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OMEGA NAVIGATION SYSTEM STATUS AND FUTURE PLANS

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INTRODUCTION

OMEGA is a very low frequency (VLF) radio navigational system operating in the internationally allocated navigation band in the electromagnetic spectrum between 10 and 14 kilohertz. Full system implementation with worldwide coverage from eight transmitting stations is planned for the latter 1970's. Experimental stations have operated since 1966 in support of system evaluation and test. These stations provided coverage over most of the North Atlantic, North American Continent, and eastern portions of the North Pacific. This coverage provided the fundamental basis for further development of the system and has been essential to the demonstrated feasibility of the one to two nautical mile root-mean-square system accuracy. OMEGA is available to users in all nations, both on ships and in aircraft.

HISTORICAL

OMEGA uses very low radio frequencies and phase-difference measurement techniques to provide radio navigation information. These principles were proposed to the Navy in 1947 by Professor J. A. Pierce of Cruft Laboratory, Harvard University.

As a result of his proposals and his experiments in measuring phase delay at VLF and establishing the phase stability of signals at VLF, the Navy developed an experimental system operating in the vicinity of 50 kHz with a sine wave modulation of 200 Hz. The system was designed by Naval Electronics Laboratory Center (NELC), San Diego, and was called Radux. Radux had an accuracy of three to five miles and a range of about 2,000 miles. While this system showed the wisdom of using phase-difference measurement techniques, the attained accuracy and desire to obtain even greater range resulted in another system which combined a separate VLF transmission near 10 kHz with the low frequency (LF) signal. This system was called Radux-OMEGA. To further increase the range of the system, the LF signals were discontinued. The single frequency VLF system was called OMEGA and, later, expanded to a multi-frequency OMEGA system. Thus, OMEGA can trace its development back over a twenty-year period.

Early transmissions from the shore-based stations were derived from a conventional primary-secondary configuration. Modern transmission of OMEGA signals is derived from a cesium frequency standard at each station and each station is controlled as a source of standard signals. This arrangement is most efficient and practical for a global system because the navigator can pair stations in any convenient way to obtain useful hyperbolic geometry and signals.

SYSTEM CONFIGURATION

TRANSMITTING ANTENNA SITES -

The OMEGA navigation system is a shore-based electronic aid to navigation that uses measured signal phase-differences from sets of stations for fix reduction. Eight stations geographically dispersed are required to provide worldwide coverage. Two of the eight stations are located on U. S. sovereign soil. The remaining six are being sited in cooperation with partner countries.

Experimental stations, operating since 1966, were located at Forestport, New York; Bratland, Norway; Trinidad, West Indies; and Haiku, Hawaii. These stations employed either existing facilities or temporary electronic equipments which proved adequate for the evaluation phase. The stations provided about one kilowatt of radiated power. Two of these four stations were selected as sites for permanent stations: Bratland, Norway; and Haiku, Hawaii.

The first high power OMEGA station of the projected configuration of eight stations is located in La Moure, North Dakota. This station has been operational since late 1972. The second station to be built on U. S. sovereign soil is located at Haiku, Hawaii. This site is the location of one of the original experimental stations. This station, like all others, will broadcast a signal of ten kilowatts.

The Bratland, Norway, site originally used during the operational evaluation phase provided signal coverage from temporary electronics housed in vans. In cooperation with the Government of Norway, this site was selected as one of the eight permanent stations. This station has since been completed with a permanent new facility housing a full set of new OMEGA electronics. It is currently broadcasting with an effective radiated power of six to seven kilowatts but once antenna problems are resolved, the station should radiate ten kilowatts.

As was the case with Norway, rather than negotiating for permission to build and operate U. S. transmitting stations on foreign soil, the Navy sought out foreign partners to join the U. S. in completing the OMEGA system. This policy emerged from the consideration that OMEGA is not peculiarly a military system, nor even a U. S. system, but an international navigation system that can be and undoubtedly will be used by all seafaring and airline operating nations of the world.

The Governments of Japan, Argentina, and Liberia have concluded diplomatic agreements with the U. S. for stations on their soil. The final agreement with France for a station on their soil is near final approval. Construction work is currently in progress on these stations. The sites are located on the Island of Tsushima in the Sea of Japan, on the Island of La Reunion in the Indian Ocean, Golfo Nuevo, Argentina, and near Monrovia, Liberia, respectively.

Diplomatic negotiations are currently in progress with the Government of Australia for siting of the final transmitting station. Figure 1 depicts the existing stations along with stations under construction and a probable location for the Australian station.

SYSTEM DESIGN

SIGNAL FORMAT -

The system design calls for a network of eight stations each transmitting a continuous wave (CW) signal which is periodically interrupted to allow it and other OMEGA signals to enter a time sharing or multiplex pattern. The various OMEGA stations always transmit in the same order with the length of the transmission varying between 0.9, 1.0, 1.1, and 1.2 seconds from station to station. Each transmitting station broadcasts three basic navigational frequencies 10.2, 11-1/3, and 13.6 kHz and is also capable of broadcasting what has been termed two unique frequencies. The original purpose of these frequencies, unique to each station, was for use in the synchronization process through interstation communication. The high stability of atomic frequency standards (cesium beam) now used in the system has made this requirement obsolete and other uses have been proposed. A final use for these frequencies has not been determined, however, and is still under study.

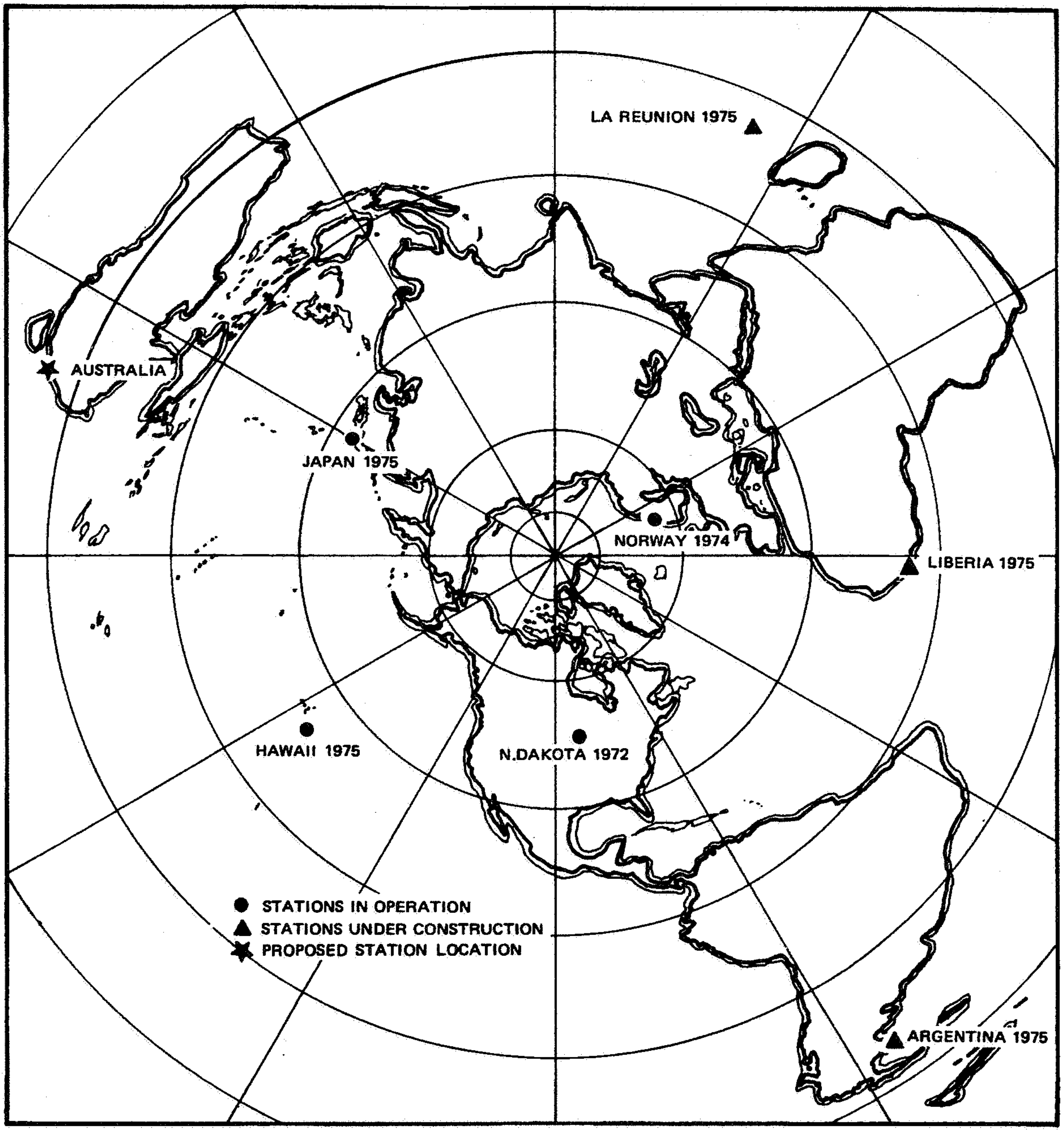
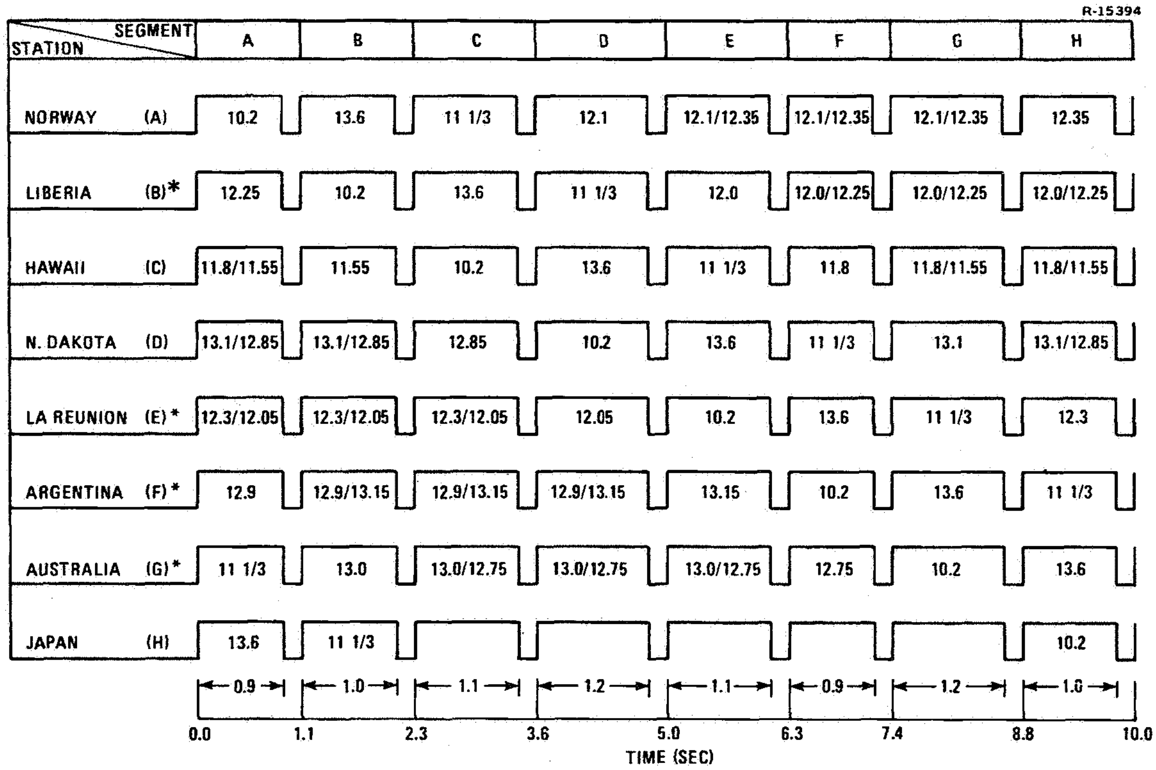


Fig. 1--OMEGA Navigation System

The complete, as originally envisioned pattern of transmission for all stations is shown in Figure 2. It should be noted that the various pulses are length-coded to provide one of several ways in which emissions of the various stations can be identified. Each of the shared carrier frequencies (that is, every frequency except the unique ones) passes through a particular phase at the end of each 30 seconds. Thus, at each half-minute of time, all carrier frequency currents in all transmitting stations pass through zero with a positive slope. Thus, all stations are synchronized to a given point in time and can be considered independent. It is important to note the OMEGA epoch does not correspond with universal coordinated time (UTC).



*HELIX NOT YET TAPPED

Fig. 2--OMEGA Signal Transmission Format

PROPAGATION -

The OMEGA navigational system is a skywave dominant system that is inherently dependent on the ability to predict propagational factors associated with such skywaves in order to arrive at a useful navigational system. Thus, the accuracy of navigation is dependent on ability to derive a useful set of corrections, such that the navigator at a given time and location can reduce the phase-difference measurements to a geographic position.

The field strength and velocity of propagation at VLF form too complex a subject for detailed discussion in this short paper. A simple summary can be given best in terms of the mode and wave guide theory. We would like to have a single mode of propagation greatly exceeding all others at all necessary distances. This condition is most nearly met near 10 kHz. At higher frequencies such as 20 kHz, the excitation of the first-order transverse magnetic wave is inferior to the excitation of the second-order wave, especially at night, while the attenuation rate of the first-order is considerably less than that of the second.

There is, at VLF, a considerable asymmetry in transmission normal to the horizontal component of the earth's magnetic field. At the geomagnetic equator, at 10.2 kHz, the daytime attenuation rate for transmission toward the West is more than twice the value for transmission toward the East. This results in large differences in useful range of a signal in various directions. Transmission toward the West (at the geomagnetic equator) cannot be used for more than 4,500 nm. Toward the East, however, transmission is satisfactory for about 10,000 nm, except that there is a region probably a few hundred miles in radius, at the antipode of the transmitter, where the large field strength is provided by rays coming from many directions and the prediction of resultant phase is difficult.

The velocity of propagation is relatively less affected by direction than is the field strength. Of major importance is the change in velocity between day and night. The velocity is reduced by transmission over land, but the effect is not major unless the land is of unusually poor conductivity, as in the arctic and antarctic regions.

From the practical standpoint, these phenomena result in resonant modes, each with a different velocity and attenuation, being developed within the spherical shell wave guide between the earth and ionosphere. At frequencies near 10

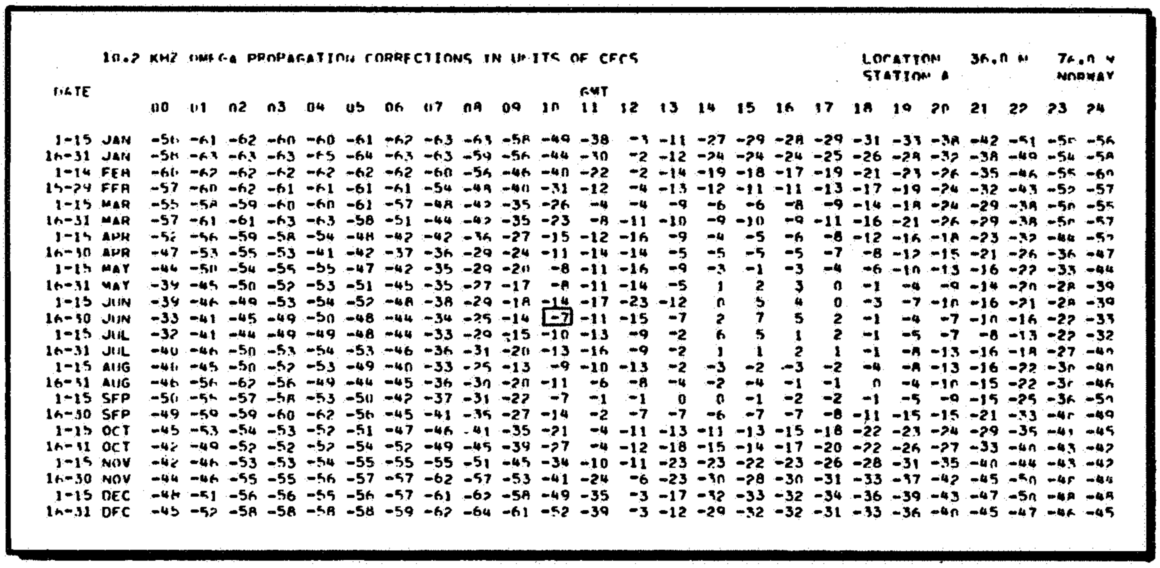
C-3

kHz, the first mode is generally dominant over others at ranges greater than 600 miles. At the same time, diurnal changes in ionospheric height are responsible for expansion or compression of the wave guide along the propagation path, with the result that there is a corresponding variation in the propagated phase.

Propagation of the VLF signal must be corrected to coincide with charted phase contours prior to navigator utilization to attain OMEGA's phase-of-the-signal fundamental measurement. Propagation corrections accomplish this melding operation.

These corrections are easily predicted because the basic parameters concerned with propagation of the first mode are known and ionospheric heights can be calculated along day/night paths. This is not to oversimplify the task of calculation, since effects of the geomagnetic field on east-west propagation paths and the secondary phase retardation factors attributed to ground conductivity must also be considered.

Previously, all published propagation correction tables were based on a global theory of OMEGA propagation incorporating theoretical and empirical principles where the relative contributions of the various effects are determined by regression analysis on millions of hours of data. The physical model has undergone continual refinement for ten years. Currently, skywave corrections for limited areas are also receiving the benefit of a "Force-Fit" wherein local prediction errors are determined by monitoring and then removed over whatever spatial extent may be justified by the statistics. Regardless of the method of derivation, the purpose of the propagation correction is to remove undesirable variations so that the observations can be corrected to charted LOP's with the best practical accuracy. A sample propagation correction table is shown as Figure 3.



10.2 KHZ OMEGA PROPAGATION CORRECTIONS IN UNITS OF CECS

LOCATION 36.0 N 76.0 W
STATION A NORWAY

GMT

DATE	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1-15 JAN	-56	-61	-62	-60	-60	-61	-62	-63	-63	-58	-49	-38	-3	-11	-27	-29	-28	-29	-31	-33	-38	-42	-51	-50	-56
16-31 JAN	-58	-63	-63	-63	-65	-64	-63	-63	-59	-56	-44	-30	-2	-12	-24	-24	-24	-25	-26	-28	-32	-38	-49	-54	-58
1-14 FEB	-60	-62	-62	-62	-62	-62	-62	-60	-56	-46	-40	-22	-2	-14	-19	-18	-17	-19	-21	-23	-26	-35	-46	-55	-60
15-29 FEB	-57	-60	-62	-61	-61	-61	-61	-54	-48	-40	-31	-12	-4	-13	-12	-11	-11	-13	-17	-19	-24	-32	-43	-52	-57
1-15 MAR	-55	-58	-59	-60	-60	-61	-57	-48	-42	-35	-26	-4	-4	-9	-6	-6	-8	-9	-14	-18	-24	-29	-38	-50	-55
16-31 MAR	-57	-61	-61	-63	-63	-58	-51	-44	-42	-35	-23	-8	-11	-10	-9	-10	-9	-11	-16	-21	-26	-29	-38	-50	-57
1-15 APR	-52	-56	-59	-58	-54	-48	-42	-42	-36	-27	-15	-12	-16	-9	-4	-5	-6	-8	-12	-16	-18	-23	-32	-44	-52
16-30 APR	-47	-53	-55	-53	-41	-42	-37	-36	-29	-24	-11	-14	-14	-5	-5	-5	-5	-7	-8	-12	-15	-21	-26	-36	-47
1-15 MAY	-44	-50	-54	-55	-55	-47	-42	-35	-29	-20	-8	-11	-16	-9	-3	-1	-3	-4	-6	-10	-13	-16	-22	-33	-44
16-31 MAY	-39	-45	-50	-52	-53	-51	-45	-35	-27	-17	-8	-11	-14	-5	1	2	3	0	-1	-4	-9	-14	-20	-28	-39
1-15 JUN	-39	-46	-49	-53	-54	-52	-48	-38	-29	-18	-14	-17	-23	-12	0	5	4	0	-3	-7	-10	-16	-21	-28	-39
16-30 JUN	-33	-41	-45	-49	-50	-48	-44	-34	-25	-14	$\boxed{-7}$	-11	-15	-7	2	7	5	2	-1	-4	-7	-10	-16	-22	-33
1-15 JUL	-32	-41	-44	-49	-49	-48	-44	-33	-29	-15	-10	-13	-9	-2	6	5	1	2	-1	-5	-7	-8	-13	-22	-32
16-31 JUL	-40	-46	-50	-53	-54	-53	-46	-36	-31	-20	-13	-16	-9	-2	1	1	2	1	-1	-8	-13	-16	-18	-27	-40
1-15 AUG	-40	-45	-50	-52	-53	-49	-40	-33	-25	-13	-9	-10	-13	-2	-3	-2	-3	-2	-4	-8	-13	-16	-22	-30	-40
16-31 AUG	-46	-56	-62	-56	-49	-44	-45	-36	-30	-20	-11	-6	-8	-4	-2	-4	-1	-1	0	-4	-10	-15	-22	-30	-46
1-15 SEP	-50	-55	-57	-58	-53	-50	-42	-37	-31	-22	-7	-1	-1	0	0	-1	-2	-2	-1	-5	-9	-15	-25	-36	-50
16-30 SEP	-49	-59	-59	-60	-62	-56	-45	-41	-35	-27	-14	-2	-7	-7	-6	-7	-7	-8	-11	-15	-15	-21	-33	-40	-49
1-15 OCT	-45	-53	-54	-53	-52	-51	-47	-46	-41	-35	-21	-4	-11	-13	-11	-13	-15	-18	-22	-23	-24	-29	-35	-41	-45
16-31 OCT	-42	-49	-52	-52	-52	-54	-52	-49	-45	-39	-27	-4	-12	-18	-15	-14	-17	-20	-22	-26	-27	-33	-40	-43	-42
1-15 NOV	-42	-46	-53	-53	-54	-55	-55	-55	-51	-45	-34	-10	-11	-23	-23	-22	-23	-26	-28	-31	-35	-40	-44	-43	-42
16-30 NOV	-44	-46	-55	-55	-56	-57	-57	-62	-57	-53	-41	-24	-6	-23	-30	-28	-30	-31	-33	-37	-42	-45	-50	-46	-44
1-15 DEC	-48	-51	-56	-56	-55	-56	-57	-61	-62	-58	-49	-35	-3	-17	-32	-33	-32	-34	-36	-39	-43	-47	-50	-48	-48
16-31 DEC	-45	-52	-58	-58	-58	-58	-59	-62	-64	-61	-52	-39	-3	-12	-29	-32	-32	-31	-33	-36	-40	-45	-47	-46	-45

Fig. 3--Sample Propagation Correction Table

The two principal sources of error are propagational variation and ability to predict propagation corrections. The distinction is significant. Propagation corrections are computed for intervals well in advance of use. Thus, they cannot be expected to reflect particular propagation conditions on any single day, but only the anticipated average phase-difference observations for the location and time considered. Error with perfect propagation corrections would still exist, since, in general, phase difference measurements on a particular day would not exactly match the anticipated normal measurements. The distinction is largely academic to the practical navigator since he is constrained to use published propagation corrections. To the system designer, however, the distinction is real, since propagation correction errors can be reduced as experience is gained and prediction techniques are refined.

Figure 4 shows a typical phase variation curve. The predicted values indicated are derived from calculations and are available in the form depicted in Figure 3. The difference in predicted and actual values includes both errors noted above. This sample is typical and would produce about one-half mile for the navigational fix.

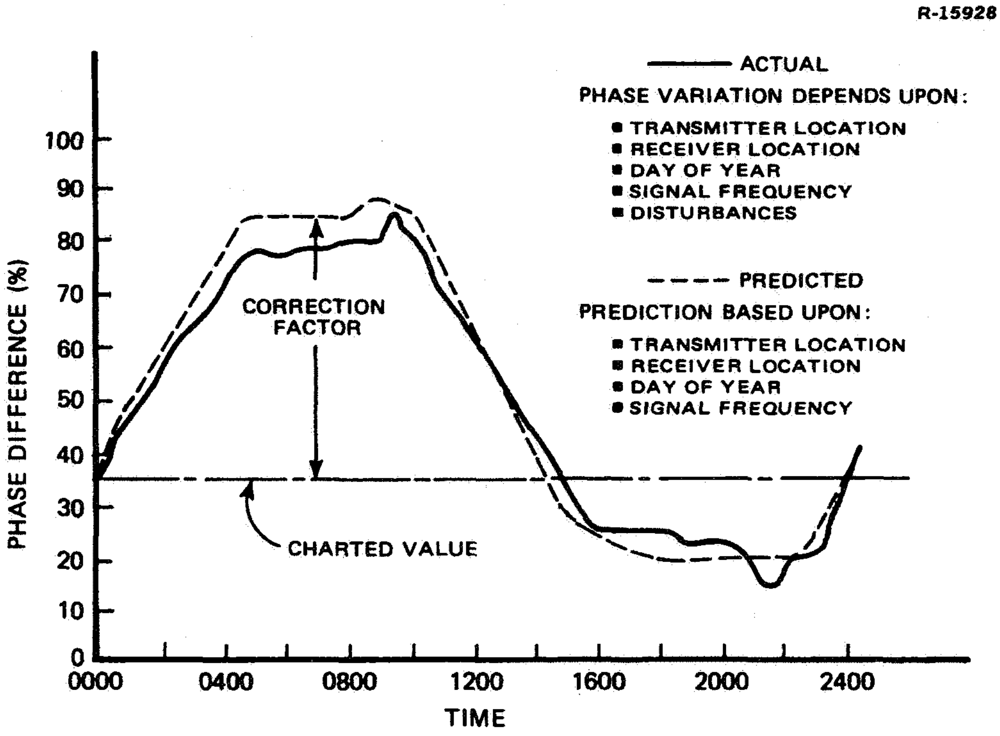


Fig. 4--Typical Phase Variation Curve

LANE IDENTIFICATION -

If positional measurements are made in terms of carrier phase at only a single frequency, it is clear that the phase observations will be identical at a large number of points in a nearly rectangular grid. At 10.2 kHz the separations of these ambiguous points would be about 8 miles, or 1/2 wavelength. This problem of ambiguity would never arise if the navigator should start from a known place and carry his positions forward by making observations (or having them continuously recorded) at intervals smaller than the time within which his errors of dead reckoning could reach 4 miles. On shipboard, this is the chosen solution. In an aircraft, however, a 4 mile uncertainty can accumulate in a few minutes, and the navigator might not care to place his entire reliance upon the continuity of operation of his equipment and of the signal reception.

For these and other reasons, the system has been designed to provide lane identification, in such a way that it may be used (or not) at the operator's convenience. In OMEGA, complete identification must be done in several stages.

If one made a second measurement of a line of position at a frequency of 3400 Hz (1/3 of 10.2 kHz), it is clear that it would coincide with one of each three possible 10.2 kHz positions, if the error of the measurement at the lower frequency were safely less than 1/2 of the period of the higher frequency. Since 3.4 kHz cannot be radiated successfully from the OMEGA antenna, this comparison is made by measuring the phase of the beat between 10.2 kHz and 13.6 kHz. These two frequencies cannot be radiated simultaneously, but in effect the 10.2 kHz phase is stored for the carrier-frequency measurement and this stored phase can be compared with the 13.6 kHz phase when it appears.

Continuing the process, a period of 3400 Hz signal can be identified by a measurement at a frequency three times lower, or at 1133-1/3 Hz. This frequency is the difference between the 10.2 kHz carrier and the 11-1/3 kHz carrier.

These multiple frequencies are employed as noted to create lanes which are larger than the basic 8 nm half-cycle wavelength. Use of the 3400 Hz frequency generates a 24 nm lane and 1133-1/3 Hz generates a lane width of 72 nm. Use of these frequencies reduces the problem of lane ambiguity commensurately. Very few receivers should need to resolve ambiguities of 72 nm unless an intermittent operation is expected. Figure 5 shows the relationship of these lanes.

FREQUENCY	
BASIC	DIFFERENCE
10.2 kHz	3.4 kHz (13.6 - 10.2)
11.3 kHz	1.1 kHz (11.3 - 10.2)
13.6 kHz	

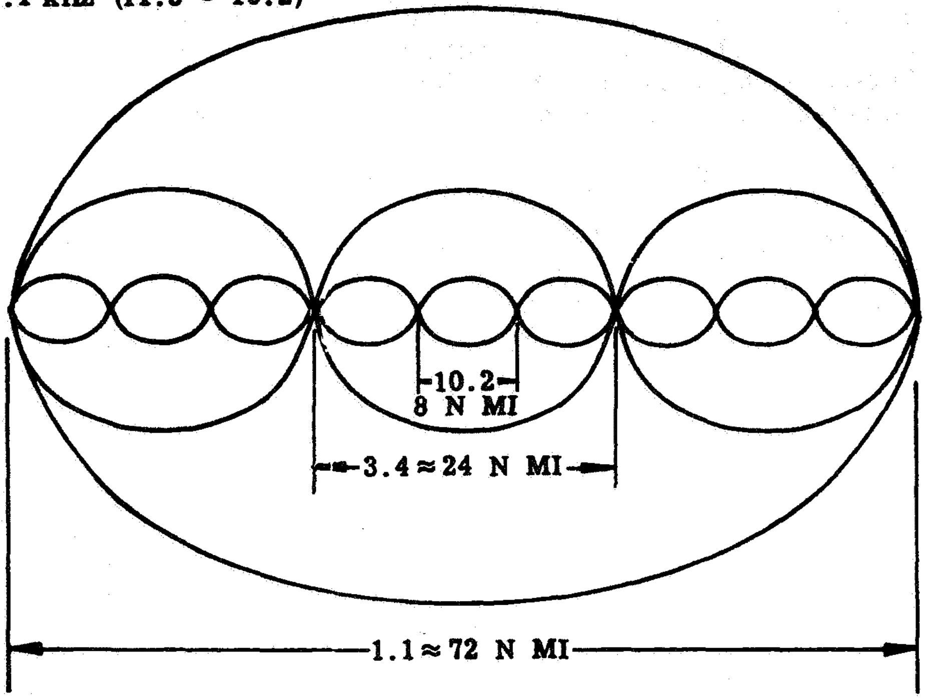


Fig. 5--Lane Resolution Relationships

SYNCHRONIZATION -

As noted previously, the definition of synchronization in OMEGA is that all antenna currents shall be in absolute phase whatever the locations of the antenna. This definition obviously neglects the fact that the various stations actually radiate their common frequencies at different epochs. The sources of frequency are, however, continuous and in phase. This condition is achieved and maintained as follows.

Each station is controlled by the mean of the frequencies of four standards, each locked to an atomic resonance but adjustable over at least a few parts in 10^{11}. All needed frequencies are derived from this combined source, and are internally checked and maintained to achieve very high reliability of phase. The precision of frequency is such that each phase can be trusted to 1 micro-second per day.

This frequency source is used to provide all radiated signals and also to drive a clock. At each station, this clock is used to record the time of arrival of every signal from every other station. Once each day these observed times of arrival are reduced to a single number for each station. By appropriate calculations, these numbers are intercompared to each other and to standard time, such as from the Naval Observatory, to compensate for any offset that may occur between the atomic clocks of the various stations.

TRANSMITTING STATION IMPLEMENTATION

The OMEGA system, when completed, will consist of eight stations as discussed earlier. For ease in identification, these stations have been assigned letter designations of A through H. Table I identifies the station by letter designation, location, and antenna type.

TABLE I

STATION	LOCATION	ANTENNA TYPE
A	Bratland, Norway	Valley Span
B	Trinidad/Liberia	Valley Span/Grounded Tower
C	Haiku, Hawaii	Valley Span
D	La Moure, North Dakota	Insulated Tower
E	La Reunion Island, Indian Ocean	Grounded Tower
F	Golfo Nuevo, Argentina	Insulated Tower
G	South East Australia	Ground-Tower (Proposed)
H	Tsushima Island, Japan	Insulated Tower

Except for the commutation pattern depicted in Figure 2, the electronics characteristics of the station are alike. The principal difference is associated with the antenna type which has some effect on the bandwidth, and thus on the rise and decay times of the waveform. These minor differences have no practical impact on the navigator. The selection of the antenna type was based on site characteristics and cost associated trade-offs.

The Norwegian Station construction was completed in December 1973 by the Norwegian Telecommunications Administration. This station is currently broadcasting the OMEGA signals at an effective radiated power of six to seven kilowatts.

The Trinidad OMEGA station, in existence as an operational evaluation station since 1966, will be replaced by a new station in Liberia. Relocation of this mid-equatorial Atlantic station to the African Coast will improve the OMEGA coverage available to the major shipping and trade routes from Europe around Cape of Good Hope. Liberia, in cooperation with the United States, has made final the site selection and survey. Construction is in progress with a scheduled completion date of September 1975.

The Haiku, Hawaii, OMEGA station renovation and upgrading has been completed. A new valley span antenna complex and ground system has been installed. Interior building renovation to accommodate a new electronic suite is included. Construction has been completed.

The La Moure, North Dakota, OMEGA station was the first permanent OMEGA station. This station has been providing operational signals since October 1972.

The La Reunion Island OMEGA station is under construction by the French Navy on a site near Port des Galets. This site is located in the Indian Ocean cyclone area which has significant impact on construction schedules, in particular the schedule for erection of the 1,400' tower. Tower fabrication and erection schedules currently support an on-air date of no earlier than December 1975.

The Argentine OMEGA station at Golfo Nuevo, located in the coastal area of central Argentina, is approximately 600 miles south of Buenos Aires. This region of the country is comparable to the southwestern United States, and its flat terrain provides an excellent platform for a tower antenna system. The tower for OMEGA Argentina is on site with construction in progress under supervision of the Argentine Navy. Scheduled on-air date is July 1975.

The Government of Australia is currently reviewing a proposal from the Government of the United States that Australia construct and operate an OMEGA navigation station on their sovereign soil. It is anticipated this station might be located in southeastern Australia. In all likelihood, it will use a tower antenna system. Until diplomatic procedures have been completed, no estimate of an on-air date can be made, but past experience has indicated about thirty-six months is required from final site selection to on-air.

Japan has undertaken to construct an OMEGA station on Tsushima Island in the Sea of Japan. This venture represents the first major OMEGA construction program to be totally directed by a partner nation. Design has been completed and construction is in progress. This station will feature a 1,500' cylindrical tower antenna structure. It is now broadcasting and it is expected that the station will be operational by April 1975. It will provide the first expansion to system coverage since 1966.

SYSTEM MANAGEMENT

Overall system implementation is continuing under the direction of the U. S. Navy OMEGA Project Manager[1]. Agencies of the other participating nations are coordinating their programs with the United States. The U. S. Coast Guard operates the U. S. stations.

The Coast Guard OMEGA Navigation System Operations Detail[2] was established in July 1971. This organization has recently assumed operational responsibility for the OMEGA system. It is intended that the Coast Guard Operations Detail operate the system for the Navy pending total implementation or when mutual agreement is reached for the Coast Guard to assume full U. S. responsibility for the OMEGA system.

OMEGA stations on foreign soil will be operated by host nation agencies who will be responsible for maintaining the OMEGA signal without interruption and in phase with the worldwide OMEGA navigation system. These agencies are listed in Table II.

TABLE II

STATION	AGENCY
A. Norway	The Norwegian Telecommunications Administration
B. Liberia	Department of Commerce, Industry, and Transportation
C. Hawaii	U. S. Coast Guard
D. North Dakota	U. S. Coast Guard
E. La Reunion	French Navy
F. Argentina	Argentine Navy
G. Australia	Department of Transport Coastal Services Division
H. Japan	Japanese Maritime Safety Agency

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