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OMEGA IN THE ATLANTIC (1963-1965)

In-Port Measurements from HMS VIDAL and HR. MS. SNELLIUS
on Oceanographic Survey NAVADO

E. R. Swanson and W. E. Davis • Research and Development Report • 10 January 1966
U. S. NAVY ELECTRONICS LABORATORY, SAN DIEGO, CALIFORNIA 92152 • A BUREAU OF SHIPS LABORATORY

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THE PROBLEM

Analyze Omega phase differences recorded in port aboard the oceanographic survey ships HMS VIDAL and HR. MS. SNELLIUS.

RESULTS

Approximately 2500 hours of recorded phase differences from 24 ports of call and five different lines-of-position indicate that a 24-hour navigation capability of about 0.9 n.mi. (c.e.p.) may be expected in an implemented Omega system, assuming only present radiated powers and prediction ability.

RECOMMENDATIONS

Plan general refinements in the methods of synchronization and prediction, employing the data compiled for this report, to improve predictions. No further analysis specifically restricted to the Atlantic is envisioned.

ADMINISTRATIVE INFORMATION

Work was performed from October 1963 to December 1965 under SS 161 001, Task 6101 (NEL A10461). The report was approved for publication 10 January 1966.

MBL/WHOI

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The authors wish to express appreciation to the many persons who contributed to the success of the operation, but especially to the engineers at the transmitting stations and the officers and men of both ships. R. Gallenberger and R. Finkle, both of San Diego State College, assisted in the data analysis. Mrs. Rita Brown programmed the 1604 computer to predict skywave corrections.

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INTRODUCTION

Although still developmental and not in continuous operation, the Omega navigation system is frequently in demand for special operations. Such an operation was the Project NAVADO oceanographic survey of the North Atlantic. Installation of an Omega receiver on HMS VIDAL was made in the fall of 1963. Subsequently the receiver was transferred to HR, MS, SNELLIUS and remained onboard until August 1965.

10.2-kc/s
measurements in
port analyzed

This report analyzes 10.2-kc/s signals received by the survey ships in 24 ports of call.

INSTALLATION OF EQUIPMENT

Installed on
VIDAL, October
1963

The installation of HMS VIDAL was made at the request of the Bureau of Ships (Code 362A). Routine installation was accomplished at Portland Dockyard, Portland, England, in October 1963 with the assistance of a representative of the U. S. Navy Electronics Laboratory. The field engineer also accompanied the ship for a period sufficient to provide necessary assistance in operation and training.

Transferred
to SNELLIUS,
October 1964

Survey assignments within Project NAVADO were changed in fall of 1964 with the VIDAL being reassigned to resurvey the first four lines. The Dutch ship HR, MS, SNELLIUS continued the northern survey lines in the Atlantic. Because of the change in assignment and at the request of the Hydrographer, Royal Netherlands Navy, the Omega receiver was transferred from the VIDAL to the

Removed
August 1965

SNELLIUS in October 1964 at Portland dockyard. Again, the field engineer assisted in the installation and rode the ship to assist in operation and training. Because of the loss of signals from Criggion, due to other commitments, the equipment was removed at Halifax, Nova Scotia, in August 1965.

Both installations were conventional and used the Omega receiver manufactured by ITT (Type II, Serial 2) with various whip and wire antennas. However, the internal Manson oscillator was not used on the VIDAL which had a precision frequency standard.

SUPPORT

Close liaison

An engineer from the U. S. Navy Electronics Laboratory spent a total of approximately five months aboard the ships during the two years of operation. When aboard, he assisted in navigation, receiver operation, and maintenance and helped train the officers and crew. Equally important, from the present viewpoint, he was responsible for monitoring when the ship was in port.

Tables and
skywave correc-
tions provided

NEL also provided support to the ships in the form of navigation tables and skywave corrections. Because of the large area involved (approximately 10 million square miles), this effort proved substantial although skywave corrections were computed more sparsely than would have been done for an operational system. All totalled, approximately 20 hours of computer time were used for support and evaluation of the operation.

Data received

Support was received as well as given. Both ships monitored Omega signals in port and forwarded the results to this Laboratory. Excellent cooperation was received and the data have been of substantial importance in refining the Omega system calibration.

RESULTS AT SEA

Equipment reliable

While it is not the intent of this report to evaluate the actual operation at sea, it is germane to note that the equipment functioned reliably. Exclusive of recorders, only a few failures occurred during each year of operation, including routine tube replacements. Reliable functioning was also noted in informal letter reports from Rear Admiral G. S. Ritchie, R.N., presently the Royal Hydrographer but then Captain commanding the VIDAL, and from LT CDR F. Bradander, R. Neth. N., commanding the SNELLIUS.*

Transmission schedule intermittent

It is regretted by all concerned that the developmental nature of the Omega system precluded continuous transmissions from all stations. Most transmissions were scheduled either on a 16-hour day, seven days a week, or on a 24-hour day five days a week. Frequently, it was possible to provide only one line-of-position (LOP). It should be emphasized that intermittent operation is particularly inconvenient because of the necessity of reestablishing lane count. Indeed, the discontinuity of transmissions was such as to render operation nearly marginal at certain times.

Correction problems

Particularly during the early part of the operation, skywave corrections were based on limited data. To improve calibration, the computed skywave corrections were frequently adjusted by local monitoring in port. This technique, while unnecessary for a navigator in an implemented and well calibrated system, is believed to have substantially improved the actual navigation accuracy obtained at sea during the present operation. Also, it should have mitigated or eliminated the effects of an offset mistakenly included in the Criggon-Forestport computations.

*See also reference 1 in list at end of report.

Good signals

In general, Forestport, Summit, and Criggion were easily received throughout the entire North Atlantic while infrequent attempts to measure Haiku were routinely successful in the Western Atlantic. In the Eastern Atlantic, Haiku was marginal in the Canary Islands (about 7000 n.mi.) and usually could not be used when the propagation path passed over Greenland (although measurements were made in the Netherlands).

It is the consensus that a system such as Omega is particularly useful for oceanographic survey work in mid-ocean. The system was also of value in standard navigation problems such as making a land-fall after prolonged operation without star sites.

Poor geometry

In addition to skywave correction problems, one of the most significant accuracy limitations in the Atlantic area is the purely geometric one resulting from the locations of the existing developmental stations. Figures 1 and 2 illustrate the expected Omega fix accuracy for various lines-of-position in the North Atlantic. These are based on system geometry existing during the operation and a theoretical model which assumes 4-centilane timing errors believed indicative of daytime conditions.² The accuracy at night and during transitions would be less than that indicated by the figures.

Figure 1. Early Omega system accuracy (Atlantic): Forestport-Summit; Criggon-Summit. (Theoretical accuracy contours based on an assumed standard deviation of 4 cel and correlation of 0.4 everywhere.)

Figure 2. Early Omega system accuracy (Atlantic): Crigglion-Summit; Hoiku-Summit. (Theoretical accuracy contours based on an assumed standard deviation of 4 cel and correlation of 0.4 everywhere.)

RESULTS IN PORT

Whenever the survey ships were in port, available Omega signals were monitored. These data are especially valuable since the positions of the ships were carefully determined.* Most of the in-port data were measured by the respective navigators and forwarded to NEL for analysis. The data have proved to be virtually free from incidental errors and nearly always significant.

Slaved
transmissions
measured in 24
ports of call

Phase differences were measured in 24 ports of call from 10.2-kc/s transmissions in the "slaved" mode. As changes in the transmission schedule caused unusual lines-of-position to be available at various times and since some of the ports were revisited, more data were obtained than might be expected from single visits using existing equipment. Also, manual and automatic time sharing were used for a few measurements. The net result was that 60 site-LOP's were obtained using five different lines-of-position. The average monitoring duration was three days.

60 site-LOP's

Half-hourly readings from a typical phase difference recording are shown in figure 3. The scatter on the graph is that actually displayed on the original recordings since no time averaging was used in the reduction. The scatter is indicative of the receiver time constant of about 30 seconds. For the particular measurement shown in figure 3, all component propagation paths are dark between

*Each position determination was referenced to local datum. Accurate conversion to international coordinates could not be made for all locations. The overall error resulting from inadequate geodetic information is believed small although probably appreciable. Errors at individual sites, however, may be important.

Figure 3. Typical 10.2-kc/s Omega phase difference. Half-hourly measurements on Criggian-Summit in-part at Chaguaramas, Trinidad, 21-24 Dec 63.

2300 and 0800Z while all are sunlit between 1130 and 1600Z. The figure shows the usual features of the Omega phase difference, namely, constant (or "flat") at night with a slow change (or "curvature") during the day.

Because phase differences tend to be constant at night, a single average nighttime phase difference may be meaningfully computed for each of the site-LOP's. The average values observed, combined with appropriate lane assignments, may then be compared with theoretical computations. Such a comparison is shown in table 1 where the theoretical computations were based on the determination of phase coefficients made early in 1965.³ The last column is

TABLE 1. AVERAGE PHASE DIFFERENCES AT NIGHT

Site-LOP LOP ^a	Site	Date	No. Nights	W _t ^b	Night Average (lanes)	Residual discrepancy with computation (cec) ^c
Normal Site-LOP's						
FP-SU	Al Yadida, Morocco	Jul 64	2	1	64.54	1.5
FP-SU	Azores	Jun 64	2	1	59.67	4.3
CR-SU	Azores	Jun 64	3	2	152.08	- .6
CR-SU	Bathurst, Gambia	Dec 63	2	1	202.04	-10.1
FP-SU	Bathurst, Gambia	Dec 63	2	1	116.06	- 2.6
CR-SU	Bridgetown, Barbados	Jan 64	5	2	432.53	- 8.0
FP-SU	Bridgetown, Barbados	Jan 64	1	1	179.82	1.2
CR-SU	Cadiz, Spain	Jul 64	2	1	74.65	- 2.9
FP-SU	Cadiz, Spain	Jul 64	1	1	56.65	1.6
CR-SU	Casablanca, Morocco	Jul 64	1	1	90.63	- 5.8
CR-SU	Casablanca, Morocco	Apr 65	1	1	53.21	- 9.9
FP-SU	Casablanca, Morocco	Jul 64	2	1	63.35	- .4
CR-SU	Chaguaramas, Trinidad	Nov 63	10	3	452.50	- 7.9
FP-SU	Chaguaramas, Trinidad	Nov 63	5	2	194.26	- 6.5
FP-SU	Den Helder, Netherlands	Nov 64	7	3	24.42	- 5.3
CR-SU	Gibraltar	Jun 64	2	1	73.09	2.5
FP-SU	Gibraltar	Jun 64	2	1	57.07	1.4

Table 1. (Continued)

Site-LOP LOP ^a Site	Date	No. Nights	Wt ^b	Night Average (lanes)	Residual discrepancy with computation (cec) ^c
Normal Site-LOP's (Continued)					
CR-FP Hamilton, Bermuda	Mar 65	1	1	308.39	- 2.7
HK-FP Hamilton, Bermuda	Mar 65	1	1	522.46	- 1.5
FP-SU La Coruna, Spain	Nov 64	2	1	43.56	6.7
CR-FP Las Palmas, Canary Islands	Feb 65	3	2	89.08	- 5.1
CR-SU Lisbon, Portugal	May 64	5	2	76.23	9.1
CR-FP Lisbon, Portugal	May 65	2	1	49.02	4.3
FP-SU Lisbon, Portugal	May 64	3	2	53.20	6.8
FP-SU Matosinhos, Portugal	Oct 63	3	2	47.95	6.4
FP-SU Portland, U.K.	Oct 63	1	1	29.35	2.7
FP-SU Portland, U.K.	Nov 64	2	1	29.39	4.1
FP-SU Rotterdam, Netherlands	Oct 64	1	1	26.08	6.6
CR-SU San Juan, P.R.	Dec 64	1	1	445.74	7.0
FP-SU San Juan, P.R.	Dec 64	1	1	168.14	3.4
"Near" Site-LOP's					
CR-FP Charleston, S.C.	Mar 65	3	0	351.20	10.7
HK-FP Charleston, S.C.	Mar 65	3	0	485.08	6.6
CR-SU Curacao	Dec 64	6	0	490.44	1.0
FP-SU Curacao	Dec 64	6	0	209.00	3.2
HK-SU Curacao	Dec 64	6	0	566.51	2.0

Table 1. (Continued)

LOP ^a	Site-LOP Site	Date	No. Nights	Wt ^b	Night Average (lanes)	Residual discrepancy with computation (cec) ^c
"Near" Site-LOP's (Continued)						
CR-FP	Den Helder, Netherlands	Jul 65	2	0	1.84	22.6
CR-SU	La Coruna, Spain	Nov 64	1	0	54.84	- 6.2
CR-FP	Norfolk, Va.	Apr 65	13	0	349.88	-11.2
HK-FP	Norfolk, Va.	Apr 65	5	0	510.19	- 7.5
CR-SU	Portland, U.K.	Nov 64	2	0	7.49	- 1.6
CR-SU	Rotterdam, Netherlands	Oct 64	1	0	.72	28.8
Site-LOP's With Arctic Path Component						
HK-SU	Den Helder, Netherlands	Nov 64	6	0	381.98	23.5
HK-FP	Las Palmas, Canary Islands	Feb 65	2	0	527.95	- 1.8
HK-FP	Tenerife, Canary Islands	Feb 65	1	0	528.26	5.0

- Notes:
- LOP's coded slave minus master as follows: HK, Haiku; FP, Forestport; SU, Summit; CR, Criggion. "Near" site-LOP's have path components less than 700 n.mi.; site-LOP's with arctic path components include propagation in arctic regions of poor conductivity.
 - Weights approximately equal to square root of number of nights of observation (except "near" site-LOP's and LOP's with arctic path components).
 - Residual positive if observation greater than computation, i.e., positive residual indicates additional net delay. Note that a delay on the path to the master station will yield a negative residual.

Discrepancy of
night averages
5.8 cec

the residual discrepancy between the observed average and the computed value in centicycles (cec). Since the observational average from only a few nights of monitoring is not necessarily equal to a long-term mean at a particular site, the rms residual discrepancy of 5.8 cec for the 30 site-LOP's, where the prediction theory is applicable, is not completely due to prediction error. Presently, the prediction theory is invalid near transmitting stations where significant energy may be propagated by the second wave-guide mode or in cases where one of the component propagation paths passes over arctic regions of very poor conductivity.⁴

Perturbations
over short paths
at night

Although practical navigation was not recommended using a station within 1000 n.mi., for tabulation purposes only measurements with component propagation paths shorter than 700 n.mi. (1300 km) have been identified as "near." A theoretical estimate of the effect of the second mode on the resultant phase over short propagation paths is shown in figure 4. The curve was produced from the work of Wait and Spies⁵ based on the isotropic model ionosphere.* The theoretical work is important since it indicates peak deviations of on the order of one n.mi. or less. However, the work cannot yet be considered sufficiently reliable to warrant additional corrections. In particular, if the quasi-wave length were only slightly off, corrections of the wrong sign might be

Theoretical
perturbations
not large

*Specifically an ionospheric height of 90 km, gradient of 0.5 km^{-1} and infinite surface conductivity were assumed. The curves of Wait and Spies were then used to obtain the relevant parameters for propagation at 10.2 kc/s, viz: relative velocity, attenuation rate, and excitation. The values obtained were, respectively, 1.0003; 1.6 dB/Mm; -1.3 dB at 6.3° for the first mode and 1.0303; 8.8 dB/Mm; and 1.4 dB at 20° for the second.

Figure 4. Phase perturbation over short paths at night. (After Wait & Spies, 10.2 kc/s.)

Short path
effects observed

applied. Nonetheless, there is a rather surprising agreement between the computed effects and those actually observed. Charleston, S. C., is 675 n.mi. (1250 km) from Forestport, while Curacao is 660 n.mi. (1220 km) from Summit, so that measurements at these sites would be expected to have +6.5-cec residual discrepancies in table 1. The actual discrepancies average 4.3 cec. The theoretical work indicates that an additional delay of 12 cec should be expected over the 395 n.mi. (731 km) path from Forestport to Norfolk, Va. The sense of the measurement indicates that a residual of -12 cec would be expected. The average residual is about -9 cec. Because of the effects of higher-order modes, the

theoretical model may not apply over shorter paths such as those from Criggion to the Netherlands sites. While the phase differences observed in Holland cannot be explained at present, the path lengths, 285 and 281 n.mi. (528 and 521 km), are comparable as are the residual discrepancies.*

The foregoing is not an adequate sample from which to verify the theoretical model. However, it is at least encouraging and may constitute an initial understanding of Omega operation near transmitters. It is noteworthy that both the observed and theoretical discrepancies are small at moderate distances from stations. Exclusive of sites where higher modes may be significant, the rms discrepancy of the observed data in this region is 7.2 cec if no second mode corrections are made.

A consistent picture of arctic propagation cannot be expected from brief monitoring at only five locations. However, some of the measurements in the Canary Islands and the Azores are of considerable value since the residual errors can confidently be said to include the effect of a decrease in the propagation velocity of the Haiku signal in the vicinity of Hudson's Bay and Labrador. In particular, the propagation paths may be compared with a recent conductivity map by E. L. Maxwell** from which it is found that about 3000 km of propagation occur over ground with a conductivity of one millimho per meter or less, nominally averaging 0.6 millimho per meter. While theoretical estimates of the additional phase delay expected for a 10.2-kc/s signal propagated over this path are not directly available,

*Criggion-Summit phase differences in Portland, U.K., reflect propagation over a very short path.

**Furnished in a personal communication to the author, 9 June 1965.

a crude estimate is possible using the work of Wait and Spies.^{5,6} A delay of 10 to 20 cec may be expected. The effect is neither confirmed nor rejected by the observed phase differences because of the brief monitoring and also because of the high scatter resulting from a poor signal-to-noise ratio.

The measurements at Den Helder include propagation directly over the Greenland ice cap and also propagation at extreme northern latitudes. No attempt at analysis is justified at the present time. In fact, the lane assignment for this particular measurement is only tentative.

Daytime
propagation

Phase-difference measurements during the day are more complicated to analyze than those at night, since phase velocity varies with the solar zenith angle and exhibits related seasonal changes. In general, for normal illumination of the ionosphere, phase prediction is more easily accomplished during the day than at night. In particular, propagation during the day is less sensitive to geomagnetic path orientation, latitude, and the effects of the second waveguide mode. Prediction methods have been discussed elsewhere and widely applied.^{4,7} The basic prediction coefficients have been in use since December 1963.

Computer
predictions

Day and night prediction coefficients have been combined in a computer program together with transition criteria to predict the phase difference observed at any location at any time of day. While neither the daytime prediction coefficients nor the transition criteria have been changed since the inception of the computer program, changes in the computation procedure at night were made early in 1965 and can affect the predictions at all times of day. Present computer results therefore differ slightly from those provided for navigational use during the early part of the operation and those used in an earlier analysis.⁸ Also, an offset erroneously present in the Criggion-Forestport corrections has been corrected. Comparisons of observed

phase differences with predicted diurnal variations are shown in figures 5 to 9. A complete set of such curves has been compiled as a supplement to this report.⁹

The computer predictions are no more accurate than the basic prediction model employed and hence the limitations previously discussed apply; the effects of the second and higher propagation modes should be considered when using a nearby transmitter. In practice, operation within 1000 n.mi. of a station was not advised although the corrections provided were valid first-mode predictions to 840 n.mi.

Figure 5. Bathurst, Gambia: Forestpart-Summit, 10.2-kc/s Omega phase difference (4 to 6 Dec 63).

Within 840 n.mi. the computations were invalid for navigation but of some interest for analysis. Recently the computer program was modified to approximate corrections near transmitters. The modification uses simplified transition criteria and still does not include the effects of the second and higher-order propagation modes. Where applicable, comparisons with observed data have been made with modified corrections. The supplement indicates that the corrections may be adequate for some types of navigation even using nearby transmitters.⁹

Figure 6. Bridgetown, Barbados: Criggion-Summit, 10.2-kc/s Omega phase difference (30 Dec 63 to 2 Jan 64).

Figure 7. Charleston, South Carolina: Haiku-Forestport, 10.2-kc/s Omega phase difference (8 to 11 Mar 65).

Results

Comparison of the observed and computed phase differences permits a system evaluation in the area.* Three periods will be considered separately, namely: night (when all component propagation paths are dark); day (all illuminated); and transition (mixed). During each period, each observed value has been compared with the

*Because of present prediction limitations, measurements including propagation over paths less than 700 n.mi. or in arctic regions have been excluded from the analysis.

Figure 8. Den Helder, Netherlands: Forestport-Summit, 10.2-kc/s Omega phase difference (16 to 26 Nov 64).

corresponding prediction and an rms value obtained.* The results are summarized in table 2. The discrepancies reflect errors of all types but especially the stability of the propagation medium and present prediction errors. The results are consistent with previous estimates. However, the rms discrepancy during the day has been seriously affected by prediction errors and may be expected to

*See ref. 9 for a description of the computations and more detailed summary of the results.

Figure 9. Las Palmas, Canary Islands: Criggion-Forestpart, 10.2-kc/s Omega phase difference (10 to 14 Feb 65).

TABLE 2. TYPICAL DISCREPANCIES BETWEEN OBSERVED AND PREDICTED PHASE DIFFERENCES

Period	RMS Discrepancy (cec)
Day	6.7
Night	8.1
Transition	10.8
Overall	9.2

Probable fix
accuracy during
survey if using
present predic-
tions:
1-1/2 n.mi.

Accuracy of
implemented
system:
Day 0.7 n.mi.
Night 0.8 n.mi.
Transition 1.1 n.mi.
Overall 0.9 n.mi.

substantially improve when the daytime propagation coefficients have been revalued.*

The overall accuracy which would be actually obtained using present prediction in the entire North Atlantic area may be estimated from figures 1 and 2 and the overall rms discrepancy. Apparently, a typical circular error probable on the order of 1-1/2 n.mi. is appropriate for the 24-hour day. However, results during the day would be better than nominal while results at night and during transitions would be worse; and, of course, the expected accuracy varies considerably with position. In practice, actual results might be either better or worse. The earlier skywave corrections provided to the ships were not as refined as those used in the present analysis. Computations for Criggion-Forestport were in error. At best, the spatial density of corrections was rather sparse, thus presenting a possibility for interpolation errors. However, adjustment of the computed diurnals by local monitoring in port may have considerably reduced the effect of prediction errors.

The results may also be used to evaluate the accuracy available in an implemented Omega system. The application is not direct but depends on assumptions of eventual system geometry, possible effects of spatial correlation, and the effect of operating in the absolute mode instead of operating with some stations actually synchronizing as slaves to a master station. It has been shown that an approximate conversion from LOP error in the synchronized mode to fix error in an implemented system may be made by multiplying the present results by 0.1 n.mi./cec.** Hence, the

*See footnote on page 8 of reference 7 and also reference 4.

**See references 2, 10, and 11. In particular, multiplication by 0.106 n.mi./cec yields rms fix error while multiplication by 0.093 n.mi./cec yields the c.e.p.

observed phase differences are indicative of an implemented system accuracy of 0.7 n.mi. during the day, 0.8 n.mi. at night and 1.1 n.mi. during transitions, based on present radiated powers and predictability.

CONCLUSIONS

Omega phase differences on various lines-of-position were measured over ten million square miles during a period of two years. Most data are well explained by present propagation theory while the additional data measured should serve as a useful basis for extending the theory to arctic and short propagation paths.

The results continue to indicate that a 24-hour accuracy of about 0.9 n.mi. will be obtained in an implemented Omega system.

The operation was also noteworthy from the standpoints of reliable equipment operation for an extended period and of excellent and mutually beneficial international cooperation. This Laboratory is especially appreciative of the fine cooperation received from the entire complements of both ships.

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Note: Since this report was prepared, the work by E. L. Maxwell referred to on page 18 has been published in:

Deco Electronics, Inc., Report 54-F-1, OMEGA Navigational System Conductivity Map, by R. R. Morgan and E. L. Maxwell, December 1965

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