

The Straits of Malacca is another area where accurate Omega navigation is not expected at night either now or in the future.

Present error budgets indicate that stations supporting navigation at night will only support navigation to an rms fix accuracy of 4.4 nmi on a 24-hour basis. Anticipated future improvements are not expected to result in a fixing capability much better than 3 nmi rms.

By far the largest coverage hole will occur in an extended area from south central Canada, through the American Midwest, into the Gulf of Mexico, and on into Mexico proper. System specifications are not expected to be met either during the day or at night either now or in the future. Degradation ranges from a virtual impossibility of obtaining fixing of any accuracy near St Louis to moderate near the perimeter of the region but is severe over a wide area.

Two regions where "adequate" coverage is expected deserve special comment: Antarctica and northern Canada. These regions are low noise areas where most signal paths experience high attenuation so that although the resultant signal-to-noise ratios may be adequate, the signal levels are weak. These circumstances are demanding on receiver design and installation. Adequate operation may not be experienced with some presently installed airborne receivers. Other areas also exist where use of signals much weaker than ordinarily available is assumed. Problems with receiver design or installation which are usually negligible may render signal reception impossible in weak signal regions. Perhaps one of the more operationally important such regions is an extended area from the North Sea southeastward through Germany.

Some Omega system management options and possible courses of action regarding the foregoing anticipated coverage deficiencies are as follows:

Navigational requirements in the two small potential holes on the perimeter of Antarctica should be reviewed. There may, in fact, be so little interest as to not even justify determining whether holes will exist. However, measurement may be warranted solely for the sake of completeness in evaluating global Omega coverage.

Coverage in the Denmark Strait near Greenland should be carefully measured. Operational experience from fishing boats in the area should be solicited. The region is of considerable interest.

The Gulf of Mannar is expected to eventually be covered by calibration improvements already planned. No special attention is needed beyond management review of progress to assure that adequate calibration here does indeed evolve. This is an area of considerable interest because of various traffic patterns rounding the tip of India.

Tahiti will require special calibration attention. Ordinary planned future calibration effort is not expected to allow Omega to meet system specifications in this region but special emphasis may. Users may also need to evaluate their operating procedures and instruments to determine whether their own accuracy requirements are being met in the region.

Coverage in the Straits of Malacca should be managed as a special problem. This is one of the greatest maritime confluence areas on earth. Some techniques may be possible to improve Omega navigation in the area whereas the basic problem is that of adequate navigation in the region by whatever means. Heroic calibration efforts might conceivably render Omega barely within specification in the area but this is unlikely. Special study may develop means of using Omega signals which will be available in the region but which are not now considered useful due to self-interference. Approaches are noted elsewhere in this report but are as yet unproven. Also unproven is

the practicality of adding coverage through addition of one or more Omega repeater stations as described elsewhere in this report. Alternative navigation means are available by radio beacons. These cover the most critical portions of the area and beacon receivers are required on merchant ships. However, beacon receivers are not carried on US Navy ships nor on most airplanes. Requirements for airborne navigation should be reviewed to determine if the anticipated eventual fix accuracy of about 3 nmi rms is adequate for planes flying through Singapore or elsewhere in the region.

The anticipated North American coverage hole is by far the largest and most significant region. The area is one of great commercial activity both airborne and maritime. The fundamental problem is, of course, that of providing navigation aids of whatever type throughout the region and it should be noted that alternative aids are readily available in much of the area. Nevertheless, Omega coverage will be very weak over a wide area. Even the most optimistic of Omega receiver improvements would not be expected to make Omega coverage acceptable at night although they might conceivably do so during daytime propagation conditions. Potential management actions include: 1) detailed determination of the extent of the coverage deficiency primarily by measurement, 2) determination of alternative navigation aids available within the Omega coverage hole, 3) development of contingency plans for Omega station relocation or construction of new Omega stations, and 4) review of requirements and options and decision as to suitable action. It is emphasized that the extent of the anticipated coverage hole should be determined by direct measurement before any action is taken. However, contingency plans for addition of a ninth station seem well warranted.

Coverage of the North Sea and Germany in the summer bears further attention but no difficulty is anticipated.

It may be noted that several of the smaller possible coverage holes are areas without airports. Aircraft navigating in the regions can thus be assumed to be transiting. Range-range navigation would thus be possible to appropriately implemented receivers which employ only moderate quality quartz standards which are calibrated in flight. This approach to Omega reception adds only about \$500 to the cost of a receiver and is often used to provide improved reliability in high noise circumstances. Of particular interest in this regard is the small possible coverage hole in the Denmark Strait near Greenland. This lies on some of the air routes between Europe and the North American west coast. Extraordinarily minimal range-range navigational capability will permit airborne units to navigate successfully over this region.

The coverage analysis was conducted for all eight Omega stations operating. Depending on station reliabilities eventually achieved, coverage consideration may also be needed under conditions of various station outages. Demands of very high reliability could vary present coverage criteria.

In summary, Omega coverage problems are expected in North America. Coverage in the Straits of Malacca is expected to be deficient and comparatively minor deficiencies are foreseen elsewhere. Remedial action to correct coverage in North America could require a new station.

OPTIONS AND OPPORTUNITIES

In the following, various aspects of Omega are reviewed to determine potential for improvement. Some aspects are rather obviously not areas of

much potential opportunity and are noted for completeness. In other areas, such as receiver design, long established technology is challenged. Here potential gains are large but prudence indicates responsible investigations should be conducted before any attempt is made to engineer a new line of equipment. Several areas are identified where designers can avail themselves of greater performance simply by making straightforward changes in software, such as to use the near field. Considerable restraint should be exercised by administrative authority on implementing schemes to add a few additional decibels to the radiated signal. Such increases are warranted if and only if coverage gains are commensurate with the effort expended and provided, further, that equivalent or greater gains cannot be obtained by other methods such as receiver modifications. Coverage deficiencies correctable by power increases of only a few decibels need to be identified with great care. Prediction technology is such that such areas can confidently be identified only by measurement. Measurements should extend over at least a year and results extrapolated over the solar cycle. Measurements may be of either two types or both. "Standard" receivers, well representative of today's technology, can be employed and coverage based on their performance. Alternatively, detailed information on both signal and noise may be gathered and then coverage based on performance of an optimum receiver can be determined. In either case a protracted series of measurements is needed.

Some of the following areas of opportunity require basic changes to the Omega transmitting system or format. However, other areas require only changes by users and thus there are not "system" changes other than those implicit in changes of user methodology. None of the major areas of opportunity are exclusive so all can be considered for simultaneous implementation.

Receivers

The performance of Omega could undoubtedly be improved by better receivers. By this is meant receivers which are more capable of extracting navigational information from signals contaminated with natural and man-made noise. It will be convenient to divide consideration in this area into two sections dealing respectively with improvement to performance in natural noise and improvement in the face of severe platform generated EMI. Implementation of the improvements would not be exclusive; both could be incorporated into a new generation of receivers.

Sensitivity Improvement

The state of the art in Omega receiver design is represented by the products of a number of manufacturers. With the exception of a few inept designs, most receivers operate well by the standards of ordinary phase tracking in the presence of noise. Indeed, most receivers employ some form of nonlinear processing so as to obtain better than nominal performance in the presence of the impulsive noise encountered at vlf. Apparently, most

designers have read the same books and produced tolerable to good designs based on recognized and established principles.*

The real signal environment at vlf is not, however, well approximated by treatments usually encountered in text books. Most particularly, noise is attributable to lightning associated with thunderstorm activity (sferics). Noise from this source has a character quite different from white noise or even simple impulsive noise. Noise pulses will affect the entire vlf band simultaneously. Noise will also arrive from certain directions where the primary thunderstorm activity is taking place. Major noise bursts pulling phase significantly may yield phase rates of change in excess of nominal values so that phase discretion can also be used to enhance signal processing as has been described in a patent.⁶ Thus, there are a number of features peculiar to the vlf signal environment which are not exploited by traditional receiver designs. Comparison of typical design criteria with the physics of signal reception thus leads to hope that revised design approaches may yield significantly better receiver performance.

After some reflection on the potential forms of optimum processing for Omega signals, it develops that perhaps one does not need to know the details of the underlying physics and certainly not the electrical engineering in order to determine optimum performance. All the information that can be used is contained in the signals themselves or other pertinent measurables and it is the statistics of these which will determine optimum performance. Computer codes for such optimum processing have already been developed and are available at NOSC. Processing of radar data is one application which has been discussed with cognizant NOSC personnel. Computer codes also exist for processing of acoustic data in the presence of noise. These acoustic programs have not yet been researched but are understood to be particularly elaborate as might be inferred from their purpose. The suggestion, then, is to sample the extended Omega band through appropriate instrumentation and high speed A/D at various points on the earth and at various times. (This is analogous to sampling used in previous research on envelope capabilities.) A typical state of the art receiver would be operated simultaneously with the data acquisition as a control. The data would then be processed by use of the most powerful

*This is the opinion of the authors and believed the consensus within the field. The majority is, of course, not always right and the dissenting view of one individual of great experience and perception should perhaps be noted. In discussing receiver design JA Pierce has written: "One of the reasons for this lecture on relatively obvious matters is that the writer has generally found that they are not understood. Only one out of many receivers brought to him for examination has been satisfactory in these various respects."⁵

5. Harvard University Division of Engineering and Applied Physics Technical Report 652, Omega: Facts, Hopes, and Dreams, by JA Pierce, June 1974 (under ONR contract N00014-67-A-0298-0008 NR-371-013)

6. US Pat 3891928, "VLF Phase Tracker with Phase Discretion"

available computer codes. Performance would be compared with the control. As an example of measurements to be made, the Omega signal would be sampled on a whip and also orthogonal loops. Also, noise above and below frequency could be sampled on cross loops since, as the medium is dispersive, noise will arrive at different frequencies at different times. That is, some of the out-of-band noise will be anticipatory. An immediate possibility is for the computer codes to operate as an adaptive goniometer setting the composite antenna null on thunderstorm noise sources. This is known to produce substantial (~20 dB) gains at least on occasion. The main advantage of the proposed approach, however, is that the physics of the problem need not be understood to determine quality available with the best possible processing. The goal of the proposed research will be determination of possible gains, not understanding of the associated physics or practical engineering approaches to obtain such gains. Nonetheless, there is clear value to the effort. If the optimum result is within effectively 1 dB of the performance of the control there is obviously nothing worthwhile to be obtained over the present state of the art and one can forever stop engineering efforts for receiver improvement. Conversely, if 10 dB could be obtained with some reliability, quite clearly a major re-examination of receiver design philosophy is in order. This is especially true today since microprocessor technology now brings even complicated processing algorithms within the realm of economic practicability.

EMI Protection

The previous section points out ways by which the natural signal environment might be exploited by receiver designers and proposes a test to determine the magnitude of potential gains. However, even if a receiver were optimized for the natural electromagnetic environment, this does not necessarily indicate it would function optimally when installed on a navigating platform. In particular, the presence of severe electromagnetic interference on aircraft employing loop antennas has already been noted. Thus, the actual environment in which a receiver may be expected to operate may not correspond to the natural quiet environment typically assumed in receiver design. This is obviously incorrect. If a receiver is expected to operate in an electromagnetically polluted environment, it should be optimized to operate in that environment.

The foregoing should not be interpreted to mean that there should not be effort to clean up the environment through elimination of offending interference generators nor should it be interpreted to mean that skin mapping can be dispensed with. All successful means of reducing electromagnetic interference should be practiced. However, there should be a recognition at the design level that a significant level of electromagnetic pollution will remain after all prudent care in installation is taken.

To the extent that sources of interference can be modeled, cancellation circuitry or software can be developed. As already noted, this can be done adaptively by measuring the interference during blank spaces in the Omega pattern. To the extent that the interference can be related to harmonics of measurable phenomena, the phase of interference can also be modeled through 1-second Omega bursts. The success of this will depend on the stability of various aircraft loads and related phase shifts in the interference. A serious attempt to incorporate such noise cancellation algorithms into a receiver-processor seems well warranted.

The possibility of installing both E- and H-field antennas and employing adaptive receiver techniques to use the best signals from each has already been noted.

Transmitter Power Increases

Appendix D discusses the engineering needed to increase the radiated power from existing Omega stations. Two circumstances are recognized: 1) potential radiated powers from stations in their present configuration and 2) available power after improvements suggested in the appendix. Capabilities are considered at both 10.2 and 13.6 kHz.

The present design goal at all existing Omega stations except Trinidad is 10 kW radiated at 10.2 kHz. As shown in the appendix, this power level is attained or approximated at most sites in good weather. Slightly greater powers up to 14.3 kW can be radiated by some stations at 13.6 kHz.

Additional power can be radiated through modifications suggested in appendix D. Gains at 10.2 kHz range from no gain at North Dakota to a possible 34 kW radiated from Japan. However, about 30 kW can be radiated from all final configuration Omega stations at 13.6 kHz.

One of the assumptions in deducing possible increases in radiated power is the simultaneous use of the two transmitters available at each site to produce a 300-kW capability. This will clearly increase power costs. Since the second transmitter is provided for reliability and to permit maintenance while the station is transmitting, reliability at the higher power levels would be somewhat less than at present. For example, backup power generation at stations will not support both transmitters. However, with proper switching arrangements, present power levels could still be maintained at high reliability by simply reverting to the present configuration when necessary.

Practical improvements of 10.2-kHz radiated power are not impressive at some of the stations. This is a reflection of the design criteria employed. As might be expected, significant improvements are impractical at some sites and can only be achieved with considerable effort at others.

The higher radiated power capability at 13.6-kHz both presently and with modifications deserves comment. Most three-frequency airborne receivers are capable of navigating on 13.6-kHz alone after they have been properly initialized. Thus, the additional power provides more reliable navigation in the presence of anomalously high local noise. Further, but not required by present system specifications, greater power would support improved maneuver response. It is suggested that the full nominal power capability at 13.6-kHz be used and that studies be undertaken to establish possible costs and benefits from higher radiated power at 13.6-kHz. The term "nominal power" as used here is not intended to imply absolute maximum power under the prevailing weather conditions. Rather, a reasonably high power level is intended which is nonetheless sufficiently below arcing levels or other operating limitations so as not to endanger overall station reliability or, particularly, reliability of 10.2-kHz transmissions. Since the purpose of the additional power is primarily to improve navigation in locally poor weather at locations remote from transmitting sites, reduction of power when prudence and local operating conditions suggest will cause little reduction in the intended gains and should protect fundamental station reliability.

Expanded Signal Usage

Long Path

Long path signals of sufficient strength can be used for navigation provided (1) they are outside the immediate region of the antipode, (2) they are adequately free of short path interference, and (3) the information

processing recognizes the long path propagation. Use of long path signals can be enhanced by using steerable antennas wherein a null is directed at the short path bearing. In theory this can provide an additional 20 dB or more selectivity. Long path signals can also be used in the presence of dominant short path signal if the vehicle is moving sufficiently rapidly that doppler variations place the undesired signal outside the tracking bandwidth. Greater efforts could be made to capitalize on long path signals.

Groundwave

Groundwave signals can be used in the region from about 20 miles to perhaps 200 miles or so from stations.* Within 20 miles groundwave signals could also be used but in this case corrections would be needed for induction and static field contributions. There are three major disadvantages to using signals at very close range: (1) geometry may be rapidly varying with position thus causing potential complications in fix reduction, (2) signal levels will be high thus making uncommonly severe demands on receiver phase shift with amplitude, and (3) the total area gained will be small. Engineering demands are well within the state of the art as monitoring equipment associated with transmitting stations has been operating in this environment quite satisfactorily for years. However, casually designed receivers not checked out for operation with very high field strength signal could experience difficulty. The overall increase in coverage will be very small but may well be worthwhile. Median range of Omega signals is 16 Mm during the day and longer at night. Assuming all the range to be useful indicates typical coverage for each Omega station of about 1/2-billion square kilometres; a spherical segment to range 300 km will include an area of only 628 km². That is, near field use will improve station coverage by only about 0.0001%.

The location of the additional coverage may, however, be important. Coverage limitations near North Dakota are discussed elsewhere in this report. Use of signals from North Dakota would slightly mitigate coverage limitations. Omega Hawaii is about 10 miles (15 km) from Pearl Harbor, Hickam AFB, and Honolulu International Airport. Although the area should be covered by Norway, North Dakota, La Reunion, Australia, and Japan, there are reports of present coverage limitations at least for some applications using the AN/ARN-131. Regardless of particular local problems with specific equipments which may or may not exist, it is hard to argue against the advantages of additional redundancy in a major confluence area such as Hawaii. Similarly, Omega Japan is located in the Korean Strait in the confluence between the Sea of Japan, the Sea of China and the Yellow Sea. Omega Australia will provide additional redundancy in the Bass Strait although, unfortunately, not from the side of the channel necessary to back up Omega Argentina. There are significant shipping or fishing interests within a few hundred miles of many Omega stations. Although the coverage gained by using near field may be small

*The 200-mile figure is nominal and for discussion purposes only. Preliminary computations by Morfitt indicate some dependence of this range criterion on path and ionospheric details. More work is needed. However, current station selecting algorithms are crude and better use of signals at short range is certainly possible, especially during the day.

by Omega standards, it is after all comparable with that obtained from Loran-A or Decca stations and greater than obtained with marine beacons or VOR. There is no reason not to use the additional coverage if circumstances permit.

Modally Disturbed

It is difficult to see how modally disturbed signals can be used, especially if interpreted manually as received on a conventional receiver. Signals propagated over long paths are of particular interest. By "modally disturbed" one implies that the total signal is composed of contributions from various modes; in particular, from a combination of modes, some of which are destructively interfering. As such, one does not know which mode is dominant and therefore does not know what the prevailing velocity is and hence cannot reliably associate changes in phase with displacement on the ground. However, some scenarios may be envisaged by which signals may be used when composed of higher than normal modes. One would expect these applications to be restricted to receivers using microprocessors or some other rather elaborately based computing system. The rules governing interpretation of multimode signals are probably too complex to ever be reduced to simple rules which could be used in the manual reduction of data. In contrast, very elaborate rules can be encoded in automatic equipment. If conditions in which the second mode is dominant can be reliably identified, appropriate velocities could be employed and the signals used for navigation in much the same way that normal first mode dominant signals are used. This implies a recognition discipline which has not yet been developed. Also, the accuracy capability of higher modes is not expected to be as high as that associated with propagation by the first mode owing to the sensitivities of the respective phase velocities to nominal changes in ionospheric height. Data on the Liberian signal on the US East Coast indicate the capabilities of higher modes at night to be useful but indicate also that the diurnal changes in dominance between first and higher modes present complications of substantial importance which have not yet been resolved.

Frequency Change

Some improvement in Omega performance could undoubtedly be obtained by changing system frequencies so as to mitigate trouble from harmonics of power frequencies. The present relationships are:

HARMONIC RELATIONSHIPS

Power Frequency (Hz)	10.2	Omega Frequency (KHz)		
		11.050	11 1/3	13.6
50	204	221	*d	272
60	170	*b	*e	*g
400	*a	*c	*f	34

* Not even harmonics: (a) 25.5, (b) 184.166+, (c) 27.625, (d) 226.666+, (e) 188.888+, (f) 28.333+, (g) 226.666+

Thus, almost half of the commutated transmissions are harmonics of some common power frequency while all the unique frequencies are harmonic at least of 50 Hz. A large frequency change is not envisaged. One would wish to stay close to the present frequencies so that the existing technology could be used with only minor adjustments. It is especially desirable to remain close to present experience so that propagation data and prediction techniques could confidently be applied to the new frequencies with but minor adjustments. If the frequency shifts were sufficiently small, signals could still be received by use of existing receiver filters. As already noted, power harmonic interference is particularly serious on aircraft where 13.6 kHz is the 34th harmonic of 400 Hz. If present attempts to stabilize aircraft power to exactly 400 Hz are widely implemented, it may be nearly impossible to use 13.6-kHz signals in aircraft. As noted, there appears no abiding reason why aircraft power cannot be stabilized somewhat away from 400.000 Hz. However, if this is not done, then an Omega frequency shift may become desirable. It is in some ways ironic that power harmonics have come to be troublesome for Omega. The original frequencies were chosen to relate to 10.2 kHz rather than 10.0 kHz in part to avoid signals related to highly stabilized laboratory frequencies such as 1 kHz, 100 kHz, or 1 MHz. Power frequencies were believed relatively unstable because of changing loads, etc. In recent years, however, great strides have been made in stabilizing power frequencies and Beukers has shown that the harmonics are in fact usually significant in the Omega band.⁷

Various shifts in the Omega frequencies have been suggested intermittently throughout past system history. One of the more responsible and reasoned of these was a suggestion by Palmer to lower the Omega frequencies about 3/4 percent.⁸ The change was shown to improve certain hierarchical relationships within the format. Alternatively, Beukers has proposed shifts so that the three major transmissions occur on 10.335, 11.483, and 13.780 kHz.⁷ The proposals are at least suggestive that different frequencies could be found which would not only offer better immunity to power harmonics but also provide hierarchical improvements within the fundamental system design.

There are a number of engineering and system considerations associated with a frequency change. Manual receivers are supported by hyperbolic charts, lattice tables, and propagation correction tables. Charts would have to be redrawn; lattice tables recomputed. Both would have to be redistributed. Propagation correction tables might also need recomputation although it is possible that judicious choices of references might obviate this requirement. As most of the investment for these items is now in the software necessary to generate the products rather than in the manpower directly associated with specific printings, recomputation costs would be affordable. However, distribution and changeover would be at best a monumental nuisance. Computing receivers would require revised software. If the frequency change were relatively large (≥ 100 Hz), it would be necessary to change front end filters in many of the 10 000 existing receivers. (Even smaller shifts would require

7. Beukers, JM, "Accuracy Limitations of the OMEGA Navigation System Employed in the Differential Mode," NAVIGATION, 20, 1, spring 1973 p 81-92

8. Winslow Palmer, PE, Omega Technical Note 17, Proposal for Standard Time and Frequency by Omega to the Naval Electronic Systems Command under contract no N00024-67-C-1416, December 1969

changes in some designs using narrow crystal filters.) Conversely, if the shift allows the frequency to fall well within existing front end bandwidths, then some suppression could occur if old format and new format signals were present simultaneously. However, as the tracking bandwidths are only a few hundredths of 1 hertz, there should be little difficulty tracking signals once they are acquired.

Primary Reliance on Frequencies Other Than 10.2 kHz

Adoption of 13.6-kHz as the primary navigational frequency is not likely to offer much improvement. On a general global basis 10.2-kHz offers greater regularity of the signal structure and the wider lane width desirable with a carrier system. Advantages of 13.6-kHz include higher potential radiated power at the higher frequency, lower environmental electromagnetic noise, and greater propagational stability, particularly during the day. However, the primary limitations in the use of Omega signals are not in power or signal-to-noise ratio but rather irregularities in signal structure due to modal or long path interference. Particularly considering modal interference, 13.6-kHz is usually less desirable than 10.2-kHz. Thus, a change to emphasize 13.6-kHz as the primary navigational frequency could result in a greater loss of coverage area through increased signal self-interference than that gained through greater range.

Theoretical and experimental support for an emphasis on one frequency or another is currently lacking. Dr Reder has recommended increased use of 13.6 kHz or, indeed, use of an even higher frequency.⁹ However, Steele has published data on one particular path showing regularity at 10.2-kHz but not at 13.6-kHz.¹⁰ This question can best be resolved through application of coverage assessment tools now being developed.

There may be local conditions wherein 13.6-kHz might be preferred. Considering present coverage weaknesses, one such case might be the use of Norway in the Northeastern or Central United States. Norway was received for years at the old Omega transmitting site of Forestport, New York, and is now received at Omega North Dakota. To be sure, the sites are quiet and the reception is not of the best quality. But clearly signals of at least potential marginal adequacy for navigation are now reaching the northern US border east of North Dakota. Utility and range of Omega Norway could be improved with somewhat more power radiated, lower noise, or somewhat lower attenuation on path. All are available at 13.6-kHz. About 2 dB more can be radiated at 13.6-kHz than at 10.2-kHz whereas the attenuation rate for signals propagating over very low ground conductivity is usually less, as can be seen from attenuation curves.¹¹ The paths from Norway contain about 1000 km of

9. Reder (verbal comment, Omega Workshop, Int'l, Omega Assn Mtg, Linthicum Hts Md, Nov 1977)

10. Steele, FK and Diede, AH, "A Comparison of Nighttime Propagation Anomalies Observed at two Very Low Frequencies," Radio Sci, 12, 5 Sep-Oct 1977, p 791-796

11. Naval Electronics Laboratory Center Technical Report 1773, Theoretical Variations in Omega Propagation Parameters, by RJ Gallenberger and ER Swanson, 23 July 1971 (AD747636)

very low conductivity ice over Greenland and parts of Baffin Island and the Quebec Labrador peninsula. The effect of this will depend on several factors. Whether the associated ground conductivity is 0.01 mmho/m or 0.03 mmho/m is debatable.* There is a further technical question on the validity of path averaging for evaluating signals propagating over a region of the extreme skin depth and layering which occur in Greenland. Nonetheless, using path averaging as a guide we expect the net field strength at 13.6-kHz to be at least the same as at 10.2-kHz and possibly up to 12 dB greater; further, the environmental noise will be less.

It is possible that there may be substantial gains in coverage through judicious use of all frequencies. Coverage at 10.2 and 13.6-kHz tends to be somewhat complementary in that 13.6-kHz may exhibit modal complexity where 10.2-kHz is regular yet 10.2-kHz may attenuate more severely at longer distances. At long distances the signal-to-noise ratio at 13.6-kHz may be quite adequate for navigation while the first mode has achieved the dominance necessary for regular phase variation.

Composite Omega

One approach to using Omega signals is to form a "composite" signal developed from measurements at two or more frequencies combined in such a way as to reduce diurnal variation, reduce susceptibility effects from Sudden Ionospheric Disturbances (SIDs), or perhaps improve accuracy. The technique has long been advocated by JA Pierce and is now incorporated into a number of automatic receivers. Pierce's enthusiasm for the approach has never been shared by the principal author of this report. There is, however, much data supporting both positions. As Pierce is now retired and no longer burdened with educating potential users of Omega or advocating particular approaches, some reflection of his views will be presented here.

Pierce began with the observation that for certain waveguides the product of the group and phase velocities remains constant. He then inferred that this property might also apply to the waveguide formed between the earth and the ionosphere within which vlf waves are propagated. He concluded that a special weighted combination of measurements at two discrete frequencies could be expected to yield significantly better accuracy than is normally available from the two carriers alone. It was observed that the form of the resultant equations was that of a statistically optimum combination of information from the two carriers. Pierce published these observations in 1968 in a report wherein he concluded the chief advantages of Composite Omega were an improvement in precision of a factor of two and decreased susceptibility to propagation disturbances.¹² The statistical form of the optimization had, however, been previously obtained by Swanson — without the elegance and insight of physical causation but also without indication of significant

*1 mho = 1 siemens

12. Harvard University, Engineering and Applied Physics Division Technical Report 552, The Use of Composite Signals at Very Low Radio Frequencies by JA Pierce, February 1968

improvement.¹³ Thus, 10 years ago, two separate observers had come to opposite conclusions on the merits of Composite Omega. An attempt to reconcile the two positions was then conducted by Swanson and Hepperley which indicated Composite Omega offered no advantage in stability over that available from the more stable carrier except over arctic paths during disturbed conditions.¹⁴ However, data analyzed by Pierce have continued to indicate advantages of Composite Omega. Indeed, in an excellent report on Omega produced on the occasion of his retirement, Pierce devoted considerable discussion to Composite Omega and provided substantial new data supporting its use.⁵ While considerable detail can be found in the referenced reports, some summary observations on Composite Omega are warranted here.

There are two optimizations for Composite Omega, the choice depending upon whether maximum stability or minimum diurnal variation is desired. As the optimizations are not the same, one cannot optimize both features simultaneously. Improved stability can lead to increased navigational precision whereas reduced diurnal variations can simplify the need for supporting propagational predictions.

Coverage requirements to support use of Composite Omega are more demanding than for standard Omega. Composite Omega is degraded by noise more rapidly than standard Omega. Also, signals must be relatively free of modal interference. For Composite Omega to work well, good signals must be received at two frequencies, which is a more stringent requirement than reception at only one of two carrier frequencies and does not capitalize on the potential synergy of coverage between the two principal carrier frequencies as noted earlier. Additionally, it must be noted that an anomalous velocity variation is expected for propagation over ground of very low conductivity, which will introduce a further coverage limitation if the composite is formed for the purpose of simplifying spatial variation.

Composite Omega also introduces navigational ambiguities not present in Omega itself. Lane identification is best conducted by initialization or by recourse to standard Omega techniques. To some extent Composite Omega should be viewed as a position-keeping rather than a position-finding system.

The foregoing notwithstanding, Composite Omega undeniably offers advantages in some circumstances. One advantage which may apply at present but lose validity in the future is that prediction errors can be less important for Composite Omega in some instances. A continuing evaluation is needed to establish the degree to which use or contingency use of Composite Omega is warranted in various implementations.

While characteristics of predictive errors at the two carrier frequencies are important to the operational accuracy of a Composite Omega implementation, the inherent accuracy capability is indicated by the carrier stabilities and the correlation of their phase fluctuations. Figure 1, computed following reference 5, shows the stability of the composite signal normalized to the stability of the 10.2-kHz carrier as a function of the composite weighting ratio, m , for various possible ratios of carrier stability, 13.6 kHz/10.2 kHz, and various correlations of fluctuations at the two carriers, r . Pierce has established the ratio of carrier stabilities between 0.61 and 0.64.⁵

13. Naval Electronics Laboratory Center Report 1305, Omega Lane Resolution, by ER Swanson, 5 August 1965

14. Naval Electronics Laboratory Center Report 1657, Composite Omega, by ER Swanson and EJ Hepperley, 23 October 1969, AD 863791

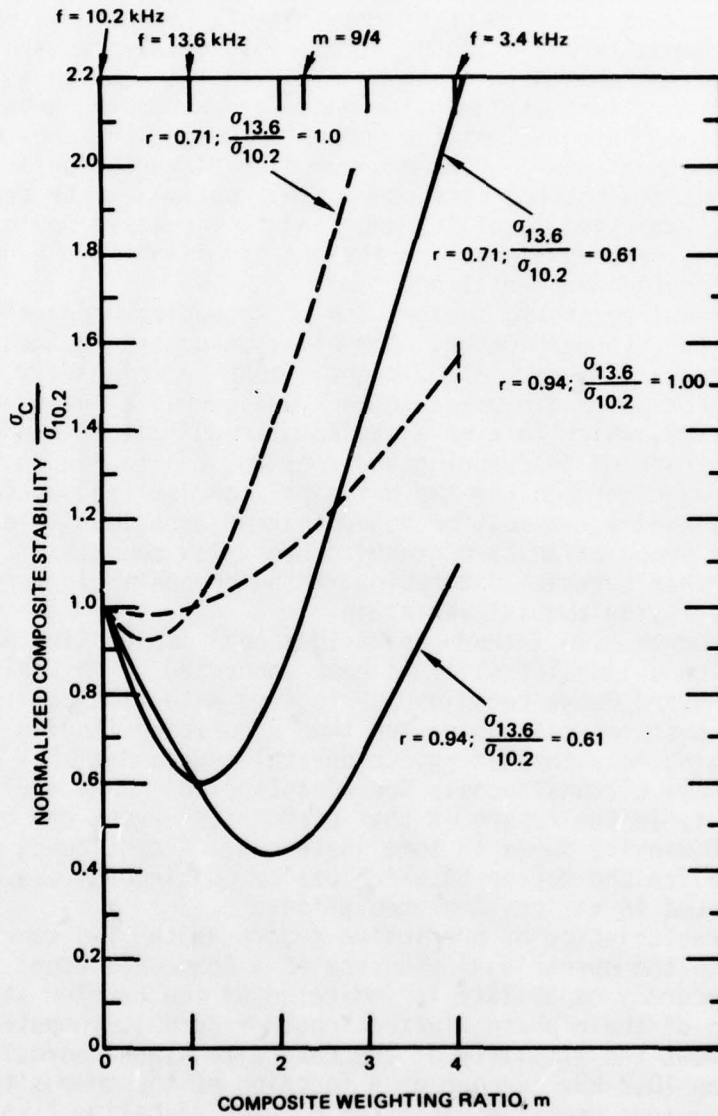


Figure 1. Stability of composite omega signal.

This is in essential agreement with the 0.65 to 0.72 established in reference 14. Less significant data samples also indicate 0.56 obtained for the variations of SIDs only^{15,*}; 1.06 obtained in a report on timing¹⁶; and 0.69 during the day, 0.86 at night, or 0.91 during transitions obtained in reference 13. That is, one expects the carrier stability ratio to be between about 0.6 and 1.0 with the more substantial estimates suggesting the lower end of the range. There is, however, substantially less agreement on the correlation. Pierce has indicated a correlation coefficient of 0.94; Swanson has consistently obtained values near 0.71. As can be seen from the figure, major advantages can be attributed to Composite Omega if the correlation and stability ratios are on the order of 0.94 and 0.61, respectively, as indicated by Pierce. Indeed, for these values the optimum weighting factor is indicated as near $m = 9/4$ as derived theoretically by Pierce. If, however, either the ratio of the carrier stabilities is near unity or the correlation of their fluctuations is lower, then the stability of the composite signal will not differ much from that of the more stable carrier. Note that for $r = 0.71$ and a stability ratio of 0.61 the stability of the composite is very nearly equal to the stability of 13.6-kHz alone. Clearly discussion here is not going to resolve a long-standing difference of opinion. It should, however, refer the merits of the system back to the fundamental physical properties of the signals on which all must depend. The argument presented may also be extended to predictive biases on optimizations to reduce diurnal variation. In this case inherent signal stabilities considered here would be replaced by the ensemble biases produced by fixes using the respective carriers and simplified predictions compatible with the method envisaged for the composite. In this case the error partitioning would be such as to indicate high correlation and a relative scatter on the order of the frequency ratio. Thus, the possibility of obtaining a composite signal minimizing diurnal variation is readily understood.

Additional Much Higher Frequency

One modification which may be considered is the addition of one or more much higher frequencies to the Omega format. Frequencies of 20 to 40 kHz or more may be considered. Additional transmissions could be added either as a single frequency within the commutated time shared format or as unique frequency transmissions. For the frequencies considered, the choice is indicated more by electronic engineering practicalities than inherent features of the navigational system design. The advantage of time shared transmissions

*A Ratio of about 0.75 is indicated in the reference when variation is measured in centicycles at each particular frequency rather than being referred to a common equivalent basis as cited here.

15. Swanson, ER, and Kugel, CP, "A Synoptic Study of Sudden Phase Anomalies (SPA's) Affecting VLF Navigation and Timing," Proceedings of the 5th Ann NASA and DOD Precise Time and Time Interval (PTTI) Planning Meeting, 4-6 December 1973, p 443-471
16. Naval Electronics Laboratory Center Technical Report 1740 (rev), Omega VLF Timing, by ER Swanson and CP Kugel, 29 June 1972, AD 743529

is in reducing the size of navigational ambiguities. In particular, in a hyperbolic system ambiguities of one-half the wavelength occur on baselines. For the frequencies mentioned, ambiguities would range from 4 to 2 or even fewer miles; that is, a fix of +2 or +1 mile or less would be needed to resolve lanes. Fixes for which the associated positional uncertainties are confidently less than these values are not readily obtained except at well charted locations or perhaps intermittently if NAVSAT equipment is available. Resolution of lanes at the high frequency using 10-14-kHz Omega transmissions would depend on the correlation of positional fluctuations at the frequencies employed. Reliable resolution is highly doubtful. Thus, the ambiguity structure associated with a time shared single frequency implementation would be unresolvable as a practical matter for most users. Thus, continuous tracking would be required. However, continuous tracking is also a requirement for use of unique frequencies so that there would be little preference between the two methods from the navigational viewpoint. Electronics considerations, however, probably favor time shared transmissions. In 1978 digital technology of the type readily employed to separate transmissions in time is well advanced whereas reception and separation of signals in the frequency domain could require a separate receiving channel for each frequency used.

The major attraction of a frequency above 20 kHz is the comparative ease with which substantial powers can be radiated; the power capability of a voltage limited antenna at vlf is proportional to the fourth power of the frequency.¹⁷ Although Omega transmitting facilities are not exclusively voltage limited, extensive engineering modifications including addition of more powerful transmitters together with associated higher energy costs could certainly result in very substantially higher power radiated.

Two propagational aspects need to be considered--those affecting field strength and those affecting the navigational utility of the signal if it can be adequately received. Environmental noise at vlf from lightning associated with thunderstorm activity (sferics) tends to maximize near 10-kHz and is less toward the upper end of the vlf band. Signal attenuation rates depend on ground conductivity, ionospheric details, and dominant modes but tend to be at least as favorable at 20-kHz as at 10-kHz. There are no large differences between 10 and 20-kHz in the ease of exciting the propagational waveguide modes in the daytime but it is significantly harder to excite the first mode at 20-kHz at night. Generally, from the viewpoint of providing high signal-to-noise for navigational applications requiring high dynamic response, a frequency choice above 10-14 kHz would be preferable considering either transmitter requirements or propagational characteristics.

The practical use of the higher frequencies for routine navigation is, however, subject to problems not generally encountered near 10-kHz. The navigational lane width and associated problems of resolving lanes if lost have already been mentioned. In addition, there are substantial propagational problems at the higher frequencies both in inherent signal stability and in complexity in relating phase changes to displacements on the ground. During the day, phase at the higher frequencies is both outstandingly stable and easily related to displacements on the ground. During transitions and at night, however, more than one mode of waveguide propagation may be supported.

17. Watt, AD, VLF Radio Engineering (Pergamon Press, 1967)

That is, the problem may be one of using a signal which is propagated by one mode during the day but by a second separate mode at night. Clearly, the two modes must be equal during transitions. Depending on details of the relative phasing when equality occurs, signals may interfere constructively or destructively, or they may add so that the phasor sum irregularly circles the origin thus giving rise to cycle slips. Indeed, circumstances may be imagined in which the total signal at night is composed of several modes all of which contribute significantly. In these circumstances the relation between phase changes and displacement on the ground may be highly nonlinear and erratic depending on random minor ionospheric variations. The problem is essentially that considered earlier of using a modally disturbed signal. There is no known way to use one modally disturbed signal reliably. With the substantial ensemble of such signals, it might be possible to detect anomalous cycle slip on any one signal. Overall reliability of this approach would depend on the probability of multiple cycle slips at the same time and also the detection probability. The problem is not, however, essentially any different from navigation using communication frequencies and this has been done with apparently acceptable reliability for years. It is also noteworthy that the lane widths for hyperbolic processing of 20 —40-kHz signals are sufficiently narrow that an occasional cycle jump may be acceptable.

Use of a very much higher frequency for navigation in the way now commonly employed with 10.2-kHz does not appear inviting. The navigational ambiguity would be severe and processing would require substantially different treatment throughout the 24-hour day. Such an additional frequency might, however, provide advantages in supporting maneuver response in the tracking of Omega signals. As already noted, maneuver response capability is not necessarily considered a proper function of a long range fixing aid but offers economic advantages in some applications.

An attractive method of adding an additional time shared frequency would be to use the spare variometer system installed at each station. In the event of a requirement for the spare variometer, transmissions at the much higher frequency would simply be discontinued until the emergency had passed. This would reduce the reliability of transmissions at the new frequency below that of the traditional frequencies, but this is not likely significant, as propagational limitations will inherently render a single such signal somewhat unreliable at night. Overall transmitting system modifications to realize the potential higher powers would, however, be extensive.

Range-range Navigation

Omega was conceived originally as a hyperbolic system but one which could be used in a range-range mode by suitably equipped users. In this context a distinction must be carefully drawn between "pseudo-range" measurement processing within a receiver implementation and true range-range fixing. The fundamental measurement with Omega is always the phase of a received Omega signal as compared against a locally generated reference. The phase of the local reference in turn depends on the time of the local clock which is generally not known on an absolute basis to the 1 - 2 μ s which corresponds to measurement precision. In hyperbolic processing, signals are immediately paired with one being subtracted from the other as:

$$\begin{aligned} M_A &= A - O \\ M_B &= B - O \end{aligned}$$

$$M_A - M_B = A - B = \text{line-of-position AB}$$

where A is the phase of signal A, B is the phase of signal B, O is the local reference phase, and M_A and M_B are the measurements of A and B, respectively. Note that the resulting hyperbolic line-of-position is independent of O provided the local frequency standard is sufficiently stable that O is unchanged from M_A to M_B as assumed. In hyperbolic navigation a third station is paired in some convenient way to obtain a second line-of-position which can then be intersected with the first to obtain a fix. In this manner signals from three stations produce a fix without knowledge of the time of the local clock.

In pseudo-range processing all signals are measured with respect to an unknown local reference. The arithmetic for the positional solution in terms of the pseudo-ranges and time is then developed and the resulting equations are solved. If three or more stations are available, one would expect to be able to solve the equations for latitude, longitude, and time barring mathematical singularity. This implementation is often used for automatic receivers as the arithmetic is readily applicable to redundant signals whereas a hyperbolic solution could require many permutations and combinations to treat the resulting hyperbolic lines-of-position.

From the foregoing, it is clear that signals from at least three stations are needed to produce a fix using either a hyperbolic implementation or a pseudo-range implementation. Fixing using signals from only two stations is possible given suitable geometry and the absolute epoch of the Omega system. It is the requirement for absolute time which distinguishes true range-range fixing.

A user may obtain absolute time only with effort and further must purchase suitable clocks with which to maintain it. Clocks are expensive. Were the absolute time requirement nominal rather than severe, Omega would have surely been designed to operate primarily in the range-range mode. This would have considerably reduced the required number of stations and resulted in a savings in system implementation costs. In practice, clock costs and operating difficulties in obtaining and maintaining time dictated support of hyperbolic navigation through additional stations.

Temporarily disregarding practicalities, there is no question that range-range navigation is both more accurate and more reliable than hyperbolic navigation. If only two signals are available, range-range could be the only technique allowing navigation. Even if more signals are available, the fact that time is known allows more of the available information to be used to improve the precision of the position fix. If absolute time should be available, range-range navigation would be attractive. In a sense, range-range navigation may be thought of as providing the equivalent of a ninth station which is always receivable.

Clock stabilities required for the durations usually encountered in maritime operations demand use of cesium frequency standards. These cost about \$20k each plus whatever additional circuitry may be needed for frequency synthesis and control and excluding any provision for redundancy. That is, use of a precision clock would more than treble receiving system costs even assuming use of modern fully automatic computer based receivers.

Clock stability requirements for aircraft use are more moderate because of decreased durations needed, and rubidium standards costing \$5 - \$10k plus ancillary circuitry could be used. This is less than the cost of existing airborne equipment and could thus be used with price increases of less than 100% and possibly as low as 10% for some of the most expensive units.

Use of precision clocks will also affect system size, weight, reliability, and power consumption as well as cost. Most important, however, is the requirement to set the clock. The Omega epoch is known with respect to

internationally agreed time. However, absolute time is available at only very few locations in the world; transfer to the using vehicle presents severe operational problems. There is no question that time transfer or acquisition is needed; the only questions are the required frequency of transfer and the needed precision. Successful solution of the time transfer problem is thus needed before the equipment can navigate. Additional efforts are needed to assure that time will not be inadvertently lost through power failure or other cause once the clock is properly initialized.

One approach to the time transfer needed by a range-range Omega system, perhaps the only practical one, is to use the Omega signals themselves to deduce time. As already noted, this is possible using three sets of Omega signals. It is also possible using only one or two sets of signals if the precise receiver location is known, as would be true before a voyage or flight. Using this method, however, time dissemination errors will clearly be comparable with nominal Omega errors and thus the initializing uncertainties will be a continuing cause of uncertainty in the resultant navigational information.

One technique is conceivable which could provide adequate navigation in a region where only two signals were available part of the time as, for example, where modal interference might limit coverage to only two stations at night. Time could be deduced during the day and the local clock reset. The clock would then be used to support range-range navigation at night. Clearly one is addressing ongoing navigation such as encountered in marine operations but not in air. Continuity is assumed. Also, the oscillator requirements are not cheaply met. Predictabilities of a few parts in 10^{11} are required. These are slightly beyond the state of the art for disciplined quartz oscillators (for example, the specifications for the AN/URQ-23 indicate changes in the type of service contemplated of 7×10^{-11} in a benign environment after 11 days' warmup). The requirements are also beyond presently projected capabilities for surface acoustic wave (SAW) oscillators. Thus, rubidium or cesium standards would be required, much increasing the cost of the receiving system as previously noted.

A form of navigation which has operational characteristics between range-range and normal three or more station implementations may be obtained by using a quartz oscillator of moderate stability. The associated receiver is implemented via pseudo-range techniques, but the local oscillator is assumed to be somewhat credible over perhaps some minutes or tens of minutes once the oscillator has stabilized and the system has been operating sufficiently long to calibrate both epoch and drift rate. Oscillators with precisions on the order of a few parts in 10^9 costing about \$500 are adequate for this purpose. Initially such systems operate like normal Omega navigators. After perhaps 0.25 to 1 hour the oscillator becomes calibrated. Should noise increase or other factors reduce coverage to only two stations after this time, navigation can still continue although accuracy will degrade with time. In particular, accurate navigation can be maintained for the perhaps tens of minutes which might be required in the event of a sudden increase in local noise. Notably, it can provide worthwhile protection against typical precipitation static effects at nominal cost.

Except for the limited capability suggested in the foregoing paragraph, range-range implementation is not generally attractive.

Pulse Timing

Omega contains an inherent navigational capability based on the envelope delays encountered by the various nominally 1-second bursts. Pulse, or

usually simply lead edge, delays have been used navigationally for years. Particular examples are Loran-A and the first positioning phase of Loran-C used to resolve carrier cycles. One feature of pulse timing systems is that the inherent system ambiguities are determined by repetition rates which are readily chosen to eliminate all practical problems. Pulse timing capability at vlf has traditionally been regarded as poor, as the rise times possible with usual antenna systems tend to be rather long (milliseconds or tens of milliseconds) and thus the capability obtained by direct application of usual means has tended to be regarded as of the same order. Navigational accuracy corresponding to 1 - 10 ms is on the order of 100 - 1000 miles, which has not been regarded as especially useful. DePrins, however, has shown lead edge accuracies at vlf of only a few hundred microseconds.¹⁸ Of more direct application is work by Swanson and Adrian showing existing Omega envelopes can reliably be used to identify lanes within a four-frequency Omega system within 3 minutes by using special but easily implemented processing techniques.¹⁹ The practical problem is not the ultimate possible precision obtainable from Omega envelopes but rather the integration time necessary to confidently obtain various operationally useful accuracies.

For many years the principal author of this report has regretted the total disregard of envelope capability in the development of Omega. In construction of Omega transmitters and antenna systems no attempt was made to keep rise times short and therefore more useful for envelope timing. Indeed, specifications could have been legally satisfied if rise times were so slow that only negligible power was radiated at the end of 1-second bursts. Rise times (and fall times) can be improved within the existing system without change of format and without effect on existing receivers. Substantial changes would be needed at the transmitting facilities.

Note has already been made of the special processing employed by Swanson and Adrian. Present technology will support implementation of a number of receiving techniques beyond simple gating. Also, however, modern technology will support transmitting a number of envelopes beyond whatever results from simple on-off keying. Brown has considered possible pulse shaping in developing a proposal for augmenting Omega with direct pulse timing capability.²⁰ In the proposal Brown concludes that accuracy of 5 to 10 miles is technically possible with what he regards as reasonable radiated power and averaging times on the order of 1 - 2 minutes.*

Improvements in direct pulse timing capability within the present format can be implemented at any time with little coordination required. If a major pulse timing augmentation is considered, it is attractive to consider this option in conjunction with adding a much higher frequency. Both high power and short rise time would be more easily achieved at a higher frequency.

Station Relocation

The system improvement that is possible through alternative placements of one or more of the Omega stations is difficult to determine without coverage assessment technology which is readily applicable. The existing technology is

18. Guisset, JL, and others, "Reception de Signaux Horaires sur Ondes Myriametriques," Bulletin de la Classe des Sciences (Academie Royale de Belgique), 5th series, v/52, p 409-499, 5 March 1966

19. Naval Electronics Laboratory Center Technical Report 1901, Omega Envelope Capability for Lane Resolution and Timing, by ER Swanson and DJ Adrian, 20 November 1973 (AD 774 891)

in many ways accurate but certainly laborious. Especially in considering a station relocation, wherein the usual approach is to evaluate full system coverage under various sitings, the computational load resulting from a reasonable number of alternative sitings can be excessive. The problem may also need to be approached somewhat iteratively in that existing technology is most adept at evaluating coverage from a chosen siting rather than suggesting the type of station displacement necessary to improve coverage. This means that the type of displacement thought to offer improvement is left to the intuition of the researcher or to random chance. Whatever the formal inelegance of the method, it is not thought to constitute too much of a liability in that station displacements are not homogeneously practical but must conform to existing islands and other usable real estate. Nonetheless, the existing technology is sufficiently tedious to discourage application for first order siting change evaluation. More responsive coverage assessment techniques are necessary for such evaluation. As a speculation, displacement of station F from Argentina to Easter Island, the Marquesas, or the Galapagos might result in better overall system coverage, particularly in North America. A full coverage assessment is, however, necessary to determine possible detrimental effects elsewhere.

Additional Station(s) and Format Changes

The cost estimate for adding a new station is between \$6.7M and \$16M as shown in appendix E.

Possible schemes for adding one or more additional Omega stations to the system are discussed in detail in appendix F. Of transcending importance is the conclusion that there are, indeed, reasonable methods by which additional stations can be added to the Omega system without obsoleting present

*Separate collocated transmitting facilities are envisaged radiating 200kW pulses at a repetition rate of 5 pps in 8 channels from 11.5 to 12.5 kHz. Since the power radiated from a voltage limited transmitting antenna is proportional to the fourth power of the frequency, it would be exceedingly expensive to obtain the indicated power level at the indicated frequency. Further, Brown cites reasons for preferring transmissions in the indicated band. However, if less accuracy is demanded, higher frequencies could be used and substantial powers could be radiated even from existing Omega antennas after some modification. In particular, dedication of one segment in the 10-second pattern to pulse transmissions could be attractive.

20. Brown, RG, read as a rough draft, A Proposal for Augmenting Omega with Direct Pulse Timing Capability, which was subsequently restructured and presented as "VLF Pulse Timing: Limitations and Potential as a Companion to Omega" at the ION Aerospace mtg, Denver, Colorado, April 13-14, 1977 and published in the Proceedings (published in NAVIGATION, 24 4 winter 1977, p 329-337)

equipment. Older equipment could continue to work with eight stations. It is even remotely conceivable that some present automatic receivers could be modified to receive nine or more Omega stations by changing only software.

A management consideration is whether a format modification philosophy should be adopted which will support some system growth beyond a single additional station or whether only one additional station will ever be desired. A growth philosophy could lead to an eventual accommodation of the vlf navigation system maintained by the USSR within a modified Omega format.

Prudence indicates that possible format modifications be carefully weighed and attractive schemes be engineered before a firm choice is made.

Clearly and by a variety of methods, new stations can be added.

Omega Repeaters

Small coverage deficiencies or areas of insufficient redundancy can be improved through addition of one or more small low power Omega repeaters assuming a format doctrine is adopted which will permit some growth. These additional stations would operate as in-phase reflectors of signals from a chosen Omega station using the older "slaved" method of operation. This approach would eliminate the need for elaborate timing equipment and might also remove the requirement for manning although at the expense of reliability. Because of error characteristics, the approach would lead to better than nominal line-of-position stability although not as good as available from Differential Omega. A vertical antenna system could be used as at other Omega stations although this might prove larger than desired even for low radiated powers. Alternatively, a horizontal Beverage antenna could be used. Propagational limitations probably render this approach attractive for only few locations such as the Bass Strait to provide redundancy for the Argentine signals or two or more repeater stations to improve coverage in the Strait of Malacca but not in the extended area.

CONCLUSIONS AND RECOMMENDATIONS

Theoretical analysis supported by some experimental data indicates that there is and will continue to be a coverage deficiency in Central North America. Correction of this deficiency is expected to require relocation of one of the existing Omega stations or construction of a new Omega station. Contingency planning to evaluate and correct this deficiency is clearly warranted and should proceed with high priority. However, some caution is in order. Initial planned construction of Omega is now almost complete. Assessments need no longer rest heavily on theoretical considerations but may incorporate direct measurements. Direct measurements are clearly indicated before major potentially disruptive and certainly expensive courses of action are pursued. A "validation" effort is needed to verify the coverage deficiency with high confidence and determine the exact limits. Users need to be advised of limitations. Concurrently effort should proceed on evaluation of the expected impact of the deficiency and development of alternatives.

Some of the areas discussed bear on resolution of the deficiency and can be arranged to follow in an orderly fashion from the development presented:

1. The potential benefits from more sensitive receivers should be determined. The results of this study can radically alter indicated coverage.

2. Noise cancellation schemes appropriate for airborne receivers should be developed and evaluated. This work will not fundamentally affect system coverage as it is now construed; however, it will provide a basis by which it may be possible for airborne navigators to realize the coverage now predicted for marine navigators.

3. More tractable coverage assessment tools are needed. This Center is currently tasked to improve display of coverage information. Accomplishment of this will entail development of more tractable assessment tools. The work should be extended to provide a tool to determine coverage impact from relocation of an existing station or addition of one or more new stations. Coverage at other frequencies and using long path signals can be incorporated.

4. Validation efforts and other direct measurement programs should be conducted to experimentally verify areas of coverage weakness.

5. Hopefully results of (4) above are in reasonable accord with expectations from (3). If not, modifications in assessment methods need to be made so that assessments match reality. The assessment tools should then be modified to reflect capabilities indicated by (1) and (2).

6. Modified assessment tools from (5) may now be applied to determine coverage impact from relocation of an existing station or addition of one or more new stations. This study will yield concrete indication of the benefits to be derived from some specific alternatives. It will also indicate the nominal design power needed from new stations, which in all probability may be substantially less than the nominal 10 kW capability of existing stations. Companion preliminary diplomatic and engineering studies can indicate the administrative and technical practicality of alternatives and their associated costs. It is conceivable that even if a station relocation might be sufficient to remove most major coverage deficiencies without detrimental effects elsewhere, addition of one or more new stations may prove expeditious.

7. If one or more additional stations are indicated by (6) above, then the various possible format modifications need to be evaluated. Preliminary to specific changes should be a decision as to whether a simple one-or-two station addition is to be implemented or a growth doctrine is to be established so that eventually some relatively large number of stations, say 16, could be accommodated if ever desirable for any reason. Within the guidelines established, engineering prototypes of the more attractive schemes should be constructed and evaluated. Based on results, a selection should be made.

8. Construction should proceed based on the outcome of the foregoing.

The preceding recommendations are straightforward and logical with each step depending on the outcome of preceding efforts. Equipment manufacturers, however, may wish to know possible format changes before there is any decision as to whether or not to implement changes. Particularly with receivers which are not computer based, it may be desirable to incorporate some ancillary circuitry to allow a growth capability as soon as even a contingent possibility of format expansion is recognized. This desire is not unreasonable and may warrant some reordering of effort.

As presented, the recommendations offer substantial potential improvement at each step for minimum commitment. Benefits will be well known before substantial costs are incurred. The order of investigation is

recommended even if the final result may simply be an indication that the existing station at Trinidad should be refurbished and worked into the format with a radiated power of about 1 kW.

Benefits can also be obtained from work in other areas including development of precise criteria to support expanded use of the groundwave and improvements in pulse envelope capability. Efforts to make stronger signals available will improve reliability in high local noise conditions, increase range and therefore improve redundancy, and also allow better maneuver response. Requirements in these areas need careful review. Work leading to stronger signals includes transmitter power increases especially at 13.6 kHz and possibly extension of the format to include a much higher frequency.

The work noted herein is not intended to substitute for normal work carried out by the Omega Navigation System Operations Detail such as routine engineering improvements leading to better maintainability and reliability, continuing coverage evaluation, or continuing improvement in system calibration. In particular, there is an acute need for a major re-evaluation of global prediction constants. Many stations have become operational since the constants now in use were determined in 1971.

The foregoing investigations are summarized in Table 1, which is arranged as a PERT chart to suggest the interrelationships of tasks and relative priorities. Very rough cost estimates are included as approximate indications of the amount of effort envisaged. Certain miscellaneous tasks are viewed as of comparatively low priority and should be pursued on the basis of time available by key personnel.

Lastly, the perspective of this report is reiterated and an informal comment on the system is offered. "Limitations" and "deficiencies" have been emphasized in the knowledge that their recognition is an essential first step in evolving corrections and improvements. Emphasis on occasional difficulties must not be construed as indicating that Omega as a system is deficient in any overall pervasive sense. Indeed, a more complacent but less useful interpretation of the material presented herein would be to conclude that with the completion of the station in Australia, Omega will perform very nearly as anticipated and substantially better than established requirements almost everywhere. A satisfying companion observation is that, after allowance for inflation, Omega has been developed at or below cost estimates. The emphasis here, however, has been on limitations so that improvements can be effected.

TABLE 1. SUGGESTED ORDERING OF EFFORT.

Priority	Task	Approx Cost (\$)	FY78	FY79	FY80	FY81	FY82	FY?	Remarks
Very High	Evaluate anticipated coverage deficiencies by measurement	50k ^a							Second effort required after Australia completed
	Disseminate deficiency information	5k							
High	Receiver sensitivity improvement	600k ^b							Decision to continue after first year
	Receiver EMI protection	400k							Decision to continue after first year
	Coverage assessment tools	10-70k ^{a,c}							
	Coverage assessment validation	30k ^a							
	Assessment modifications (if needed)	10k?							
	System analysis w/new station(s)	30k							Decision to proceed with new construction in mid-80s
	Format evaluation & choice	80k							May require earlier scheduling as contingency if American coverage continuity is required after Australia on
	Construction of new station(s)	6.7-16M							
Low	Groundwave coverage criteria	15k							
	Review reliability and maneuver requirements	50k							
	Engineer methods for greater power	120k							
	Implement power increases	2.6M							
	Envelope studies	100k							
	Envelope engineering & modifications	?							

Note:

- a. Cost is that beyond related work already funded, eg, normal acquisition of data base.
- b. Cost is \$200k/year. First year establishes feasibility and is followed by decision point as to whether to continue. Second year expands data base to global sampling and yields definitive information on potential gains. Third year develops practical implementation approaches.
- c. Lower cost covers assessment development for carrier frequencies independently. Perhaps an additional man-year should be beneficially spent addressing joint coverage by at least one frequency. Schedule is shown for lower effort.

APPENDICES

Appendix A: General Limitations

Accuracy

The Omega system has been advertised to have a fix accuracy of 1-2 miles circular error probable (cep) or a 95% fix probability of 2-4 miles.* Several, but not all, recent evaluations have yielded results in this range.²¹⁻²³ An earlier evaluation based on early North American observations of transmission from Hawaii, New York, Norway and Trinidad indicated an accuracy of about 1 mile.²⁴ The deterioration in accuracy shown in the more recent results is believed to result primarily from propagation prediction errors. The earlier results were in a region of considerable experience and the system was thus relatively well calibrated. The recent advent of transmissions from newly constructed stations particularly into regions of limited experience such as the equatorial zone has resulted in not unexpected prediction biases.²⁵ Severe biases have been observed in Europe and the Mediterranean when using North Dakota, studied, and corrected.²⁶ Biases have also been observed near Japan but not yet corrected.²⁵ It is speculated in appendix C that when biases are better understood and reduced, general system fix accuracy will become about 0.5-1 nmi root sum of squares (rss), or about 1-2 nmi at 95% probability. Because of the global character of Omega, accuracy with Omega will be far more uniform than with most navigation systems. Nonetheless, it will vary both spatially and temporally. As discussed in the appendix C section on coverage, areas are expected wherein accuracy will be substantially less than the usual expectation and less than defined system requirements. By definition, such

*This work does not have pretensions of precision in the accuracy figures quoted and values have therefore been rounded. Further, the fix error distribution will vary from Rayleigh to Gaussian depending on the eccentricity of the error ellipse and thus there is no simple relationship between median, 67%, or 95% statistics. Distinctions are important in considerations of safety as well as clarity in partitioning between on-track and cross-track errors.

21. Naval Electronic Systems Engineering Activity Report on Proj No 77-28-24, Final Report, Test and Evaluation of Two Analog Differential Omega Systems, by JP Davey, 7 April 1978
22. Navidyne Corporation, Sea Validation Trail Report Navidyne Automatic Omega Navigator Model EXZ-1001/2000, by A Clifford Barker, 8 Sept 1977
23. Omega Navigation system Operations Detail Report 01-78 prepared by Systems Control, Inc (vt), Western Pacific Omega Validation, vol I, by FG Karkalik, GF Sage, and WR Vincent, April 1978
24. Naval Electronics Laboratory Center Report 1675, Accuracy of Omega Navigation System Using 1969 Skywave Corrections, by ER Swanson
25. Naval Ocean Systems Center Technical Note (in preparation), Omega Errors Observed at Various Locations, by ER Swanson
26. Naval Electronics Laboratory Center Technical Note 3191, Omega Prediction Errors in the Mediterranean, by ER Swanson, 16 July 1976

areas constitute coverage holes. With Omega, however, which differs in this respect from most navigation systems, a coverage hole is not a region totally unserved by the system. Two-station range-range fixing will be possible everywhere. When three-station fixing accuracy degrades beyond requirements, a hole is said to exist, although fixing at some perhaps vastly degraded accuracy will usually still be possible.

Any discussion of accuracy must mention alternative Omega techniques such as Difference Frequency Omega, Composite Omega, and Differential Omega. The accuracy figures for these implementations are characteristically different from those for standard Omega, as are their error budgets. In particular, all the systems mentioned are more susceptible to environmental noise than standard Omega although all are also less susceptible to propagation disturbances or to propagation prediction errors. (The latter insensitivity combined with present prediction problems may explain why some of these implementations are presently in vogue.)

Discussion of relative accuracy or spatial or temporal correlation is beyond the scope of this work.

Responsiveness

It is important that navigation systems respond promptly to changes of position. A system requiring days to obtain a fix might be useful to geodesy but would be useless in any practical navigational application. The problem is in establishing a working definition of "prompt." It can be argued philosophically that the purpose of a long range navigation aid is to provide basic fixing, not provide short term steering information. Under this interpretation and considering a nominal accuracy of 1 mile and ship speeds of 60 knots or less, 1-minute integration and processing times are reasonable. This responsiveness is also compatible with aircraft requirements using elementary rate aiding such as air speed and magnetic heading. Time constants of 1 minute are often employed in receivers and are adequate to track signals with sufficient precision. The relationship between signal strength and responsiveness has been discussed in the literature and is needed to determine the signal-to-noise criteria used to evaluate coverage.²⁷ or ²⁸ Coverage is thus defined to provide sufficient accuracy and responsiveness in the sense noted for global fixing.

There is an understandable tendency on the part of many designers to attempt to rely on a primary fixing aid to develop dynamic maneuver response. This is understandable in that if the long range aid is capable of providing the maneuver response, no other sensors are needed. This saves both sensor costs and integration costs and may improve reliability. However, it also places high demands on the quality and character of the signals from the long range aid. In the case of Omega, desired power levels quickly become totally unreasonable. Further, with the 10-second commutation cycle, there is a limit

27. Naval Electronics Laboratory Center Technical Report 1944, Propagational Assessment of VLF Navigation Signals in North America and the North Atlantic, by ER Swanson and MJ Dick, 4 February 1975 (Also designated as Dept of Transportation Report FA74WAI-425-2), AD-A013 092

28. Naval Electronics Laboratory Center Technical Report 1974, Omega Coverage in India: A Case Study, by ER Swanson, November 1975, AD-A022035

on how responsive the system can be. Responsiveness for maneuver also depends on spatial and temporal correlation properties of the signals.

The foregoing is not meant to imply that Omega cannot provide maneuver responsiveness, only to question whether it should. Many augmentations are available including vlf communication signals. It is, however, important to note that coverage assessment is not based on high maneuver applications.

Ambiguities

Most navigation systems have ambiguities--even a noon sun line is ambiguous between northern and southern hemispheres. Potential ambiguities always need to be carefully defined; then engineering attention can be directed to minimizing potential faults. This is especially important since failures to properly resolve ambiguities are best considered blunders. Fixes associated with ambiguity errors are not members of the statistical family usually associated with fix errors but may exhibit gross anomalies readily associated with hazardous conditions. Ambiguities do not arise in Omega if the system is properly initialized and tracking is continuous. If, however, an ambiguity must be resolved, there is some inherent probability of error. The associated blunder probability can be reduced to nearly an arbitrarily small figure by the technique of selective resolution.²⁹ This technique achieves confidence at the expense of lane resolution duty cycle or availability. Difference frequency or other navigational techniques may be employed if lane resolution is not available with sufficient confidence.

It should be noted that Omega lanes may often be resolved by using alternative navigation aids such as intersections with depth contours, sun lines, etc.³⁰ Some resolution capability is also inherent because of signal redundancy even when only one frequency is used.³¹ Usually, however, ambiguity resolution is associated with the spectral content of the format itself. Resolution capability associated with format content is a self-contained capability of the system which should be generally available with some probability of success on a global basis. A format containing only transmissions at 10.2 kHz would be ambiguous every 8 miles on the baseline of a hyperbolic system. There would be no method whatsoever to resolve fixes separated beyond ± 4 miles. Addition of transmissions at 13.6 kHz causes a virtual 3.4-kHz beat to be available which is ambiguous by 24 miles on the baseline. The present system contains transmissions at 10.2, 11-1/3, and 13.6 kHz which have a combined ambiguity of 72 miles on baselines. Transmissions at 11.050 kHz are being added which will expand this to 288 miles.^{1,3} The 10-second commutation pattern has an associated ambiguity of approximately 1 million miles; that is, far larger than the size of the earth. Thus, envelope measurement is essentially unambiguous if not particularly accurate.

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29. Swanson, ER, "Application of Omega to Aircraft Navigation and Traffic Control," Journal of the Institute of Navigation (British), vol 24, no 1, January 1971, p 125-128
30. Swanson, ER, "Omega," NAVIGATION, vol 18, no 2, p 168-175, summer 1971
31. Pierce, JA, Palmer, W, Watt, AD, and Woodward, RH, Omega: A World-Wide Navigational System -- System Specification and Implementation, first ed, Pickard & Burns pub no 886 of 1 June 1964; second ed, Pickard & Burns pub no 886B of 1 May 1966 (AD 630900)

Ambiguity resolution using hierarchies of frequencies and phase comparison has been extensively described in the references. Improvement using this technique would require increasing the spectral content of the format. The inherent capability of the envelope for lane resolution has also been described.¹⁹ Improvements using this technique could be obtained by decreasing pulse rise and fall times. An alternative technique that has been proposed is that of wave forming.²⁰

Cost

Cost and affordability reflect our application of economic priorities and thus are limits on most of mankind's undertakings. A work of this type is not a governmental cost--benefit analysis nor is it an industrial marketing review. A few observations are, however, included for the sake of completeness.

Thus far, between \$10⁸ and \$10⁹ has been spent on Omega. This includes \$170M expended by the US Navy for both system development and construction and also Navy receivers (Herbert, NF, personal communication, May 1978). Additional expenditures have been incurred by other governmental agencies both US and foreign and also by users in the purchase of their equipment. The total is impossible to determine with any accuracy but may be on the order of \$300M at this time. These expenditures have resulted in the establishment of an international navigation capability which is very cost effective in terms of expense per square mile of coverage. Since system development costs have been mostly incurred at this time, primary attention need only be directed towards maintenance costs and costs of new receiving equipment.

Transmitting station facility maintenance cost incurred by governments should be relatively nominal. Major costs will be associated with the continual manning of eight facilities. Much of this cost would be the same for any sites which were permanently and continuously manned regardless of the function being performed. The only moving parts are associated with the variometer tuning and high voltage switching. Tube replacement is an appreciable but not overly significant cost. After salaries, electric power costs are the most significant expenses. A depreciation fund to cover occasional major antenna maintenance will also be an appreciable expense.

Receiver cost is not a limiting factor for use in long range commercial aircraft where major alternatives such as inertial or doppler are substantially more expensive both initially and in maintenance costs. The only competing systems on a global basis on the high seas are NAVSAT, SINS, and celestial. Accurate SINS is prohibitively expensive except for use in strategic missile submarines. NAVSAT is more expensive than Omega and does not provide continuous fixing, although accuracy is better. Celestial is somewhat unreliable as clear weather is necessary; costs are minimal although fix reduction requires some skill and is tedious. Considering acceptance of Omega on the high seas, cost is not a limitation for use on merchant ships, naval ships, or larger far reaching fishing fleets such as the tuna fleet.

Cost significantly limits the use of Omega on yachts and by general aviation. Navigational support to general aviation is provided within the contiguous United States by the VOR system. The system is also closely interrelated with the air traffic system. Thus, a shift from VOR to Omega would present an immediate and serious problem of interface. Further, private aviation aircraft rarely fly on intercontinental trips, although some executive aircraft do. Many would have no reason to shift to Omega even if

cost was less than that of present VOR equipment. In fact, airborne Omega sets are considerably more than the \$1-2k usually spent on VOR receivers. It is likely, however, that good use would be made of a low cost Omega receiver by general aviation aircraft in many regions of the world such as Alaska, which are not well served with VOR. Some yachts are used on a global basis and some are already Omega equipped. Other yachtsmen like to feel that their vessels have global capability even if they never leave coastal waters. It may be speculated, however, that vastly more would be Omega equipped if receiver costs were down to on the order of US \$500. Receivers can certainly be constructed at this price. The problem is that substantial amounts must be allowed for dealer markup, installation, training, etc. Margins sufficient to support responsible marketing have reduced production quantities and resulted in selling prices of several thousands of dollars. The economics of Omega receiver manufacture and sale are, of course, well known within the industry. Nonetheless it must be noted that a large potential user community is excluded because of high cost.

Costs of options and opportunities considered herein can all be considered "minor" when viewed with appropriate detachment. That is, even addition of a new station would only add about 10% to the capital investment cost in the system and would thus be a relatively small fraction. Of course, the expenditure would be large and could only be justified if system utility were significantly enhanced. It is also noteworthy that none of the options would significantly affect the cost of new construction receivers.

Human Interface

Human interface is primarily a consideration associated with receiver design. Within the established system context assumed herein, the various system options considered have little effect either advantageously or disadvantageously on human factors.

Reliability and Availability

Reliability data for individual stations have been developed by ONSOD. Bruckner and Auerbach have published on system reliability³² while continuing statistical compilations are studied by Frye (Frye, EO, personal communication, May 1978). Fully detailed assessment of coverage and accuracy degradation associated with various stations' outages or combinations of outages awaits future work using new and more rapid assessment tools. Present reliability figures are quite satisfactory to support intended system use in the open ocean and to support many aircraft applications as well. Other than the work previously cited, the authors are not aware of system studies relating system reliability to specific applications. It is possible that higher total operational reliability and availability figures may be desirable if the system is used directly in support of traffic control applications rather than for open navigational use. If analysis indicates this to be the case, it may be that significant improvements in availability can be obtained

32. Bruckner, JMH and Auerbach, "LF/VLF NAVAID Signal Reliability in Airborne Applications," NAVIGATION, 23, 3, fall 1976, p 209-216

by revising scheduled maintenance procedures to require less station outage time.

None of the options considered herein are expected to have great impact on system reliability and availability as viewed by users. Addition of a ninth station would improve coverage and redundancy thus improving reliability. Various movements of existing stations could also improve coverage and might well improve redundancy. Increases in station power would improve coverage and redundancy. Power increases would have a mixed influence on availability. Improvements in signal-to-noise would improve availability in fringe areas. However, operating equipment at higher power levels may lead to more frequent failures thus lowering reliability. As in all engineering work, changes in reliability will depend on how individual options are executed. Major changes are not anticipated except as associated with coverage improvement.

The considered options are not expected to make substantial differences in the blunder rate in using the system although some format changes could provide a means for receiver manufacturers to develop more navigationally reliable equipment. Some of the proposed investigations and technique studies could also provide means for major improvements in navigational reliability through changes in receiver design.

Navigational safety is closely related to the probability of extreme variations or outages. One method to improve safety is to provide timely warning to users of outages or extreme variations. A device has been constructed for this purpose and is undergoing evaluation.³³

33. Swanson, ER and Levine, PH, "Automated OMEGA/VLF Monitoring and Forecasting for Air Traffic Safety Enhancement: A Progress Report," Proc, Inst of Navigation Aerospace Symposium, Atlantic City, 27-29 April 1978

Appendix B: Receiver Installation and EMI

Occasional sources of degraded Omega performance are local noise and harmonic electromagnetic interference (EMI) generated aboard the platform on which the equipment is installed.

Platform types divide primarily into submarine, surface ship, and aircraft. Within the types there are further divisions as between yachts, fishing craft, merchant vessels, and naval ships; and between helicopter, small civil aircraft, and large commercial or military jets. It will be convenient to consider ships and aircraft separately and to disregard submarines, which constitute a specialized application. On submarines, working depth is directly related to platform noise and hence local noise receives special attention aside from the general implications addressed here.

Ship

Shipboard platform noise does not constitute a serious problem for either civil or military ships. E-field antennas (whips) are universally used aboard surface ships. In 20 years' experience with Omega this Center has never encountered what would be called an insoluble "noisy" installation on a Naval ship under normal weather conditions. Local EMI generally will be recognized by a skilled and experienced installer who will take steps to mitigate the problem. Thus, serious shipboard installation problems are not frequently encountered, and one would expect the problems that do arise to be solved and Omega to be operating properly when the installation is completed. That is, EMI is more an installation inconvenience than a performance limitation for shipboard Omega.

Of course, there may be occasional exceptions. An installer may think he is adequately qualified and that the installation is good when neither circumstance is true. Further, there is little protection from a yachtsman who may attempt a do-it-yourself installation although reputable manufacturers attempt to discourage this practice. Even with the best skill and experience, installation could present unusual problems on a specific ship. There is evidence that installations on ships with wood or fiber-glass hulls are more difficult than on a steel hulled vessel. One engineer of considerable experience with commercial installations failed only once to make a satisfactory installation. The failure occurred on an aluminum hulled yacht with ungrounded power on which the owner also placed severe restrictions on antenna and coupler locations.

Nonetheless, Navy experience with the AN/SRN-12 is more typical and indicates that there is good reception at sea off Norfolk while degraded performance is obtained at Norfolk itself. Thus, berthing at Norfolk is in a sense equivalent to a noise injection test. If the installation itself were markedly noisy, noise would tend to swamp operation at all times rather than just in port. No one surveyed was aware of any naval installation compromised by ship's noise.

Air

Aboard aircraft, however, EMI is a serious problem particularly with H-field antennas (loops) used by most manufacturers. Navy experience indicates that local EMI is usually, if not always, the limiting factor for Omega reception. The typical installation algorithm has been described by Mr Sakran in his inimitable way as:

1. Map the skin
2. Install the antenna at a relatively favorable location
3. Blame Omega signal coverage for resulting limitations

This tends to direct attention away from the installer but is not a useful step in improving reception. It is hard to overemphasize the seriousness of the problem. Millions of dollars are spent to transmit an extra dB or two at the transmitters while the Omega signals are then self-jammed aboard the using aircraft. In a first attempt to install one antenna with an active coupler, it was noted that 400-Hz power harmonics completely saturated the coupler. TACAN in the transmit mode also may cause problems as may some search radars wherein the pulse repetition frequency (PRF) is keyed to power line frequencies and thus introduces additional interference. High frequency transmissions on longwire antennas and even VORs have been noticed to cause interference. Some full multifrequency Omega receivers offer a measure of protection from power harmonics since the harmonics may not jam all frequencies simultaneously. However, difference frequency receivers such as the Norden Systems (formerly Dynell) built AN/ARN-131 require good reception of two or more frequencies at the same time. Generally the aircraft power frequency is sufficiently unstable as to cause more or less random jamming of various frequencies. However, turbine powered aircraft tend to have constant frequency power since turbine shaft speed is operationally maintained constant while propulsion power is adjusted by varying blade angles. The Naval Air Test Center has had some success stabilizing such power sources at between 394 and 398 Hz so as to place offending harmonics away from the Omega frequencies. This frequency adjustment has not caused harm to any other equipment. There is, however, a general trend to stabilize aircraft power. (This is a significant but interim trend; the long term change is to 270 V dc) The Air Force is now purchasing equipment employing crystal stabilization. Depending on how stabilization is implemented, it could render reception of Omega signals difficult if not impossible and, in the opinion of the authors, jeopardize the ability of some aircraft to perform their missions. Increasingly many aircraft function as electromagnetic probes. Thus, their primary activity is reception or radiation of electromagnetic signals. If power supply stabilization results in generation of coherent harmonics which can jam needed signals, mission performance could be affected. It is essential that power stabilization efforts properly evaluate the effects of power harmonics on navigation, communication, and detection equipment. This is especially true if stabilization is accomplished with SCRs or other devices leading to power waveforms with sharp rise times. Renewed attention to aircraft power can undoubtedly produce benefits; however there are considerations vastly more important than the design of power supplies. Instabilities and reliability problems with aircraft ground power sources also have been recognized and incorporation of three-phase 400-Hz distribution systems has been proposed for naval airfields. Without care, harmonics from the power lines could render ground checkout of Omega impossible. Summarizing, there is need for greater coordination to determine the electromagnetic environment on aircraft and airfields. The coordination should include attention not only to power frequency and harmonic content but to all electromagnetic emissions from equipment.

A survey of all major manufacturers of airborne Omega sets was conducted to determine commercial experience with platform noise. Experience is divided depending on whether E- or H-field antennas are used.

Most manufacturers routinely use H-field (loop) antennas although almost all can, and sometimes do, use E-field (blade, wire, whip, or plate) antennas. H-field antennas are preferred by most because of their comparative insensitivity to precipitation static although it is recognized that E-field antennas will often work quite satisfactorily and are much easier to install. Commercial experience using H-field antennas is essentially the same as military experience. Installations are almost never "clean." Skin mapping is routine. Installation difficulty varies among different types of aircraft and even among specific aircraft of the same type. Some essentially clean installations have been successfully made on DC-8's whereas 727's have a reputation for being especially noisy. While the usual installation eventually works quite satisfactorily, platform rather than nominal environmental noise almost always limits reception.

Two companies, Global Navigation, Inc, and Communications Components Corporation use blades. They experience far less trouble with most sources of electromagnetic interference but devote special care to installation and condition of wicks and other devices to drain off precipitation static charge build-up. These two companies have been responsible for a substantial fraction of the airborne Omega installations. Both have a historical background in vlf or vlf/Omega systems rather than pure Omega. Vlf communications signals are usually much stronger than Omega signals. The view has been expressed that precipitation static must cause a very substantial degradation before the initial installation advantage of E-field antennas is overcome; further, H-field antennas are not entirely immune to precipitation static effects.

In summary, both commercial and military experience indicates that airborne antenna installation and noise control are significant problems.* It is understood that KLM considers the reception problem of sufficient gravity to warrant reconvening the group developing the ARINC 599 Mark 2 characteristic.

*Reception problems are apparently not unique to the vlf band. A study of noise from 20 to 200 Hz generated by a KC-135 was recently conducted to determine reception conditions for ELF Strategic communications. Electrostatic noise up to 65 dB greater than typical atmospheric noise was observed. The report concluded: "Aircraft-generated noise...will make reception...difficult at all ranges from the transmitter".³⁴

34. Naval Research Laboratory Memorandum Report 3663, ELF Noise Observed in the Vicinity of Large Jet Aircraft, by J A Goldstein and R J Dinger, December 1977.

Appendix C: Coverage

This appendix has two major portions: 1) a discussion of coverage criteria and factors affecting fix accuracy and, 2) a rather lengthy perturbation and geometric evaluation to determine coverage during the day and a similar analysis for coverage at night. Coverage arranged by area rather than diurnal period is summarized in the main body of this report.

Criteria

Accuracy and performance of a navigation system like Omega depend on many factors.³⁵ The primary considerations are:

Adequate signal strength for timely measurement.

Sufficient propagational repeatability so that phase is reasonably well defined.

Sufficient propagational regularity that changes in phase may be related to displacements on the ground.

Adequate prediction theory to support exploitation of signal capabilities.

Sufficient receivable signals from diverse bearings to provide adequate fixing geometry.

It is necessary to comment briefly on each of the above areas although the scope of this work limits development.

Signal adequacy for timely measurement is a question of field strength of the signal, local noise, and the responsiveness desired in the system. Responsiveness is discussed in appendix A and in the references, where it is noted that coverage determination is based on criteria suitable for general navigation rather than high maneuver response. Prediction of field strength given ionospheric conditions is extremely complicated but is now sufficient to support coverage prediction with some accuracy.³⁶

A particularly powerful tool for Omega coverage assessment is the Integrated Propagation Prediction (IPP) program developed at the Naval Ocean Systems Center (then Naval Electronics Laboratory Center/Naval Undersea Center) by Snyder, Ferguson, and others based on original work published by Pappert, Gossard, and Rothmuller, also of NOSC or predecessor organizations, following the formulation of Budden. The program allows computation of vlf signals including Omega signals over any path over the earth and allows for earth curvature, ionospheric inhomogeneity, and anisotropy. Characteristic ionospheric parameters are input to the program to distinguish, for example, between day and night conditions or between normal and disturbed conditions. The program is organized with subroutines to provide ground conductivity, ambient electromagnetic noise, and the earth's vector magnetic field at all points of interest. Output are the phase and amplitude of the complete field as well as a breakdown of the composition of various propagation modes.

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35. Norwegian Defense Research Establishment Internal Report (in preparation), Factors Affecting Omega Accuracy, by TR Larse, ER Swanson, and EV Thrane
36. Swanson, ER, "Propagation Effects on Omega," AGARD Conference Proceedings no 209, AGARD-CP-209, paper 15, EM Wave Prop Panel Specialists' Mtg, Istanbul, 20-22 October 1976 (also published in French: "Effets de la propagation sur L'Omega," Navigation, Rev Technique de Navigation Maritime Aeriennne et Spatiale, part I vol XXV, no 100, October 1977, and part II, vol XXVI, no 10001, January 1978)

Signal-to-noise ratio may also be output based on whatever noise model is incorporated.

Noise prediction necessary to determine signal-to-noise ratio or adequate tracking capability is substantially less advanced than full wave signal prediction theory. Not only is it necessary to know the typical or root mean square (rms) noise for various diurnal periods and various seasons, it is also necessary to know something about the statistical distribution. Only fragmentary data are available on noise Amplitude Probability Distributions (APDs). Vlf noise is known to be highly impulsive. Thus, appropriate non-linear processing, such as hard limiting, can yield a measurement ability substantially better than would be obtained in Gaussian noise. The exact improvement possible is poorly known. Vlf folklore indicates processing gains are equivalent to about 15 dB in field strength. Measurements by Swanson and Adrian suggest 15 or possibly 20 dB.¹⁹ Measurements of equipment operation by Britt using simulated noise suggest at least 10 dB.³⁷ Since a nearly universal performance specification for vlf receivers is that adequate tracking should be obtained at a signal-to-noise ratio of -20 dB in 100 Hz in Gaussian noise, this suggests actual performance should be practical to -30 dB or more.

An early application of the IPP program to assess Omega signal availability on a global basis both during the day and at night was published by Bortz, Gupta, Scull, and Morris in 1976.³⁸ Unfortunately, this work uses a -20-dB criterion for signal-to-noise. (There is also a major error in the assessed coverage of Argentina in North America at night as noted elsewhere.) However, because of the wide availability of the work it was taken as the starting point in the perturbational analysis to deduce expected signal coverage. This choice of approach deserves some comment. Perhaps a more straightforward approach would have been to correct some of the underlying problems and repeat the Bortz et al analysis. Revisions have been made by Morris and Tolstoy, who used a revised noise map as well as improved criteria (Morris, PB, personal communication, May 1978). However, complete results were not available in sufficient time for this study. Further, reference to the older work not only allows the present effort to be traceable but may offer some practical advantage in that shortcomings of the earlier work are becoming well understood and thus confidence may be inferred in extrapolations from known conservative calculations. In any event, in the critical area of North America the results cited herein are in substantial concurrence with those obtained by Morris and Tolstoy. Results of both analyses should be viewed as suggesting areas warranting direct measurement.

Regretably, while it is well established that a -20-dB criterion is unduly conservative, it is less clear precisely what the most appropriate criterion should be. Thus, the analysis herein has been conducted somewhat informally but with attention to the prevailing physical details and with reference to suitable data when available. Although the results are therefore qualitative rather than clear go/no-go indications based on well defined criteria, this is considered an appropriate reflection of reality wherein the field strengths vary even at the same time from day to day (small) and

37. Naval Ocean Systems Center Letter Report, MAGNAVOX 1104 Omega Monitor Receiver Noise Response Tests, by JE Britt, 3 June 77 (as forwarded by NOSC ltr ser 733-41 of 15 June 77)

38. Bortz, JE, Sr, Gupta, RR, Scull, DC, and Morris, PB, "Omega Signal Coverage Prediction," NAVIGATION, 23, 1, Spring 1976, p 1-9

throughout the day (medium); the noise varies seasonally and diurnally (large); and the noise statistics may vary (unknown). Further, since the scatter of a phase measurement is inversely proportional to the square root of signal-to-noise ratio, it would require 6 dB one way or the other to effect a doubling or halving of accuracy. Thus, one expects adequate reception in signal-to-noise ratios of worse than -20 dB and probably in ratios of -30 dB using well designed receivers reflecting the present technology. To some degree, predictions herein reflect a 30-dB criterion. Possible receiver improvements suggested elsewhere in this report could yield adequate performance in substantially poorer environments.

Propagational repeatability is sufficient to adequately define phase unless there is interference such as between competing modes or from signals arriving over both long and short paths. In case of interference, propagational regularity will also be inadequate. Repeatability ranges from better than 1 centicycle on summer days during occasional quiet periods to worse than 10 centicycles on some paths at night under somewhat disturbed conditions. Five centicycles may be considered typical.

Signal regularity is expected except for interference as noted above. Even in the case of long path interference an interpretable signal may be obtained in some cases as described in the section on expanded signal usage. However, there is no known method for using a single signal which is undergoing severe modal interference. Regions of modal interference are excluded from coverage in the work of Bortz et al.

Prediction biases have been repeatedly addressed in the literature and most recently summarized by Swanson.²⁵ However, as noted in appendix A, there is some question as to how past, present, and future biases may be related owing to the current use of signals with which little experience has been obtained. Speculatively, system biases will eventually become as low or lower than were once obtained with the old developmental network. Previous work with the limited data available from the older network showed long term predictive biases both during the day and at night and at both 10.2 and 13.6 kHz of $3\frac{1}{4}$ μ s on single paths or about 5 s (5μ sec at 10.2 kHz) on lines-of-position using global prediction techniques.¹⁶ Reference 25 shows similar daytime biases on modern data obtained in 1976 to have a median bias of 5 cec and an rms bias of 7.9 cec. Modern data at night have not been analyzed; however, it may be speculated that they are substantially worse than those experienced during the day owing to increased sensitivity to various poorly understood parameters. Additional predictive errors may also be expected during transitions. A force fit procedure used on measurements in the older developmental system indicated prediction biases of about 6 cec on a 24-hour basis.*³⁹

*The referenced paper shows an rss error in measurements reduced using adjusted propagation corrections of 8 cec which, if repeatability is about 5 cec, suggests that the bias component must be on the order of $6 = (8^2 - 5^2)^{\frac{1}{2}}$ cec.

39. Calvo, AB, and Bortz, JE, Dr, "Evaluating the Accuracy of OMEGA Predicted Propagation Corrections," NAVIGATION, 21, 2 summer 1974, p 102-112

Whatever the exact predictive errors, they are sufficiently large to be usually the greatest single system error contribution.

Geometric effects on fix accuracy can be determined from station bearings.²⁸ Figure C1, from reference 28, shows a geometric dilution factor, G , as a function of the angle subtended between the most remote of the three stations being used to determine a fix and parametric in the location of the central station in such a way that $p = 2$ indicates that the central station is on the bisector of the angle formed by the other two; $p = 3$ indicates the central station on the trisector, etc.* G has been normalized to be unity for four-station hyperbolic fixing on the orthogonal intersection of the two baselines. As can be seen, dilution is minor if three stations are available subtending an angle of greater than 180° and the central station is on a more or less central bearing. The dilution factor G reaches a factor of about two at about 150° and increases rapidly for smaller angles subtended.

The foregoing may be synthesized to obtain coverage criteria for adequate accuracy. As the best single approximation, one may take the root-sum-of-squares (rss) combination between measurement induced scatter, day to day repeatability, and prediction bias to obtain the anticipated line-of-position measurement errors which one can then convert to an estimated fix error knowing prevailing geometry and using figure C1. Noise induced error of 10 cec could occur under very poor signal conditions although noise induced scatter is usually negligible. Typical propagational repeatability of 5 cec has already been noted. An allowance of 10 cec for prediction biases is more than needed during the day but may well be less than presently required at night. The rss combination of the foregoing is 15 cec, including 10 cec allowed for measurement noise or 11 cec if measurement noise is negligible. If typical system geometric dilution is on the order of $G = 1.2$ to 1.4 , this indicates typical fixing might often be slightly over 1 mile under fair measurement conditions but could be on the order of 1.5 nmi rms under poor signal conditions at 10.2 kHz. This is sufficiently close to much practical experience to tend to support an rss error budget in the assumed 11-15-cec range at least under circumstances in which prediction biases are not gross. To the degree that signal character and predictability are homogeneous, the tolerable geometric dilution to support nominal fixing accuracy within the 1-2 miles rms (or roughly 2-4 miles at 95% probability) specified for Omega can now easily be computed as $G = 2$. This occurs at a subtended angle of 141° if the third station is on a central bearing or at 154° if the central station is in the central third of the sector formed by bearings to the outer stations. Thus, the present expectation is that specified system accuracy will not now be available in areas where the stations subtend an angle of only 140° or worse.

Future improvements in prediction can reduce the total error budget. The limit for three-station single frequency fixing will obviously be determined by the nominal 5-cec repeatability of lines-of-position and may be computed to be about 0.5 nmi rms under typical geometric dilution. This limit also indicates that dilution factors of five or greater will not support navigation within specified accuracies even in the absence of any prediction or measurement errors. As a practical matter some allowance for prediction

*It should be noted that the dilution factor was derived for the rms fix accuracy and assumes equivalent stability over all propagation paths and no correlation of fluctuations.

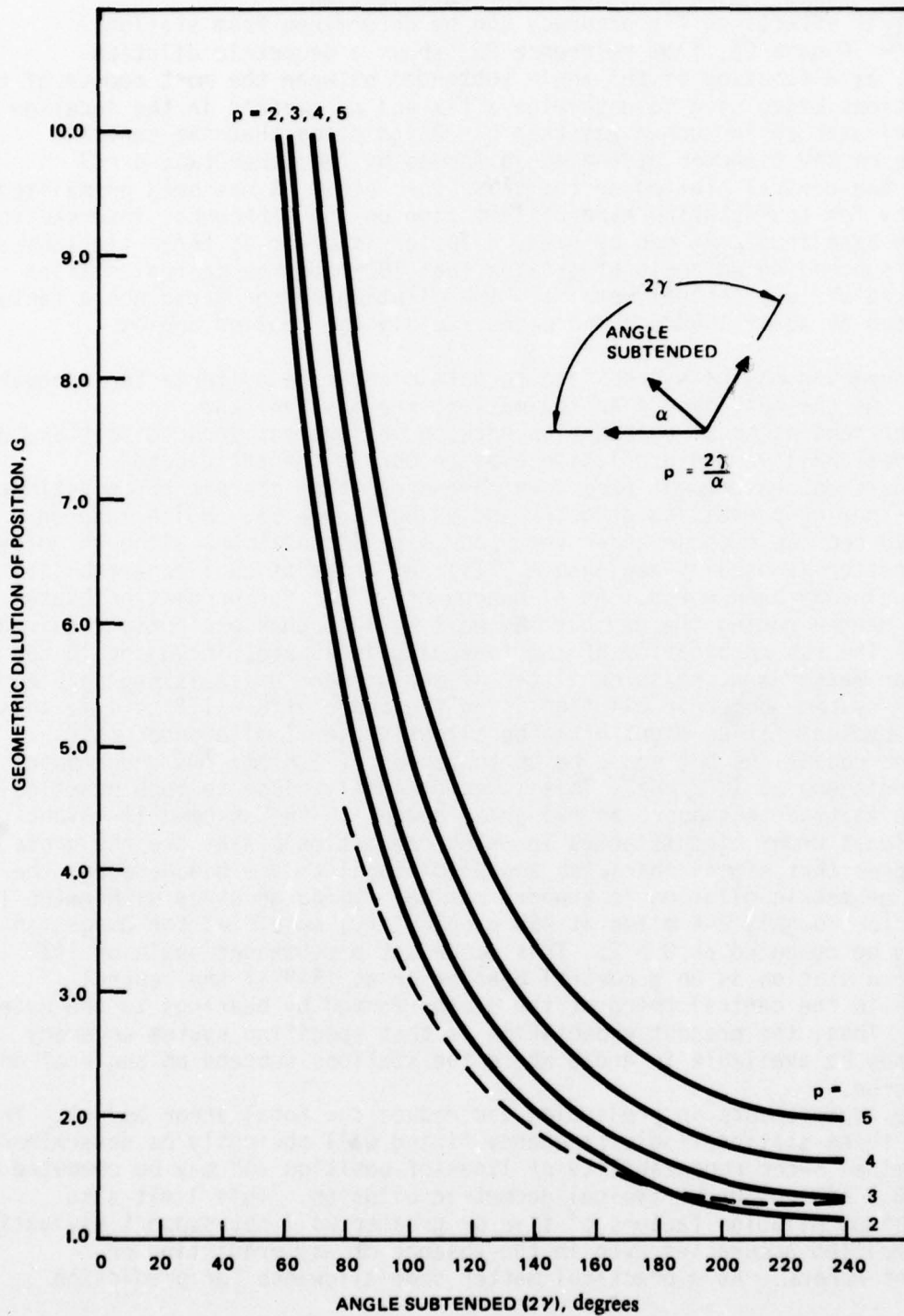


Figure C1. Geometric dilution of precision.

errors must be made; measurement errors may indeed be negligible much of the time. As previously noted, bias errors within the old network were once reduced to 5 cec rms both during the day and at night. It may be speculated that this value may eventually be equalled or exceeded within the fully implemented system after calibration and refinement of prediction theory. In any case it is a useful point of reference as gains from improvement in prediction will come relatively slowly after the prediction biases match the inherent repeatability. The rss combination of matched 5-cec errors is 7 cec. Some additional prediction biases are expected during transitions. An 8-cec rss error was obtained by Calvo and Bortz using measurements from the older developmental system as noted earlier.³⁹ Under typical geometric dilution, such accuracies will support general navigation to an rss fix error of between 0.5 and 1 nmi; that is, yield a 95% probable fix of between 1 and 2 nmi. Perhaps more important, if such line-of-position accuracies can be achieved at some future time, then operation within system specifications can be obtained while tolerating geometric dilution as high as slightly greater than 3. Dilution of a factor of three in three-station hyperbolic fixing occurs for a subtended angle of 110° if the central station is on the bisector of the angle to the remote stations and for 119° if the central station is in the central third of the sector formed between bearings to the outer two stations.

Coverage criteria can be readily developed in terms of bearings to usable stations based on the foregoing. Assuming the central station to be well but not necessarily optimally located allows the criteria to be developed using only the angle subtended to the outer stations as a parameter. This is particularly convenient as the total angle subtended is easily determined for any given set of circumstances. Three regions may be identified (table C1): It is reiterated that the "present" accuracy figures in the foregoing are based on assumptions which may be conservative during the day but are perhaps optimistic at night or during transitions and that regions of gross calibration error must be excluded. However, near term calibration improvements should bring these accuracies or better well within reach. It is also reiterated that the foregoing applies to signals of usual quality which can be measured without significant measurement error. Specific error budgets are a line-of-position accuracy of: 1.00 nmi (12.6 cec at 10.2 kHz) at "present" and 0.63 nmi (8.0 cec at 10.2 kHz) in the future.

Accuracies somewhat better than indicated in the foregoing may apply when multifrequency techniques are used. This will certainly be true in the future when all frequencies are well calibrated. That is, the assessments presented herein apply to the vast majority of present users who operate on the single frequency of 10.2 kHz only.

Assessment

Global Omega navigational coverage can be estimated based on signal coverage deduced by Bortz, Gupta, Morris, and Scull³⁸ and the foregoing

Table C1

Geometric bearing coverage criteria

Total Angle Subtended (Deg)	Fix Accuracy
>150	Presently expected to be better than 2 nmi rms (4 mi at 95% probability). Dilution is minor at 180 but is tolerable if increasingly unwelcome as 150 is approached. Future accuracy in this region may become better than 2½ nmi at 95% probability.
115-150	Present accuracy is expected to be outside system specification of 1-2 nmi rms (2-4 miles at 95% probability) and may degrade to about 3 nmi (6 mi at 95% probability). However, with effort in improving system calibration, it is speculated that system specifications may eventually be met. Accuracy under these circumstances will always be mentionably worse than typically obtained.
<115	Future accuracy is expected to be outside the 1-2-nmi rms (2-4 mile 95% probable) system specification. Present accuracy may be grossly outside this range. By definition, a coverage hole is said to exist in this region. Heroic calibration effort may be able to reduce this minimum angle somewhat but gains are expected to be hard won and expensive. Further, special and expensive user techniques might be required to fully exploit detailed calibration data.

geometric accuracy criteria.* As previously noted the signal coverage work is conservative but has been adopted because of its general availability. The analysis has been conducted as a perturbation on the older work with attention to physical details and as such the following description is laborious. The effort has been divided into consideration of day and night conditions separately. Each coverage region of station sets as described by Bortz et al has been manually examined systematically perturbing their signal coverage criteria and applying the geometric criteria derived herein. Descriptions of potential problems suggested in the original work or as developed through application of geometric criteria are given in the following sections.

Day

At local noon limited coverage is indicated near various stations plus seven additional regions: Tahiti, Antarctica, Southeast Brazil, in the Atlantic off Southeastern Greenland, near the tip of India, the North Sea to Germany, and a rather extensive area from Northern Canada throughout the Central United States and into Mexico.

Regions around a number of stations are shown by Bortz et al as covered during the day by only two stations: Norway (by B and H), North Dakota (C and H), La Reunion (B and F), Argentina (C and H), Australia (E and H), and Japan (A and E). As the calculations are conservative where limits are imposed by signal-to-noise ratio and since the stations are sited mutually far apart, it is not surprising that application of somewhat more realistic criteria can add additional coverage near stations. By inspection it is clear at least two more stations than indicated will provide coverage near stations E, F, G, and H. Data are not yet available near station G but fragmentary data from E, F, and G now available indicate reception of at least one more station than indicated by Bortz et al. This is especially welcome near Argentina, which was indicated as being served by only C and H, which come from nearly the same direction. The region near Norway will be covered by at least La Reunion in addition to those indicated and also may be covered by Hawaii. Data indicate La Reunion signals are received and also those from North Dakota. Hawaii presently is expected to serve the Omega Norway station itself and is observed to provide good signals. As discussed elsewhere, Norway or indeed any station can serve an immediate region around itself until the region of skywave--groundwave interference occurs. The problem is a very small region

*This two-step evaluation is clearly not as desirable as a single integrated assessment. An approach of some elegance was developed by Kourilsky for assessment of Loran coverage⁴⁰ and was subsequently applied to Omega (Stoltz, J, personal communication, May 1973). Similar work has also been recently published by Thompson.⁴¹ These approaches, while formally preferable, were implemented with propagational assessment routines much less realistic than used by Bortz et al.

40. Teledyne Systems Company Report 676, Loran Performance Analysis, by G Kourilsky, April 1973

41. Thompson, AD, "Omega System Performance Predictions," NAVIGATION, 24, 4 winter 1977-78, p 304-311

at the western extreme of the Norway near field where Norway cannot be used and Hawaii may be shielded by propagation over the Greenland icecap. Hawaii is known to be useful in Oslo, for which the signal must pass through the region of interest. Thus, it may be speculated that Hawaii as well as La Reunion will be useful through the Norway near field. Coverage may, however, rest on relatively noisy signals in a very small region near $67^{\circ}\text{N } 20^{\circ}\text{E}$. The only station near field region where there seems to be a significant coverage problem during the day is around North Dakota. As will be discussed later, this entire region even outside much of the near field is an area of coverage weakness. The only additional stations which could be of much value in the region are Norway and Liberia. Norway is known to be receivable at the station but only weakly. There is a chance that Liberia might be received but again reception would be very weak. Australia may not be received but would be geometrically useless in any case. Considering that the only navigators in the region will be airborne, it is quite unlikely that navigation will be possible in the skywave--groundwave interference region around North Dakota.

Coverage limits in the antarctic may not materialize in practice as they may be related to the details of the coverage computation by Bortz et al, who show no signals whatsoever at the south pole and yet show three- or four-station coverage in most of the surrounding waters. Both signals and noise will be severely attenuated propagating over the antarctic ice but the signal-to-noise ratio should remain relatively constant as there are practically no local noise producing thunderstorms in the region. However, obtaining adequately quiet antenna installations on aircraft will be especially critical here. A region of possibly limited coverage may be the Weddell Sea, within which regions of one- or two-station coverage are now shown. Noise from the central Amazon and Central Africa thunderstorm centers can propagate to the Weddell sea over low attenuation paths whereas the geometrically desirable signal from Australia must pass over the antarctic continent. If the Australian signal is not usable, then navigation will depend on useful signals from Argentina, Liberia, La Reunion, and/or Hawaii. Considering that the coverage maps are somewhat conservative, signals from all four stations should be available throughout much of the Weddell Sea. However, in the extreme southern portions toward Gould and Halley Bays, the Hawaii signal will be severely attenuated by propagation over the Antarctic Peninsula and/or Ellsworth Land and/or Marie Byrd Land while the La Reunion signal is severely attenuated by propagation over Queen Maud Land. If La Reunion is unusable and three-station fixing is necessary using Hawaii, Argentina, and Liberia, the angle subtended will be a marginally acceptable 142° , whereas if Hawaii cannot be received but La Reunion can be used, the angle subtended by Argentina, Liberia, and La Reunion will be 129° , which also is marginally acceptable. If only Liberia and Argentina can be received, there would be only a range-range fixing capability with a crossing angle of 60° . It will probably require specific measurements to determine whether or not there is a coverage problem near Gould Bay. If there is, the region must be small and is in any case a region of practically no commercial or military interest, although both Argentina and the United Kingdom maintain scientific stations in the area. A similar area may exist near the antarctic coast south of Australia. Here three-station coverage is indicated, but coverage is by La Reunion, Australia, and Japan which subtend an angle of only 118° , and the geometric dilution factor is 3.4.

The second major region where there may be a coverage limitation is Southeastern Brazil. Southeastern Brazil is shown on the Bortz et al maps as being covered by only two stations during the day. It is believed that the conservatism of the predictions is such that signals from Hawaii and North Dakota actually can be used in the area and hence there is no limitation in this region.

Near Tahiti three-station coverage is shown by Hawaii, Australia, and Japan which subtend an angle of only 112° . Thus, the indicated stations provide poor coverage. However, conservatism in the calculations indicates that most likely North Dakota, La Reunion, and Argentina will also be useful.

A third region of possibly limited coverage is Southeastern Greenland and adjacent waters. This is shown as being covered by only two stations. Conservatism in the predictions of either North Dakota or Japan coverage may mitigate or eliminate the indicated area of weak coverage. However, there may be a relatively small area of weak or two-station coverage in the Denmark Strait near the Greenland coast at the Arctic Circle. The circumstances here are similar to those already described in the Weddell Sea; namely, relatively low attenuation paths from thunderstorm centers in the Amazon and central Africa whereas two desirable signals are attenuated by propagation over the ice cap. Direct measurements will be necessary to assess coverage and perhaps such measurements can be made in conjunction with the North Atlantic Omega validation. Although the region in question is small, it is of both commercial and military importance. Air traffic routes between Europe and North America pass through the region which is also a significant fishery.

There is a region off the tip of India from the Gulf of Mannar to the Maldive Islands where coverage is indicated by only Liberia and La Reunion. In practice at least Norway and Argentina and possibly Japan also should be available although the area is on the baseline extension from Argentina to La Reunion. If Norway and Argentina are also available but Japan is not, the stations subtend a marginally acceptable angle of 122° and serious geometric dilution will be present; errors nearly twice nominal will occur. Present 24-hour error budgets indicate a fix accuracy near 2.5 nmi may be obtained by using the indicated stations. The area is one of major maritime importance, lying on the petroleum routes from the Mideast to the Orient and Japan and trade routes between Europe and the Orient and between Europe and northern Australia. Good geometry might be available if Australia could be used, but this is doubtful, as the signal will be weak and may exhibit long path interference. Japan, however, will probably provide a useful signal presenting good geometry.

The sixth major area of coverage weakness indicated by Bortz et al for daytime conditions is an area extending from the North Sea to Germany where only two-station coverage is indicated by Norway and Liberia. Conservatism in the calculations suggests, however, that up to four additional stations may be received; viz, North Dakota, La Reunion, Argentina, and Japan. Of these, either North Dakota or La Reunion together with the well received stations would present excellent geometry in the area whereas Japan reaches the North Sea over Norway and may be useful for redundancy but not accurate fixing. The bearing to Argentina is somewhat similar to that of Liberia so that degraded fixing could be supported if the signal were well received. The four additional stations will all, however, be received rather weakly. The circumstance with North Dakota is that the signal must pass over the southern tip of Greenland and will thus be very highly attenuated. In particular, adequate reception of North Dakota at the southern edge of the region is likely, but reception will degrade in the central and northern portions. Considering conservatism in the calculation, La Reunion should certainly be easily used in the eastern portion of the region, but the signal may become somewhat noisy in the North Sea. Preliminary reduction of recent measurements in Germany in the winter and spring by Mr Rider confirms strong 24-hour reception of Norway and Liberia, fair reception of La Reunion and Argentina, and also intermittent reception of North Dakota. Thus, on the basis of the analysis conducted here and available measurements, one would expect weak but

adequate coverage in the area. However, recent full wave computations by Morris and Tolstoy using an improved noise model suggest there may be some difficulty in the North Sea even using a signal-to-noise criterion of -30 dB. Thus, on the basis of the analysis conducted here and available measurements one would expect weak but adequate coverage in the area.

The seventh major area of coverage weakness during the day is by far the most extensive and the most important. It extends from Northern Canada through the Central United States and into Mexico. Here the map of Bortz et al shows three-station coverage by Hawaii, North Dakota, and Japan throughout most of the area except in the immediate vicinity of North Dakota, where only two-station coverage is indicated. The problem is geometric coverage limitation throughout much of the region. Table C2 shows station bearings and angles subtended for several sites selected within the region. As can be seen, geometry will support position fixing to usual Omega standards in the extended vicinity of Edmonton (Western Canada and the Pacific Northwest). Geometric dilution of precision will cause serious deterioration of fixing accuracy obtained by using the indicated signals at all other sites. At San Diego the dilution parameter is about 2-1/2; that is, twice nominal.

Dilution is similar but slightly less at Ellesmere Island and South Hampton Island because the third station is more centrally located, even though the angles subtended are lower. Dilution reaches almost four in the Davis Strait and is about six to seven in the region from Mexico City to Galveston and Houston. That is, if nominal Omega accuracy is 1-2 miles, then the system would have a 5-10-mile accuracy in these regions. This is sufficiently far from the system specification as to be considered only a coverage hole. Fixing is essentially impossible near St Louis, which is on the Japan-North Dakota baseline extension. Not only are coverage holes forecast, they occur over wide regions of great civil and military interest. In particular, the combined annual shipping tonnage for the Texas coast and New Orleans is 382 million tons. Some of the North American coverage deficiencies are not likely to be as serious as forecast from coverage maps by

Table C2. Primary coverage indicated for North America.

Name	Site Location		Station Bearings (deg)			Angle Subtended (deg)	Approx Present rms fix Accuracy (nmi) 24 ^h Day
	Latitude	Longitude	Hawaii C	N Dakota D	Japan H		
Edmonton	54	113	244	123	311	188	1.5
San Diego	32	117	264	40	311	136	2.4
Ellesmere Island	80	80	262	203	333	130	2.3
South Hampton Island	64	85	264	209	332	123	2.5
Davis Strait	60	70	279	243	344	101	3.9
Mexico City	19	99	283	1	319	78	5.6
Galveston-Houston	29	94	278	350	324	72	7.2
St Louis	37	90	275	329	328	54	180.1

Bortz et al. The conservatism of the coverage calculations and operational experience receiving Norway in the Davis Strait and elsewhere in Northeastern Canada and in the Northern United States indicate Norway will be usable at least to surface craft in the Davis Strait or near Ellesmere or South Hampton Island. Whether or not Norway will be usable to aircraft on the important routes from Europe to the Western United States will depend on the quality of the individual installations. There is also a good possibility that Liberia will be received in the Davis Strait and Baffin Island areas. Another mitigation from the bleak picture of North American coverage presented thus far is conservatism in the forecast coverage of Australia. This is shown to end just off the west coast whereas in practice one would expect Australia to be usable in the west. Australia is geometrically favored on the California and Mexican coasts.

Near San Diego the angle subtended will improve to 162° , which ordinarily would be associated with tolerable accuracy but which may be somewhat marginal considering the still unknown quality of the remote Australian signals in the area. Even if Australia is usable in Mexico City and the Gulf, the geometric dilution still will be serious with the angles subtended being barely over 100° near Galveston. It is questionable whether Australia will be usable near St Louis, but the geometry is unacceptable in any case. Thus, even making allowances for the conservatism of Bortz et al, a large region of daytime coverage deficiency is expected in central North America.

Night

Bortz et al show only one area of two-station coverage at night. This is in central Antarctica and is believed due to the details of the coverage calculation as noted for the daytime case and the same performance is expected. Several areas of three- or four-station coverage are noted near the magnetic equator. As the signals usefully received near the equator at night are those received from the west, these areas are especially likely to be associated with high geometric dilution.

An area off the tip of India passes from three-station coverage in the Arabian Sea to four-station coverage in the Bay of Bengal. The problem is that all usable signals are from the west. Geometry is poor from the Arabian to the Andaman Seas but is worse near the Gulf of Mannar, with subtended angles ranging down to 122° .

Three-station coverage is indicated for the Straits of Malacca. The stations providing coverage are Norway, Liberia, and La Reunion, which subtend only 93° , which presently supports fixing to an rms accuracy of only 4.4 nmi on a 24-hour basis. Thus for all practical purposes a coverage hole is predicted for one of the greatest maritime confluences on earth. It is of course possible that the computations of Bortz et al are unduly pessimistic. However, it is not clear in this instance what stations might be expected to provide coverage which are not now doing so. Hawaii, Australia, and Japan will presumably all be limited by self-interference in ways which are well understood. Argentina is shadowed by the Antarctic ice cap. This leaves only North Dakota for consideration. North Dakota is 14 megametres distant over a somewhat westbound land path; the long path is mostly over sea. Thus, there is a possibility of long path--short path self-interference at least at some times of the year. While direct monitoring at Singapore and analysis of the Western Pacific validation data will supply more precise guidance on signals in this area, the situation is not encouraging.

Proceeding eastward the next area of weak coverage is Tahiti, where four stations are indicated as usable in the area west of Tahiti and three stations usable to the east. The three stations indicated as usable through the area are the same as will be available during the day; viz, Hawaii, Australia, and Japan. As already noted these subtend an angle of only 112° and therefore will not support accurate navigation. To the west of Tahiti, La Reunion will also be usable, thus improving the angle subtended to 134° , which will only support appreciably degraded navigation. Conservatism in the calculations of Bortz et al is such that Norway also might be usable to the west of Tahiti, although the signal offers little geometric advantage over that from Hawaii. To the east of Tahiti signals from La Reunion and Norway will be shadowed by Antarctica and Greenland respectively. Signals from Liberia, North Dakota, and Argentina are likely to be useless because of self-interference, although direct monitoring is warranted. In summary, an area of coverage weakness is expected.

The same three-station geometrically degraded fixing is expected on the antarctic coast below Australia at night that was found during the day, although accuracy may be somewhat better if Liberia can be received.

The most extensive area of coverage weakness at night will be in North America. Here the calculations of Bortz et al show Argentina usable over much of North America when in fact it will be usable only in New England and eastern Canada. This reduces coverage in the north central United States, where North Dakota cannot be used, to three stations; viz, Hawaii, Australia, and Japan. Unfortunately, these subtend a crossing angle of only 78° at St Louis and thus will not support accurate navigation. Hence, a coverage hole is predicted at night in the same location one has already been found to exist during the day. Although the geometry is so poor as to render simple availability of "usable" signals a somewhat academic consideration, it is perhaps notable that there may well not be even degenerate three-station coverage available throughout the 24-hour day. North Dakota covers St Louis during the day whereas Australia provides coverage at night. Shortly after sunset, the short path to North Dakota will be dark and unusable whereas most of the 15-megametre path to Australia will be illuminated so signals will be too weak to be useful. Coverage does not improve adequately in the more extended North American region even where North Dakota is also useful at night. Normal coverage is provided in the Pacific Northwest, where the geometry is good. However, geometry causes accuracy to deteriorate down the Pacific coast, through Mexico and into the Gulf of Mexico. Angles subtended range from 162° at San Diego through 125° at Mexico City to 108° in the Galveston--Houston area. Data measured in the Gulf of Mexico also suggest limited coverage.⁴² Thus, there will be unacceptable coverage in the Gulf both during the day and at night. Predicted coverage at night from San Diego to Mexico City presents more favorable geometry than found during the day but the geometry still will be worse than nominal. Geometric effects at Mexico City will dilute accuracy to half nominal, and, although geometric effects alone will not be especially severe in San Diego, it must be remembered that the minimum path length from Australia to North America is over 12 megametres and the associated navigational capability of the Australian signal may be somewhat less than usual. Unfortunately, most of the signals ruled unusable

42. Naval Ocean Systems Center Technical Note 187, Differential Omega Evaluation March - April 1977: Preliminary Report, by ER Swanson and J Davey, 27 June 1977

in North America by Bortz et al are indeed expected to be unusable because of well understood self-interference or attenuation (the only remotely inviting prospect would be use of La Reunion via some type of long path/short path discretion and this would appear potentially useful only in the west). Thus, an extensive coverage hole at night must be expected.

Range-Range Coverage

Radial range-range fixing with two stations is possible at all sites by using special equipment and assuming the local clock is properly set. Absolute timing to within a few microseconds is required. If necessary conditions are satisfied, accuracy will tend to be slightly worse than nominal but nowhere grossly degraded. It can be shown that the relative geometric dilution factor for range-range fixing is $2/\sin x$ where x is the angle subtended by the stations and relative dilution has been normalized to unity for orthogonal hyperbolic lines-of-position as in reference.²⁸ Root-mean-square fix accuracy varying inversely with the sine of the line-of-position crossing angle is common to both radial and hyperbolic fixing. The radical two arises from the combination of improved measurement stability due to measurement over a single path but a doubling in the associated positional significance of the measurement errors. The worst angle subtended in the investigation was 54° , corresponding to a relative dilution factor of 1.7, which is quite acceptable. The problem is the engineering and operational difficulties performing range-range navigation as described elsewhere.

Outages

It also must be stated that the foregoing coverage analysis has assumed all stations are operational. Signal redundancy is poor or nonexistent in many areas of weak coverage which can be instantly turned into coverage holes by incidental station outages.

Coverage Summary

The foregoing has been a specific discussion of areas of suspected Omega coverage limitations by diurnal period. Because of the approach used, not all areas considered are expected to be associated with any navigational difficulty. A summary of areas with anticipated accuracy limitations arranged by operational area of interest is contained in the text of this report.

It is educational to classify here the various areas of weak coverage according to general conceptual limitations; viz, (1) attenuation of signals over great range, (2) ice shield effects, and (3) signal structural limitations through self-interference, particularly by modal interference on signals near the equator.

It is in the nature of a global system to locate the stations mutually far apart. Thus, coverage at each station and in its near field interference region must rest on signals all of which must propagate over long paths.* Here the geometry would be expected to be excellent but the signals relatively weak. Although average ranges are of limited utility because of propagational anisotropy, it may be noted that the two-station coverage areas shown by Bortz et al near many of the stations reflect this generalization.

For this to be a real limitation, however, would imply a gross underpowering of the system. That is, a general pervasive design error. No such error occurred. Final station design power was determined after much experience with Omega signals including reception of Forestport, New York, in Hawaii, Africa, and South America despite a maximum radiated power of 165 watts.

The North American coverage hole is primarily associated with shadowing of Norway by Greenland, although, were it not for equatorial effects, Liberia could be more useful. Ice shielding effects were also responsible for the minor limitations possible near the coasts of Antarctica and Greenland.

Numerous minor areas of coverage weakness occur around the equator at night as a result of signal structural limitations near the equator.

Thus, most anticipated coverage limitations can be associated with ice cap shielding effects or with signal structural limitations particularly near the equator but not with general low signal level through normal attenuation of signals propagated to great distances.

A number of areas of anticipated coverage weakness have been identified. All warrant further investigation by actual monitoring.

The most significant area is, however, clearly central North America. This is significant in terms of severity of degradation, commercial importance, geographic size, and also the 24-hour duration of the weakness. To eliminate the North American coverage hole, it will be necessary to somehow arrange for a signal to be available from some direction other than the west. Increasing power radiated from Norway would help as would increased use of the Norwegian 13.6-kHz radiation, although it is unlikely any increase within reason would make any appreciable difference throughout much of the hole. Substantially more sensitive receivers would also help receive Norwegian signals and possibly those from Liberia and Argentina during the day, as would additional power from those stations. 24-hour coverage improvement would seem to necessitate addition of a ninth station or relocation of one of the existing stations.

*The distance from each Omega station to its three nearest neighbors will average 7940 km ranging from a low average of 6906 km at Norway to a high of 9529 km at Argentina. Individual paths to neighboring stations range from a low of 5992 km between Hawaii and North Dakota to a high of 10 432 km between North Dakota and Argentina. (The average baseline in the system considering all possible combinations will be 11 030 km, with the most nearly antipodal stations being Argentina and Japan, which are 18 441 km apart.)

Appendix D: Transmitter Power Increase

A possible way to increase the coverage in a given noise environment from a radio source is to increase the radiated power from the source. Such an increase is attractive from a systems point of view because it increases the reliability and utility of the signals received at a given distance from the source. It must be kept in mind, however, that the Omega Navigation System was optimized slowly over its developmental period to utilize the present eight stations incorporating vlf transmitters of moderate power with major components conservatively rated and of known characteristics and availability. The antenna systems were configured so as to use the structures and insulators presently available at supposedly well defined limits of voltage so as to provide simultaneously the desired radiated power and bandwidth necessary for adequate system performance. The thrust of this section is to show: (1) that while in some cases particular stations may be capable of handling moderate increases in power, in general this is not true and is in any case difficult mainly because the optimization process for the present power and bandwidth is a thing of the past; and (2) that reoptimization not only may not be possible but may really be a word substituting for one more relevant, namely, "redesign."

The communicator/navigator generally hands his problem to the communications systems engineer in the form of a desired reliability (availability in some noise environment) in a coverage area for some signal format yielding a specified information rate or from which a navigation system may develop a given responsiveness. These requirements filter down to the antenna system designer as a minimum radiated power (P_r) at some frequency (f) or range thereof in some specified minimum bandwidth (B_{as}). Present-day technology supplies an upper limit on operating voltage, (V_i), and previous generalized studies give a range of desirable efficiency, η_{as} (and hence input power P_{as}), functionally related to radiated power level so that costs will probably be near a minimum. For the present Omega system, the respective values were established as $P_r \geq 10$ kW, $10.2 \leq f \leq 13.6$ kHz, $B_{as} \geq 10$ Hz @ 10.2 kHz, $V_i \leq 250$ kV, $P_{as} \leq 150$ kW; $\eta_{as} \geq 6.7\%$.

At vlf, where transmitting antennas are almost unavoidably electrically short, these six variables and four others are related by the four equations given below (applicable in general to any simple tuned circuit of lumped parameters and specifically also to the electrically short antenna to the extent it can be considered a lumped circuit):

$$P_r = 6.95 \times 10^{-13} C_0^2 h_e^2 V_t^2 f^4 \equiv I_a^2 R_r$$

$$B_{as} = 1.108 \times 10^{-13} C_0 h_e^2 \eta_{as}^{-1} f^4 \equiv f/Q_{as}$$

$$V_i = I_a (2\pi f C_0)^{-1}, \text{ MKSQ units}$$

$$P_{as} = P_r / \eta_{as}$$

The remaining four quantities C_0 (electrostatic capacity), f_0 (self-resonant frequency), V_i (antenna insulator voltage), and h_e (effective height) are thus determined if the original six are fixed. Usually, this is not the case, but certain ones are allowed to take on values below well defined upper limits, so that cost and performance trade comparisons can be carried out for several candidate sites as well as for several configurations in the final selection for a single site. A significant aspect of the trade to minimize cost is the balancing of various possibilities for tuning helix resistance R_h against ground system resistance R_g , which are the two major loss components in antenna system loss resistance R_{as} , always in regard to the condition of required antenna system efficiency. In performance trading, one quickly finds that specification of both power and bandwidth at more than one frequency in the operating band overdetermines the system. Thus, one may specify only the minimum acceptable value of these performance parameters for each one at whichever frequency it is hardest to attain; eg, for $P_r = 10$ kW at 10.2 kHz, and $B_{as} = 45$ Hz (under an earlier concept) at 13.6, but not both at both frequencies. V_i is the voltage on the top load insulators, and it must be corona-free. It is related to base voltage V_b by:

$$V_i = V_b / [1 - (f/f_0)^2]$$

Radiation resistance can be alternately expressed as

$$R_r = 160\pi^2 (h_e/\lambda)^2 \quad \lambda = \text{Wavelength at freq } f;$$

and efficiency is also

$$\eta_{as} = R_r/R_{as},$$

where R_{as} is the antenna system resistance, including radiation resistance, tuning system losses, coupled-in losses, and ground system losses.

The site environment is significant to performance determination in two respects: geometrical, relating to C_0 , h_e (that is, radiator size) and electrical, relating to the nature of the impedance plane, losses in which must be controlled by design of some ground system so as to simultaneously permit attainment of P_r and B_{as} with a stated restriction on allowable transmitter power, at present 150 kW. Since the cost optimization process must consider both fixed (installed) and operating (capitalized over some stated period of years) costs, some latitude is offered in system pricing to charge against site modification for efficiency (such as elevating spans on towers) versus more transmitter and prime power.

The power, bandwidth, voltage, and efficiency figure ranges given above imply, through the fundamental equations, that there were required sites yielding effective heights for Omega applications, from 100 to 200 metres and capacity from 0.050 to 0.030 μ F; the inverse relationship of capacity and inductance usually results in f_0 between 24 and 40 kHz, so that V_b is within 10% of V_i at the low end of the band. Reactances to tune were then such as to require helix Q's between 1500 and 3000 in order to hold R_h to values such that the residual ground system loss R_g could be obtained with reasonable installation, considering that soil conductivity usually turned out to be the order of 1 to 10 millimhos per metre.

Without going into a great amount of detail it can be seen that antenna system efficiency is not really independent of antenna configuration when the

Loss budget computation for the ground system is displayed in the form

$$R_g = (R_H + R_E)_{\text{inside}} + (R_H + R_E)_{\text{outside}} + R_{\text{wires}} + R_{\text{termination}}$$

in which

$$R_H + R_E = \text{Re} (1/I_a^2) \int \left[\eta(H_0)^2 + \frac{h\omega}{\sigma}^2 \epsilon_0^2 E_2^2 \right] dA \quad \begin{array}{l} \text{inside: } a_i \text{ to } a_o \\ \text{outside: } a_o \text{ to } 1/\beta_0, \beta_0 = \frac{2\pi}{\lambda} \end{array}$$

This representation shows the critical role that field distributions and antenna geometry play in making performance predictions having to do with loss budget.

For the Omega antennas it turned out that in some cases extremely high soil conductivity at the site was not advantageous if there was a large seasonal decrease in effective conductivity (eg, snow) for which provision had to be made in ground system design to meet the radiated power requirement because during the high conductivity portion of the year bandwidth could not be met without artificially supplying the extra loss. Bandwidth at 10.2 kHz for some installations became critical so as to insure that switching transients in the tuning system would be controlled to a level small enough not to destroy the variometer relays in stepping from one radiated frequency to the next during the keying format.

During the optimization procedures of 10 years ago table D1 was constructed to show what would be possible or likely for various potential sites, mainly for valley-spanning types of radiators. The principal conclusion to be drawn from it was that--at those locations restricting the physical size of the antenna and hence its intrinsic radiating properties that are geometrically related, rather than efficiency related--the 150-kW power limitation made simultaneous attainment of the objectives of 10 kW radiated at 10.2 kHz and (at that time design goal) 45-Hz bandwidth at 13.6 kHz very difficult and in some cases impossible. Later the bandwidth requirement at 13.6 kHz was dropped, but another bandwidth requirement of 10 Hz at 10.2 kHz remained. This was because of a limit on the tuning variometer relays to withstand the arcing from breaking residual ringing current in the antenna circuit unless it was restricted to a level below that defined by 10-Hz bandwidth, if the switching was to take place in the 100-ms interval between successive transmissions on each of the Omega frequencies. This 10-Hz bandwidth proved almost equally difficult to obtain with 10 kW radiated under a transmitter limit of 150 kW for the smaller sites, and indeed at some of the existing stations has not been attained to this day.

Table D2 shows the characteristics of the Omega stations as constructed to the extent that present information is available. Four of the stations have been measured in their final configuration; one of the remainder is a carry-over interim station, and the others are either design predictions or estimates based on similarity to existing measured stations. It can be seen that all fit rather well in the midrange of sizes indicated in table D1. In

Table D1.

Allowable ranges of efficiency and major losses for various C₀ and H_e and resulting performance capability limits for

P_{as} = 150 kW.

CONFIGURATION	1	2-A	2-B	3-A	3-B
Parameter	140	140	200	200	200
he metres	100	140	200	200	200
C ₀ μF	0.086/0.05*	0.045/0.036*	0.065	0.033	0.045
f kHz	10	14	10	14	10
R _r ohms	0.0174	0.034	0.068	0.136	0.136
η _{as} %	6.7	8.7	7.0	10.0-13.0	7.0-13.0
R _{as} ohms	0.26	0.39	0.58	0.68-0.45	0.97-0.53
P _r kW	10	13	10.5	15.0-19.5	10.5-19.5
B _{as} Hz	14	42	14	55-43	21-14.5
V _t kV	140/240*	81/139	196/245*	112/140	162-195
Q _h	≥ 2000	1500-2000	1000-2000	1500-2000	1000-2000

Omega antennas listed below correspond approximately to the following configurations:

Smaller than 1

- 1
 - 2-A
 - 2-A to 2-B
 - 3-A
 - 3-B
 - 2-A
 - 2-B +
 - 3-A
 - 3-A -
 - 3-A +
 - 3-B
- Trinidad, 6 spans, no towers
 Trinidad, 8 spans, no towers**
 Trinidad, 8 spans, 300' towers**
 3-Span Lake Pearson**
 2-Span Forth 3, no towers**
 3-Span Norway**
 6-Span Haiku
 2-Span Haiku**
 2-Span Norway
 La Moure, Argentina
 Liberia, La Reunion, Australia
 Japan

Capacity and voltage marked (*) are situations requiring more than 150-kW P_{as}. Those unmarked are transmitter limited at 10 kHz. If P_{as} is dropped to 100 kW, then indicated power P_r drops to 67% listed values and voltages to 81%. If P_{as} is raised to 225 kW then indicated power P_r rises to 150% listed values and voltages to 123%.

**Possible configurations studied but not built.

Table D2

Existing station characteristics.

STATION	Norway	North Dakota	Liberia*	Argentina	Hawaii**	Japan	Trinidad
h_e metres	205 217	184 185	179 184	192 197	142 142	215 215	96 96
C_0 μ F	0.036 --	0.0267--	0.037 --	0.0267 --	0.044 --	0.032 --	0.038 --
f kHz	10.2 13.6	10.2 13.6	10.2 13.6	10.2 13.6	10.2 13.6	10.2 13.6	10.2 13.6
R_r ohms	0.077 0.152	0.062 0.111	0.055 0.109	0.067 0.126	0.037 0.065	0.084 0.149	0.0168 0.030
η_{as} %	5.9 10.0	S13.7 23.0 W(11.3)(12.3)	D 6.1 12.2 R(5.3) (11.1)	11.4 21.4	6.0 9.0	12 20	0.93 1.78
P_{as} kW	150 143	73 44 (89) (52)	150 82.2 (150) (89.8)	88 47	150 150	88 50	70 67 (100) (100)
P_r kW	8.9 14.3	10.0 10.0 (10.0) (10.0)	8.6 9.9 (7.5) (9.9)	10 10	8.9 13.5	10 10	0.67 1.2 (1.00) (1.8)
B_{as} Hz	31 61	1.5 14.3 (2.1) (17.2)	22.2 38.4 (25.5)(42.2)	10.3 18.3	17.7 36.9	14.6 27.7	43 67
I_a A	341 307	402 300	396 302 (370)	386 282	491 453	345 259	200 200 (240) (240)
V_b kV	144 100	222 125	160 80 (153)	217 116	165 109	160 110	80 57 (96) (68)

*La Reunion and Australia are similar

**From final engineering design

Scaled from Argentina by 1400/1200

S = Summer D = Dry

W = Winter R = Rainy (Wet)

some cases, however, design goals are not quite met, and some further adjustment in the characteristics of the existing radiator may be desirable. It is worth remarking in this connection that in two cases this further adjustment may not be economically feasible.

With the above discussion as a background, the possible increase of radiated power can now be considered. A 3-dB increase in power has been mentioned as a possibility, perhaps mainly because the present Omega stations are equipped with two identical transmitters only one of which is ordinarily on line at any one time. Table D3 has been constructed to show how this increase in delivered power can be used. In constructing this table it has been assumed that a 225-kV limit on the antenna system may not be exceeded because of the existing insulators, replacement of which would be a major redesign undertaking in which use would have to be made of materials whose high voltage characteristics under exposed weather conditions are presently not well defined. It should be remarked here, and it will be considered in detail later on, that at some of the stations the 225-kV supposed limit is fictitious under adverse weather conditions. Beyond this, however, it turns out that even at those few stations where the radiator is not the limiting structure the details of the helix house circuitry are already limiting, in such a way as to pose the most serious aspect of the problem in upgrading the radiated power capability of the stations. It is noted further that in this table where direct use of the increased power cannot be made to increase the radiated power beyond the insulator limit when this occurs first (ie, increase antenna current), the extra power is shown diverted into an increased bandwidth capability, if that seems to be a good use of it, up to the point at which the transmitter becomes limiting also at 300 kW delivered to the antenna system.

It is noteworthy that none of the existing base-insulated stations can make use of the increased transmitter power for much increase in radiated power because the limit on the insulator voltages has pretty much been reached. The figures for Japan indicate otherwise at first glance until it is recalled that the station must drastically reduce input current to the antenna during rainy conditions because of the flashover of the insulators. Thus, the insulated tower stations can mainly use increased transmitter power to permit increased bandwidth, which at Argentina and North Dakota would be desirable to decrease the residual current that the relays presently must break during the keying cycle. Since Japan has a greater intrinsic bandwidth because of its greater size, this is not so necessary. In any case, the radiation system for these three stations is a fundamentally limiting factor which has already been reached, especially during bad weather.

Hawaii and Liberia are interesting borderline cases in which the system becomes transmitter limited and insulator limited at nearly the same power level for the increased transmitter. Neither is a base-insulated tower, but one is a rather small valley span, and the other is a grounded tower. In both, troubles with arcing at the tower base and in the guy insulators are avoided, since they are absent. The voltage limit is imposed simultaneously by the exit bushing rating and by the insulators at the top load span ends, at 10.2 kHz.

Norway and Trinidad are both relatively inefficient valley spans, one being much larger than the other, and neither is voltage limited even with 300-kW input, although Bratland Norway may have problems handling the increased power and voltage in the transmission line from the transmitter to the helix house. At Trinidad there is a serious limitation in the current rating of the helix conductor, which presently is limited to about 300

Table D3. Possible upgrade by doubling transmitter power rating
from 150 to 300 kW.

STATION	Norway	North Dakota	Liberia	Argentina	Hawaii	Japan	Trinidad
f	10.2 13.6	10.2 13.6	10.2 13.6	10.2 13.6	10.2 13.6	10.2 13.6	10.2 13.6
η_{as}	5.9 10.0	3.6 10.9 (13.7) (23)	6.1 12.2	3.6 12.6 11.4 (21.4)	5.5 9.0 (6.0)	12. 13.9 (20)	0.93 1.78
P_{as}	300 300	300 300 (75) (142)	300 300	300 300 (94.6)(177)	300 300 (278)	300 300 (209)	300 300
P_T	17.8 30	10.3 32.4 (10.3)(32.4)	12. 36	10.7 37.6	16.5 27 (16.5)	34 42 (42)	2.8 5.2
B_{as}	31 61	14.6 29 (7.5)(14.3)	22.2 38.4	32.7 31 (10.3)(18.3)	19.1 36.9 (17.7)	14.6 39.7 (27.7)	43 67
I_a	482 445	406 540	560 425	400 547	669 640	487 529	415* 415*
V_b	201 145	S225 225	225 153	225 225	225 154	225 225	166 118
Limit:	T T	(I) (I) Summer only	T/I T Dry only	(I) (I)	(I) T	T/I (I)	T T

* Exceeds present helix conductor capability, which is about 300 A.

Figures in parentheses are maximum allowable transmitter power input to antenna system to give insulator voltage limit without inserting bandwidth resistor.

T: Transmitter
I: Insulator

amperes. At Hawaii, the helix conductor is marginally capable of handling the increased current, up to about 700 amperes.

As indicated above, the insulating system for the base-insulated towers deserves some detailed consideration. The insulators were produced and accepted under ANSI C 29.1 and C 68.1 procedures at 60 Hz. They were tested extensively after experience with them in the towers had shown that they were inadequate under wet conditions at rf. The tests showed that the long term withstands for wet conditions of the base insulators and the guy insulator strings for the North Dakota and Argentina stations were roughly two-thirds the required 250 kV. Therefore, the allowable voltages in snow, rain, and blowing wind are about 160 kV, and the stations must go to somewhat less than half power under these conditions to avoid excessive arcing. Experience with the Japanese installation is even more adverse, as these insulators are not of the petticoated type and the hardware is reputed to have additional problems. Therefore, it cannot really be said that 225 kV is allowable on the insulated tower stations except in fair weather.

Various fixes have been investigated, again in connection with a long series of tests carried out by NOSC in the 5 years from 1972 through 1977, which indicate that the base insulators can be improved to a wet withstand of about 180 kV rms. They could probably be marginally operated up to 200 kV wet if there is no strong blowing of rain directly against the porcelains. The guy insulators incorporating petticoated insulators in the quadri- and penta-post insulators could be improved only in respect to defining arcing paths that would minimize possible damage from the heat of the arc on the porcelain or on the end cap sealants, but the ratings could not be improved. It is clearly evident that the number of these insulator sets (four) in each guy is inadequate, especially when it is realized that there are six and sometimes more breakup insulators in the guy sets for Annapolis and Lualualei vlf communication station towers, which were designed for similar voltages under an identical procurement specification. It is out of place here to discuss why the A&E wound up with the smaller number in the Omega stations, but the fact is he did, and no fix is possible to increase the withstand behavior of these towers without increasing the number of the breakup insulators. The Japanese installation is probably in the same situation.

The insulator sets in the ends of the active toplead spans at all the stations except the Japanese are all of the same rating and manufacture, differing only in the number of parallel sets required by structural considerations. These insulators have never been tested at rf, but similar single units have been so tested and with suitable grading rings are known to be adequate. Therefore, it is expected that 225 kV rms is probably a realistic rating for these insulators for all conditions of use. The grounded tower stations and the valley-spanning stations are therefore not expected to be seriously voltage limited by any aspect of the radiation system if the power is raised.

All the Omega stations share a common design for helix house and automatic tuning system. They are therefore similarly limited in respect to power handling capability quite beside any aspect of the radiating system. The exit bushings are all the same, and by use and test appear to be adequate for the 225-kV limit assumed under all conditions, although at only two of the stations are they presently used anywhere near this limit. The litz conductor was selected so that it could be conservatively rated at 700 amperes, a figure greater than any that will ever be used for antenna current even if the power is doubled. The buswork is 6-inch copper sewer pipe laid out in a manner such that there is at present evidence that some components operate up

to about 180°F, (82°C) as read from the thermotabs installed. It may well be that increasing the currents significantly will require careful tests of temperature rise in the solid tubular copper components in the helix house.

There are doubled solid stranded jumpers used as connectors to some of the switches by which variometers are connected or grounded. The switch blades in these switches have shown some evidence of burning already, and because of the layout of the jumpers it is evident that most of the copper cross section in them is wasted and that temperatures may be quite high. These components, then, are already operating close to their limits at 400 amperes current, and any significant increase will probably call for a redesign.

During preliminary tests of North Dakota numerous hardware items in the helix house, such as switch handles, showed corona problems which were remedied ad hoc to the limit of voltage then in use. Since that station operates at the highest voltages already, and very close to those that are limiting for other reasons, these hardware items may not show further problems if and when the voltage limits are raised at the other stations. However, these items are worth remembering as possible causes of problems that have not as yet become evident at these stations.

There are numerous other irritants already being fought, such as the premature failure of some of the floodlights in the helix house and the tower warning lights (Liberia) in the presence of rf fields that appear to be leaking into the lamp enclosures because of inadequate shielding. The litz connectors to the main helix from the variometers and from the matching transformer to the variometers, as well as some of the metal buswork, are supported on sometimes metal end caps and sometimes G-10 insulating brackets in sleeves that combine metal brackets with Teflon sleeve liners. The highly inhomogeneous fields and the wild variation of relative dielectric constant and dielectric puncture strengths in these combinations of components in conjunction with the small air spacings have led in the past to "firefly" arcing problems which, again, were fixed ad hoc at North Dakota. The basic design faults involved could and should be remedied by redesign and re-equipment with brackets and conductor junctures at these supports such that there is solely metal-to-metal contact at the insulator end cap supports, many of which should be equipped with anti-corona rings where none exist now in many cases. If the field intensity, directly related to operating voltage, is increased significantly around some of these fittings, it is expected that there will be serious corona and arcing problems as well as material surface degradation.

A final item to be considered in raising the full time radiated power from the stations by 3 dB is the adequacy of the prime power source. There seems to be no question about the ratings of the power line substations feeding any of the transmitters, as every station has been run with full radiated power from one transmitter while the other is operated at full power into the dummy load during tests simultaneously. However, when the stations go to the standby diesel-electric generator as the prime source during commercial power failure, it is not possible to operate the two transmitters together as the standby generator is only rated for 550 kV, 760 kVA, against 380 kW for each transmitter separately not counting housekeeping power for the buildings. It seems evident that with the present equipment the station would go to one transmitter online during emergency power use, and to do this without tripping breakers would require some modification to the line power switch gear. This would mean of course that a user in a marginal situation for use of the 20-kW source would lose it when the station went to the standby generator. The alternative of providing both transmitters uninterrupted during emergency power use would require replacing the existing power plant with a larger one.

To summarize briefly, it appears that the voltage ratings of insulators in the radiating systems of the base-insulated tower stations have already been nearly reached, and any further increase in transmitter power can be usefully employed only in broadbanding the system. At the other stations, it seems that an increased transmitter power can be used to increase the radiated power, but only if some of the deficiencies in the helix house and tuning systems are carefully considered and improved. These deficiencies relate mainly to allowable currents in buswork and switches, and allowable fields around some of the conductor supports. To place the base-insulated stations on an equal footing with the others in regard to an increase in transmitter power bringing about an increase in radiated power, either the insulator ratings will have to be increased, a patent impracticability, or the capacity and/or effective height must be increased at no decrease to the other. What comes to mind is a companion tower, similarly insulated, and having about 50% of the capacity of the original, with about the same electrical height.

Appendix E: Cost of Additional Station

The following major breakdown can be applied to the costs of an Omega station:

1. Site acquisition cost.
2. Site engineering including: access, utilities, grading, and buildings.
3. Antenna system construction including towers and helix.
4. Antenna tuning system.
5. Transmitter set (2 transmitters).
6. Timing and Control set (T&C).

Site acquisition and engineering costs are virtually impossible to specify without detailed knowledge of location. Land may be available from suitable governmental authorities without cost. Access and grading may be severe problems or quite minor. Certainly some buildings are needed and provision for standby power must be made. However, costs cannot be meaningfully estimated without knowing the remoteness of the site and prevailing labor rates. Costs might fall between \$200k and \$400k, but this must be considered a speculation rather than an estimate. Antenna system costs are impossible to estimate without knowing power level and site details. Costs of 10-kW Omega antennas including antenna, ground system, and helix but excluding site details were of the order of \$6M (ca 1972). A relation published by Watt several years ago showed cost proportional to the square root of power, thus suggesting that antennas to transmit 1 kW could cost one-third of the amount required for 10 kW.¹⁷ More detailed consideration suggests that the cost differential for radiation of 1 vs 10 kW at the Omega frequencies is slight; in fact, about 10%, lacking details of where the antenna would be located, whether a tower or valley span antenna would be used, or the power level. Indeed, at low power level a horizontal long wire antenna might be attractive. One can only approximate cost within a gross range of between \$3M and \$5M (1972) with the expectation that the cost would be toward the upper end of the range.

Electronic costs include that of the antenna tuning system, transmitter set, and timing and control equipment. In the initial Omega construction, contract costs in each of these three areas were about \$2M; ie, about \$750k per station. Although the initial contracts included some development and documentation which would presumably not have to be duplicated, it is nonetheless to be expected that 1978 costs would be substantially greater. When previous equipment was purchased it was very much a buyer's market in the electronic industry. Substantial inflation has occurred in the intervening period. Also, whatever advantage would accrue to the quantity purchase of eight systems at the same time would not be available today. Further, it is unlikely that a "carbon copy" approach to construction of a ninth station would be cost effective. Whereas interchangeability of station components must contribute to maintainability, reliability of some newer components may offer a potential to contribute to system performance. Thus, cost, reliability, and parts availability suggest considerable latitude be given the manufacturer of the ninth station and simultaneously imply a need for considerable care in selecting an appropriate manufacturer. One consideration is whether a 150-kW transmitter is needed at the ninth station as at existing Omega stations or a less expensive, lower power transmitter could be used. For estimation purposes, it is assumed that maintainability requirements dictate that essentially the same transmitter be used. Considering the foregoing but without detailed pricing suggests that new electronics could cost about \$1.5M in 1978.

Summing the foregoing costs and adjusting to 1978 dollars but disregarding possible site acquisition costs yields a total cost estimate for a ninth station in the range \$6.7M to \$10.3M. An alternative method of estimating station costs is simply to assume that a new station built today but at lower than nominal power would cost slightly less than the \$17M cost of Omega Australia (Herbert, NF, personal communication, May 1978). Thus, prudence indicates the range of cost uncertainty be expanded to be from \$6.7M to about \$16M (1978).

Appendix F: Format Changes

The addition of one or more Omega stations is a potential way to mitigate coverage deficiencies. The problem is to separate station signals. Theoretical possibilities include separation by: time, frequency, space, or polarization. Polarization is unattractive because of depolarizing properties of the ionosphere and near cancellation of horizontal polarization on the earth's surface. Spatial diversity may be implemented in two ways: through geographic separation and through directionality. As even very low radiated powers tend to yield global signals at vlf, geographic separation is not attractive. Directional antennas can be constructed at vlf by, for example, the use of long wire antennas. Such an approach may have limited application. Primary methods for adding additional stations are by time and frequency separation. These are developed more completely in the following paragraphs.

Many of the methods considered impact seriously on existing receivers. Such methods have serious political, practical, and operational effects but are not necessarily prohibitively expensive. If there are 10 000 receivers in use which could be modified for \$1k each, the total modification costs would be only \$10M, which is comparable with station construction costs. However, scheduling of the modifications to all occur on precisely some assigned changeover date is clearly impossible. Transition details need to be addressed as well as costs.

One possibility which should be considered in conjunction with format changes involving modifications to the commutation pattern is that of developing an LSI chip incorporating all changes. This could be provided at low or no cost for modification of existing receivers. There is a question, however, whether a chip sufficiently universal to interface with all manufacturers could be developed.

It seems reasonable that if an additional station is to be added, a shift to more than nine segments be considered. This would allow for future growth and/or the occasional use of temporary stations. Allowance for inclusion of the three stations operated by the USSR might also be prudent.

Considerable thought has been given to methods for expanding the present eight-station format to nine or more stations. Old and new ideas are presented here with advantages and disadvantages. Table F1 lists the methods in brief for a simpler comparison. For addition of a single new station method 1 offers advantages although it impacts on existing receivers. Several other approaches offer advantages. A number of approaches are not recommended but included for completeness. In the following, discussion of required transmitting station modifications has been restricted to the transmitting function only. It is to be understood that monitoring complexes associated with Omega stations would require modifications similar to those for all full format receivers.

1. G Segment Share

An attractive method would be to fit transmissions from two stations into the time slots reserved for station G. The transmission pattern would be as shown in figure F1. This approach is attractive for the following reasons: (a) No impact on existing seven stations; (b) No impact on existing receivers insofar as tracking existing seven stations; (c) New station (stations G and G') electronics would be identical to existing station electronics with the exception of the necessary commutator change; and (d) New receivers could be

Table FI.

Summary of possible format changes: Features and impact.

No	METHOD Description	Unique Relation-ship (a)	Multiple Station Additions	Degrada-tion (b)	EXISTING HARDWIRED RECEIVERS		NEW HARDWIRED RECEIVERS		SOFTWARE BASED RE-CEIVERS. Software (c)		EXISTING TRANSMITTING STATIONS (d)		COMMENTS
					Present Format	Full Format	Full Format	Design Changes	only mod conceivable	Modifications	Sys Cost		
1	6 Segment Share	Some-what	Initially	duty cycle	none (7 sta) minor (8 sta)	minor com-mutator	minor commutator	yes			\$ 10k	Viabie, RImods needed for 8 sta., Power loss	
2	Stepwise to 10seg; 10 s	no	Initially	duty cycle	none (but format slightly reduced)	extensive	new design along existing principles	yes (unlikely)			450k (e)	Viabie. Allows smooth transition. Outage req	
3	Sequential Insertion	yes	Initially	yes	major commu-tator	extensive commutator	commutator only	yes			15k	20 s between some transmissions. 90-s cy	
4	Seq inser-tion w/ flipped ph	yes	Initially	yes minor	none (but some degradation)	extensive	commutator plus unique circuitry for 9th sta	yes			15k	20 s between some transmissions; 90-s cy	
5	Antipodal Placement	yes	no	yes	none	none	none	yes			0	Not recommended; possible gross nav errors	
6	Flipped phase; anti-podal site	yes	yes - anytime	low	none	moderate	unique phase flip ckt for 9th station	yes			0	Viabie	
7	Frequency Warble	yes	yes - anytime	no	none	extensive	detection scheme for 9th station	yes			0	Viabie	
8	Direct shift 10sta; 10seg	no	Initially	duty cycle	new commutator	new commutator	Direct extension of present designs	yes			30k	Not recommended; transition chaos	
9	Offset Frequency	yes	yes - anytime	no	none (or minimal)	extensive	extensive	yes			0	Viabie but unproven technology	
10	Transmit in 0.2 s blanks	yes	no	no	automatic comm-sync	extensive commutator	extensive commutator only	yes			30k	Not recommended; pattern complexity and length	
11	Full Format Strobe	no	Initially	duty cycle	major commutator	extensive commutator	commutator	yes			0	Not recommended; low avg power on 9th sta	
12	Longer Pattern	no	Initially	duty cycle	new commutator	new commutator	commutator	yes			30k	Not recommended; trans-ition chaos; low power	

(a) Notes the formal property of all stations being of equal status as opposed to some being a unique relationship. Method 1, 6-Segment Share, is unique only in that assigned segment lengths for some stations are markedly shorter than for others. Methods 6, 7, and 9 establish a discipline in which up to 8 additional stations can be operated with the existing format.

(b) "Duty cycle" indicates degradation of existing stations will be due to decrease in their duty cycle only. Methods 6, 7, and 9 may occasionally cause some signal suppression or acquisition difficulty.

(c) As some hardware is employed in all software based receivers, ease of modification will depend on partitioning of functions within individual models. Important details include whether commutator is software or hardware implemented; whether reference frequencies are software or hardware synthesized; front end bandwidth; and whether sampling is sufficiently fast to allow subsequent mathematical adjustments to approximate the intended direct measurement of new signals.

(d) Costs and modifications of monitors associated with transmitting stations are not included. Modification to these monitoring equipments to extend their capability to 11.050 MHz was estimated to cost \$250k in 1975. It was noted that at this price level it might be more attractive to spend somewhat more and replace the present AM/FM-30 monitoring equipments. These costs were in part due to limitations in the telemetry modem. Expansion of monitoring capability to include provision for more stations would cost little additional if done at the same time. Cost of new station is not included (cf text). Commutator modifications are based on changes to printed circuit boards or board replacement as needed. Methods 8, 11, and 12 require development of sets of replacement boards to support rapid change of format. Costs are estimates based on engineering experience but not review of detailed preliminary design.

(e) At a minimum this method will require new commutators, development of new Omega Format Generators, new Format Comparators, and retapping of the helices. Retapping costs will be \$300k or more while electronic changes will be on the order of \$150k. Significantly higher cost may be required if nearly full format is to be maintained during transition. Pricing has assumed conventional electronics designed according to the techniques now employed. Conversion to minicomputer or microprocessor based generation may be an alternative but is not likely to offer large cost savings.

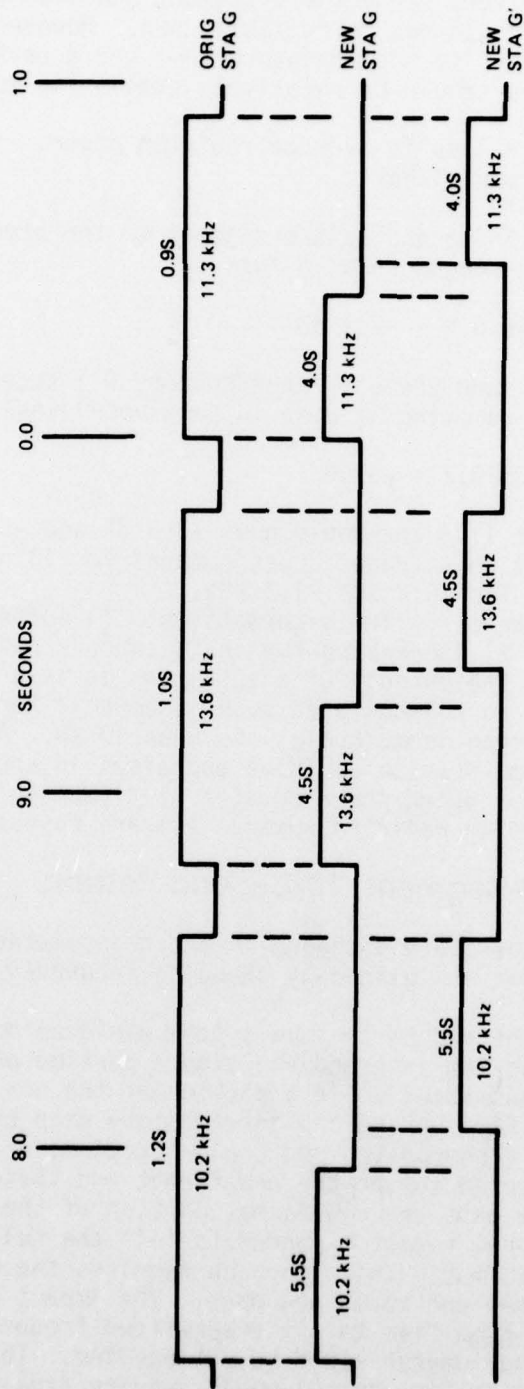


Figure F1. "G" Segment Share.

identical to existing receivers with the exception of the necessary commutator change and possible addition of a ninth phase tracking/measuring channel.

This approach does have two disadvantages:

a. Existing (unmodified) receivers would normally operate as seven-station receivers since the G-Segment position would contain two transmissions and could not be reliably used. However, modification of existing receivers to accommodate either the G or G' proposed commutator segments should be relatively simple for most receivers.

b. There will be a loss in average radiated power. This is quantized in the following comparisons:

Comparing a 0.55-second square segment to the present shortest segment of 0.9 second shows a loss of:

$$10 \log 0.55/0.9 = -2.1 \text{ dB}$$

Comparing the same segments shortened by 0.1 second on each end (this shorter sampling is done in some receivers) shows a loss of:

$$10 \log 0.35/0.7 = -3 \text{ dB}$$

Similar comparison for 11.3 kHz would give -3.5 dB and -5.4 dB, respectively. This is the worst case. Loss numbers for 13.6 kHz will fall between the numbers given for 10.2 and 11.3 kHz.

With respect to (b) there are two alternatives: 1) suffering the indicated power losses or 2) increasing the instantaneous radiated powers to compensate. Certainly if the purpose of one station is as a "filler" to provide improved coverage in a local area such as central North America, the requirement for this function is markedly less than 10 kW. Adequacy of coverage from the companion station could be appraised in specific areas of interest either accepting reduced power or at nominal design power. There are several methods of increasing radiated power. All are discussed elsewhere.

2. Stepwise Shift to 10-Segment, 10-Second Pattern

This method would necessitate a change in the transmitted frequencies for the Omega system. The benefits gained by changing frequency were addressed earlier.

The transition from the old to the new system would be done with an intermediate step. During the intermediate step a portion of the old format would be retained and transmitted while a portion of the new format would be transmitted. See figure F2. During the intermediate step existing Omega receivers would still be accommodated and could function; all new receiver manufacture would be directed toward the new format and these too could function. At some future date the old format portion of the transmissions would be deleted and the new format expanded to fill the full 10-second period similar to the original format. This approach requires the use of six frequencies, three old ones and three new ones. The impact on the station electronics due to going from five to six transmitted frequencies is substantial. The spare variometer would be put on-line. The carrier phase detector and transmission keying control would require expansion from five channels to six channels and an additional digital phase shifter would be

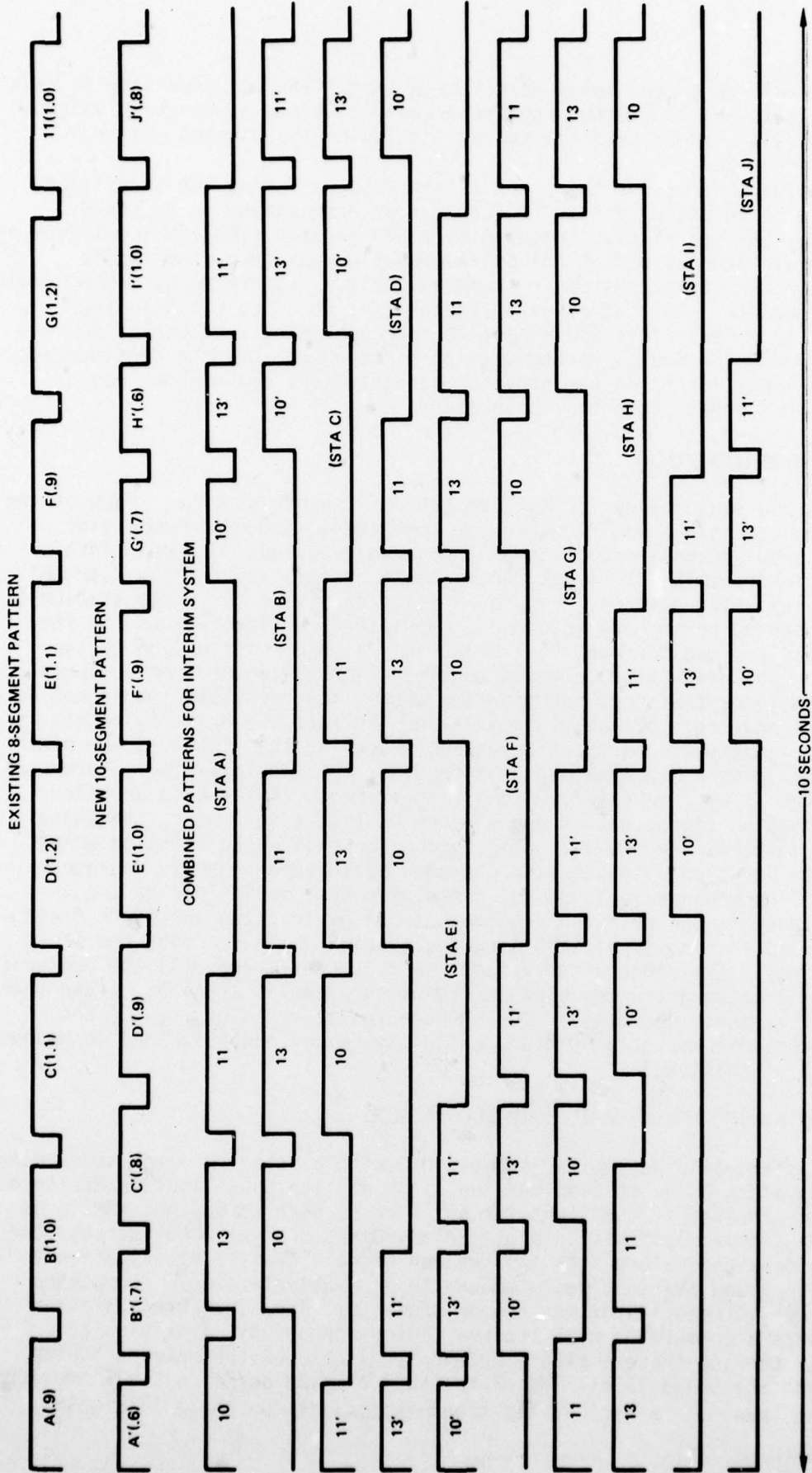


FIGURE ILLUSTRATES COEXISTENCE OF 8-SEGMENT AND 10-SEGMENT FORMATS; PRIMED FREQUENCIES (EG, 10') ARE NEW FREQUENCIES OFFSET FROM OLD ONES. TEN-SEGMENT PATTERN USED IS FOR PURPOSE OF ILLUSTRATION AND NOT NECESSARILY OPTIMUM.

Figure F2. Stepwise Shift to Ten-Segment, 10-Second Pattern.

required as well as a new signal format generator. The big advantage to this approach is that existing Omega receivers could continue to function without modification and without performance degradation on the limited original format that remained.

Alternative choices for the transmission pattern during the transition period would be to use only five frequencies or even expand up to seven frequencies. The use of five frequencies would greatly simplify the impact on the station electronics but at the price of having only two-frequencies available for one of the systems. It is unlikely a two frequency system would be deemed adequate. A total of seven frequencies could be fit into the available time slots. This would provide four operating frequencies for one of the systems. The impact on the station electronics would be considerable. Besides the items listed in the previous paragraph the helix house would require an additional (seventh) variometer.

3. Sequential Insertion

This method would allow for the addition of a ninth station. Each of the existing eight stations would delete one complete 10-second transmission period every 90 seconds. This would be done in rotation. The new ninth station would transmit its format during these periods and thereby "strobe" through the existing pattern. Figure F3 illustrates how the ninth station (I) would be inserted on any one frequency. Modification requirements for the existing stations would amount to a relatively simple modification to the commutator. The ninth station would require essentially the same equipment. Existing receivers that were not modified with a new commutator would not be able to take advantage of the ninth station. In fact the existing receivers would suffer some phase degradation due to absorbing the signal of the ninth station. Assuming equivalent signal strengths, this would typically produce an rms lop error of $(\sqrt{2})(1/\sqrt{2})\tan^{-1}(1/8)=2$ cec. In the case in which the ninth station signal was strong and the desired signal weak, the phase pulling could become excessive. This system does allow the existing Omega receivers to function although with degraded performance. Newly designed Omega receivers would have a special commutator that would lock to the 90-second epoch in the rotational pattern to allow tracking the ninth Omega station and to eliminate phase pulling degradation while tracking the basic eight stations. Two other disadvantages to this system are: (1) the periodic 20-second gap between transmission bursts by the regular stations, a gap that could well be excessive for fast moving maneuvering vehicles and (2) the unique 90-second commutation pattern which may be sufficiently long to become operationally undesirable.

4. Sequential Insertion with Flipped Phase

This system would be similar to method 3 with a rotating blank spot being filled by a ninth Omega station but the ninth station phase would be flipped 180° at the midpoint of the transmission. The purpose of the phase flip is to produce a net zero offset in phase to any Omega receiver that accepts the ninth station signal along with the desired Omega signals. Modification to the existing Omega stations would amount to a relatively simple commutator change to permit deletion of the proper segments. The ninth Omega station would require a commutator with the new timing capability, provision to reverse all carrier phases, plus a momentary disable of the antenna tuning servo during the phase flip. The ninth station would suffer a small amplitude notch (less than 0.1 second) in its transmissions at the phase flip point.

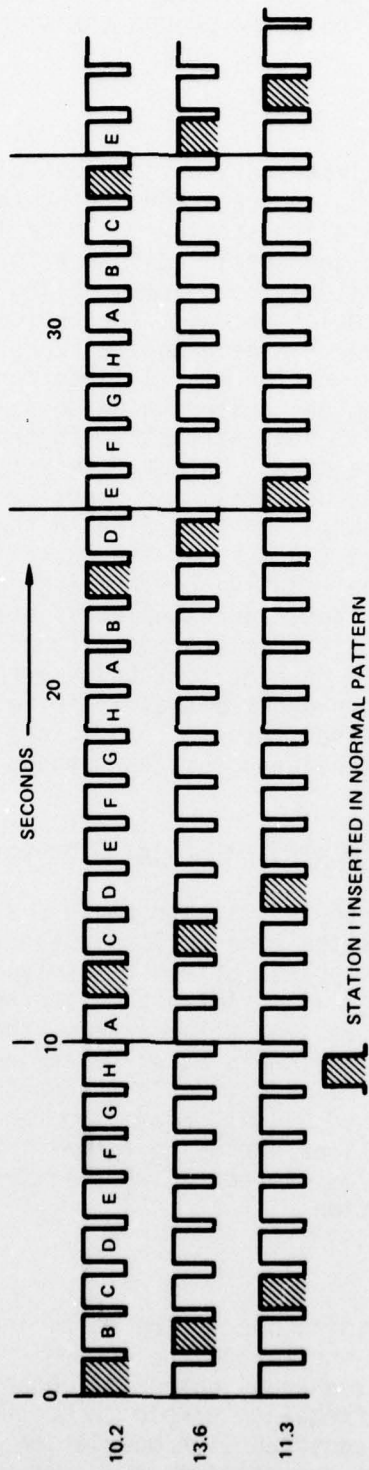


Figure F3. Sequential Insertion.

The impact on existing Omega receiver performance would be the loss of one transmission out of nine but without the phase pulling degradation of a non-phase-flipped signal. New receivers would be designed with proper commutator gates to prevent mixing of signals in the tracking filters plus a phase flip tracking circuit to allow proper tracking of the ninth Omega station.

5. Antipodal Placement

By surveying existing eight-station locations pick "best" antipodal location for a ninth station. Operate the ninth station simultaneously with the antipodal station. The ninth station would be identical to the others, therefore would not require any special design effort. Existing receivers would perform as before, the only requirement being that user choice must be made between the two antipodal stations. The choice would be by geographical location of the user receiver. A geographical zone would be designated for station X, another zone for station X'. A large nonoperational zone (interference zone) would be designated in which neither station could be used successfully. This system is very attractive in that existing hardware, both station and receiver, can be used. Unfortunately it has three shortcomings: (1) In a manual receiver the potential for operator error is great; (2) An excessive amount of geographical area will be in the interference zone and will be lost to service; and (3) Much of the operational zone for either station will depend upon the relative power being transmitted simultaneously by both station X and X'. Thus, for example, if station X inadvertently went off the air, trackable signals from station X' would be unmasked in parts of the prime zone for station X leading to totally erroneous navigation results. Because of these very serious shortcomings it is felt that this method is not by itself a viable alternative. However, judicious placement of stations added using other format techniques such as methods 6 and 7 can mitigate undesirable side effects.

6. Flipped Phase Signal with Antipodal Placement

As in the previous method this scheme employs simultaneous transmissions in the segments employed by the more or less antipodally sited station. However, in this method the phases of new transmissions are flipped 180° at midsegment. This approach will minimize the interaction between the two simultaneous transmissions as seen at receivers, the major disadvantage of the previous method. Minor errors could occur depending on relative field strength of the normal and flipped signals and nominal errors in commutation synchronization. This method allows unmodified receivers to continue to operate with the eight stations employing normal transmissions. Modifications and unique circuitry would be needed to track flipped signals transmitted by one or more additional stations.

7. Frequency Warble

This scheme has its inspiration in the foregoing but differs in that the phase is gradually shifted throughout the segment rather than abruptly shifted 180° at the midpoint. As a gradual change of phase is a change of frequency, it is called a frequency warble technique. Technically a tangential modulation is suggested with modulation index such that the carrier is suppressed; that is, the new station would not radiate spectral components at the existing carriers. The resultant signal has some amplitude modulation

but minimum sidebands. In implementation the offset warble would be set at a few hertz so that signals could pass through existing receiver front end filters without modification. Some suppression could occur if the competing transmission on the assigned segment was of much larger amplitude but the practical effect of this could be mitigated by selecting more or less antipodally sited stations for assignment to the same segments. Existing receivers would work well on the primary eight stations without modification. Rather unusual and unique receiver changes would be necessary to permit use of the new station or stations. The method is readily generalized to handle at least eight additional stations.

Essentially this method entails double sideband suppressed carrier transmissions and can be compared with method 9, which employs single sideband suppressed carrier. Other than well known signal-to-noise considerations associated with the two methods, a principal difference is the absolute timing requirement associated with recovering the phase of the virtual carrier.

8. Direct Shift to 10-Segment, 10-Second Pattern

This method would entail instantaneous change from the existing eight-segment (eight station) pattern to a new nine- or ten-segment (station) pattern. The impact on the existing Omega station hardware would be rather minimal. It would only require a new commutator. All Omega stations would switch over instantaneously and simultaneously. The disadvantage would lie in the impact upon the Omega receivers. To remain functional they would require a modified or new commutator which would need to be installed or activated at the precise moment of format change. New receivers could be designed simply along the lines of previous receivers but allowing for the expanded format.

9. Offset Frequency

It may be possible to work in a ninth station by operating the new station at slightly offset frequencies such as 10 201 Hz instead of 10 200 Hz and then tracking and using the information directly with transmissions at the present frequencies using special receivers. The mathematics of this option have not been developed. Ordinarily, navigation using different frequencies results in an ambiguity structure related to the least common multiple owing to the arbitrary position of dividers in the chains developing reference frequencies within the receiving circuitry. That is, for transmissions at 10 200 Hz compared with transmissions at 10 201 Hz one expects ambiguities approximately every metre. As Omega is normally employed, this ambiguity is clearly intolerable. However, the absolute phase of 0.1 Hz must clearly be known by the receiver for the commutator to be set properly. Indeed, since the segment lengths are typically on the order of 1 second, the phase of an equivalent 1 Hz must also be known. The fact that this phase must be known on an absolute basis may provide a means of recreating an equivalent 10.2-kHz phase from tracking a slightly offset frequency. If so, transmissions at a ninth station could be offset so as to cause no interference with normal Omega although some suppression would occur where transmissions occurred simultaneously. Existing acquisition techniques, including both tracking and commutation synchronization, might require revision. This method can easily be generalized to handle up to eight additional stations. Assigning new stations to segments corresponding to present more or less antipodally sited stations would be wise. A speculation is that it might be possible to implement this scheme by making only software changes to automatic receivers.

10. Transmit in 0.2-Second Blanks

One additional method needs brief mention; that is, filling part of the 0.2-second blanks between station transmissions with short transmission bursts from a ninth station. This approach has two serious deficiencies: (1) There is only 1.6 seconds total time available. A station using the available time would have to yield approximately half of it to provide buffering space between itself and existing stations. This would leave eight 0.1-second periods for transmission with a total time availability of only 0.8 second. Within this 0.8 second the ninth station would have to transmit its entire format. For a four-frequency station this would amount to only 0.2 second per frequency. In addition we must remember that the typical Omega antenna system would require a major portion of the 0.1-second interval to "ring-up." (2) Any filling of the blank spaces would impair or totally negate the self-synchronizing feature built into many Omega receivers.

11. Full Format Strobe

One method which has little recognizable merit but should perhaps be mentioned for completeness might be called the full format strobe. In this case, in frame 1, station A would transmit on segment A while in frame 2 station A would transmit on segment B, etc, with the ninth station having been worked into the pattern on segment A of frame 2, then segment B of frame 3, etc. This is in some sense a convolution of the present pattern to accommodate a ninth station wherein all stations follow the same pattern. It has the formal elegance of treating all stations similarly with no station in any special relationship to the others. However, it obsoletes all existing commutators. It shares most of the disadvantages of simply strobing in a ninth station although there would never be a 20-second delay between transmission bursts from any station.

12. Longer Commutation Pattern

One way to expand the format is to retain the present existing eight segments with 0.2-second separation, then simply add one or more additional segments for a total commutation cycle of, say, 12 seconds. This requires only commutator changes at both transmitters and receivers. It has an operational disadvantage in the reduced flow of information from each station due to the decreased duty cycle and the perhaps 20% increase in delay before receipt of new information. A severe and probably unacceptable immediate impact is the obsoleting of all existing receivers until commutators are modified. Automatic receivers using software commutation could be easily modified by program change. However, commutator modifications to many existing "hardwired" receivers would be severe.

Other Methods

Several other methods may be considered including some fairly obvious combinations of the foregoing.

One perhaps less obvious observation is that some of the foregoing methods would allow an additional station to be inserted with a continuous or at least longer than nominal duty cycle. For example, the frequency warble technique of method 7 or the offset frequency of method 9 could be implemented not on a single segment corresponding to the existing station most nearly at the antipode, but on several segments corresponding to the existing stations

associated with the least suppression. Disregarding the effects of suppression, the new station could be added with a continuous duty cycle. This would provide an immediate advantage of 10 dB. With this great an initial advantage, it is speculated an elaborate quintuple tuned antenna might be constructed to support simultaneous transmission of five frequencies at less cost than existing antennas. More likely, adding a single new station on several segments at each frequency would appear potentially appealing.

Summary

The foregoing clearly indicates that there are attractive methods to add one or more additional stations to Omega. It is deemed premature to recommend a particular method from among the alternatives at this time. If necessary, choices can best be made after wide discussion of the various alternatives particularly regarding the relative importance of maintaining minimum impact on existing receivers compared with system modification costs. Further, prudence indicates that candidates be engineered, constructed, and evaluated before a firm selection is made.

It is noteworthy that some of the possible format changes may allow some automatic equipments to use additional stations with only software changes. Further, since the exact location of Omega Australia is not yet known, there must already be a conceptual plan to burden users with a software change. From the view of the user, the complexity of software changes is irrelevant; he is affected only by the administrative complication of scheduling and loading new program tapes or installing new Read Only Memories (ROMs).

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