RESULTS OF RECENT EXPERIMENTS WITH DIFFERENTIAL OMEGA

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SUMMARY

Evaluation tests of the Differential Omega mode of electronic navigation associated with an original procedure for transmission and application of skywave corrections (SWC) by automatic means have recently been conducted at land-based locations and on board ships at sea.

The procedure under review, which is capable of an accuracy better than 1 centicycle (CEC) in the transmission of SWCs by a single station is quite simple and cheap up to a distance of 400 n.m. The system has been designed to permit up to eight such transmitters being included in one frequency range (total bandwidth 1.2 kHz). With the chain of transmitters thus constituted up to 5 000 km of ocean coast may be covered at little cost. The correction receivers are constructed to function in either the 285-315 kHz or the 1.6-3 MHz range.

Tests have been carried out using a SWC transmitter with a coverage of 400 n.m. and a mobile receiver unit comprised of a conventional Omega receiver, a Differential Omega receiver, and a Toran radiolocation receiver with a position location capability better than 50 metres for calibration purposes. All these were digitized instruments and their outputs were, in addition, simultaneously recorded on paper tape (analog presentation) and punched tape (teleprinter ASR 33).

A comprehensive program was used to translate the data thus collected to geographical coordinates, and to compute errors in terms of Omega phase discrepancies, and also in terms of distance and azimuth with respect to the reference position given by Toran readings.

Recordings have been made ashore over distances of from 5 to 300 km, in addition to two experimental campaigns at sea. A total of over 10 000 measurement points have been logged over a 3 deg × 3 deg area having its centre at 46°N and 3°W.

Results have fully substantiated what was expected of the system in its present configuration. Considerable improvements will undoubtedly result from the increase in power of station D, and when a better geometry is obtained with the additional four Omega transmitters now planned in operation.

INTRODUCTION

Since 1966 SERCEL has been investigating the problems connected with the Omega system. The outcome of this investigation has been the production in limited numbers of two types of receiver, M2 and RR. FX. 2.A (*), and the development of a prototype whose performance and technology make it fit for aircraft use.

Particulars of these receivers are shown in table 1.

TABLE 1

Characteristics of the SERCEL'*s Omega receivers*

Type	M2	RR. FX. 2. A	Airplane prototype
Frequencies	10.2, 11.33, 13.6	10.2, 13.6	10.2, 11.33, 13.6
Mode	Hyperbolic	Hyperbolic	Hyperbolic
Readout	Needles and counters	Nixies	L.E.D.
Synchronization	Manual	Automatic	Manual
Lane identification	Manual	Automatic	Direct display
Accuracy	1 CEC	1 CEC	1 CEC
Maximum speed for an error of	50 knots 1 CEC	50 knots extension 800 knots 1 CEC	1 500 knots 1 CEC
Weight	15 kg	17 kg	22 kg
Power supply	45 VA ; 50 Hz 35 W ; 12 V	100 VA ; 50/400 Hz 85 W ; 27 V	110 W ; 27 V

More recently, in 1970, a feasibility study has been conducted on a system having capability for automatically transmitting and applying SWCs to Omega signals. The ultimate aim was the development at a later date of a comprehensive network of SWC transmitters for Differential Omega navigation. One objective of this work was maximum simplification of the additional equipment (SWC receiver) necessary for automatic reception and application of the corrections to conventional shipboard Omega receivers. It is expected that this system will, at very low cost, completely relieve navigators of the thankless task of applying corrections

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(*) Model accepted by the French Navy.

taken from tables when the ship is hugging the coast, while at the same time materially improving position location accuracy as compared with conventional Omega navigation using SWC values given by USNOO tables, or alternatively a computer associated with the receiver.

FIG. 1. — Dual-frequency receiver, model RR.FX.2.A, with automatic lane identification, as accepted by the French Navy.

As interest in this project was being shown by French governmental circles, development work was started on models and prototypes for at-sea tests. A first series of tests was completed between June and October 1971, and further test series are planned to take place in 1972. As all results have been recorded in digital form, the analysis is materially facilitated by using a computer.

PRINCIPLES OF SWC AUTOMATIC TRANSMISSION AND APPLICATION

The heart of the system is an Omega receiver located in a position whose geographical coordinates are known. This makes it possible to accurately determine the theoretical phase values corresponding to the signals from the respective Omega transmitters received at that position. The receiver actually reads, for each station, phase values which are in error with respect to the theoretical value by a quantity varying with time according to ionospheric fluctuations and to physical phenomena which affect wave propagation velocity all along the path from the Omega transmitter to the receiver.

The phase values corresponding to the Omega stations capable of being used at the chosen position are compared with the calculated theoretical values. The differences, variable with time, constitute the correction values.

In other words, there are as many correction values to be retransmitted to the mobile receivers as there are usable Omega signals at the chosen position. In the system under review the number of corrections has been limited to four, and in the tests discussed in this paper they apply to the Omega stations now in operation, i.e. A, B, C, and D.

In fact, the phase measurements effected by the receiver are referred to the phase of its local oscillator. As, however, the phase difference is the same for all stations its effect is cancelled by subtraction in the correction receiver of the mobile unit. Incidentally, the phase reference of this local oscillator is also transmitted by the system, which makes it possible to use the Omega receivers in the mobile units in either the circular or hyperbolic mode.

As transmission of the phase correction values for the respective stations is by an analog process, this results in a very simple receiver construction. Phase correction signals for the respective stations are continuous 1 kHz sine waves, the value of the phase correction to be transmitted being in the form of a phase difference with the 1 kHz internal reference, the latter in turn being phase coherent with the local oscillator.

In effect, the analog transmission contains a total of five signals : four phase signals plus the reference signal. In order to minimize the transmission band width *all* the signals are first reduced to a conveniently low (20 Hz) frequency, which constitutes a satisfactory compromise between the full transmission width and the effect of transmission defects likely to result from transmission speed and signal fading.

All five signals are then multiplexed over time with a format corresponding to the original Omega format : this results in a synchronized demultiplexing format being available at reception point. Phase correction information for all four stations is then routed via a single channel and can be used for phase modulation of a 100-watt transmitter in the 2 MHz or 300 kHz range.

Shipboard installations include a correction receiver which accepts and handles the phase correction signals. The receiver is connected via a single cable with the standard Omega receiver. The correction receiver contains a double superheterodyne section, the second frequency converter being driven by a small frequency synthesizer : this offers a choice of four frequencies above and four below the reception frequency, the interval between any two frequencies being 160 Hz. The second channel has a bandwidth of 50 Hz adapted to the frequency spectrum of one transmitter. The receiving system is thus capable of receiving the signals from eight correction transmitters capable of being used in chain formation. In fact any frequency may be chosen.

Selection of a station may be effected by simply selecting the frequency of the second local oscillator in the receiver. A discriminator and a filter placed after the second frequency converter are used to separate the 20 Hz signals. The Omega segments corresponding to the four stations used are taken from the ship's Omega receiver and used by the correction receiver as demultiplexing commands for the 20 Hz signals. The four 20 Hz demultiplexed signals are then demodulated according to two quadrantal components by a 20 Hz signal generated locally in the correction receiver. The demodulated signals are routed through a narrow-band filter and the resulting voltages appear across four pairs of leads (one pair per station).

These voltages are proportional to the sines and cosines of the angles corresponding to the corrections.

The ship's Omega receiver receives the Omega signals carried by as many LF signals as there are stations being received. In conventional Omega operation these signals are applied to the meters which show the phase differences between the respective stations : in hyperbolic mode each meter receives the signals from two stations; in circular mode it receives the signal from one station and a signal from a high-stability standard.

In Differential Omega navigation, all four LF signals which carry the phases from the four stations used by the receiver are taken from the Omega receiver and routed over a cable to the correction receiver which contains four electronic phase-shifters. Each of these is driven by voltages equal to the sines and cosines of the correction angles. Each of the LF signals from the Omega receiver goes through one of the phase shifters where it is subjected to a phase shift equal to the correction angle prior to being returned to the Omega receiver meter input.

It is apparent from the above that the corrections effected by the correction transmitter are received and decoded by the correction receiver, and automatically applied to the ship's Omega receiver.

TECHNICAL CHARACTERISTICS OF CORRECTION TRANSMISSION SYSTEM USED DURING THE TRIALS

- Omega receiver, land-based, used as correction transmitter.
  This is a model M2 unit with a phase comparator pass band of .003 Hz. A 1-metre antenna is fitted. Accuracy of the phase comparators is better than ± .5 CEC for a 0 dB S/N ratio over a 40 Hz band.
- Correction encoder :
  - Accuracy of theoretical phase difference settings better than .5 CEC.
  - Carrier frequency : may be anywhere between 1.6 and 3 MHz (1607.5 kHz was used in these tests).
  - Phase modulation index : never exceeds .8. Modulation linearity better than 1 per cent.
  - Crystal stability : better than 1×10^{-6} per month from $-10°$ C to $+60°$ C.
- Transmitter :
  A 100-watt fully transistorized unit with a frequency range of 1.6 to 3 MHz was used with a 20-metre antenna. Effective coverage, night or day, 350 n.m.
- Transmission spectrum :
  A single station covers a spectral width of less than 50 Hz. Up to eight correction transmitters might, therefore, be used in chain formation at 160 Hz intervals for a maximum total bandwidth of 1200 Hz. Thus a single frequency allocation (band) is sufficient for an 8-station chain.

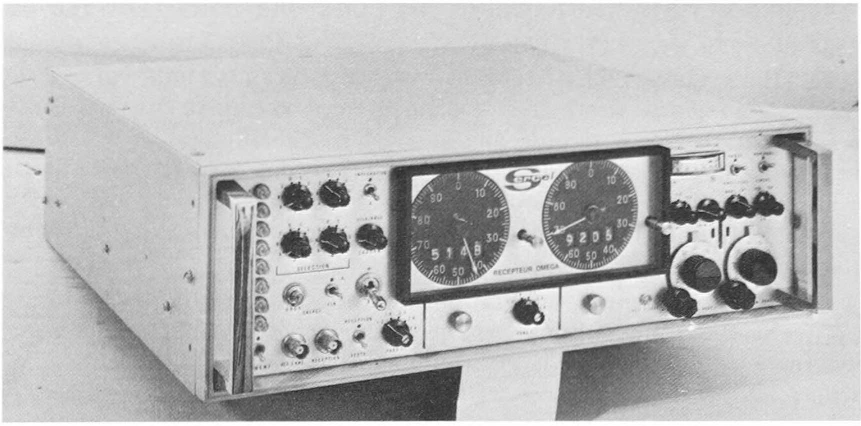


FIG. 2. — Marine Omega M2 receiver.

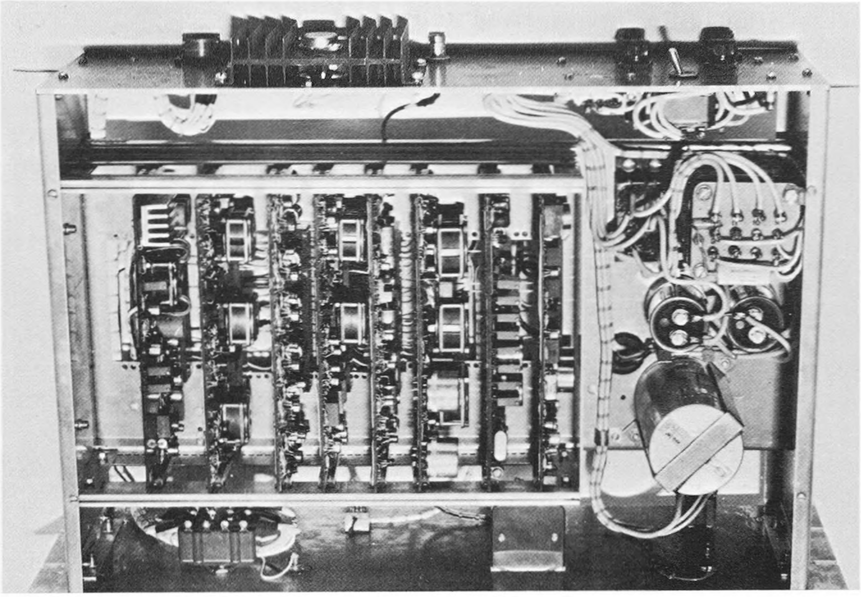


FIG. 3. — Phase corrections receiver (engineering model).

- Correction receiver :
  - Frequency range, 1.6 to 3 MHz. Double frequency converter, with second local oscillator pretuned to eight frequencies.
  - Band pass, 2nd IF frequency, 60 Hz/7.2 kHz; demodulator/phase shifter, .06 Hz.
  - Phase correction accuracy : better than ± .3 CEC for a 0 dB S/N ratio at input, over a 5 kHz bandwidth.
  - Power supply and consumption : 12 V DC, 12 W, or 110/220 V, 18 VA.

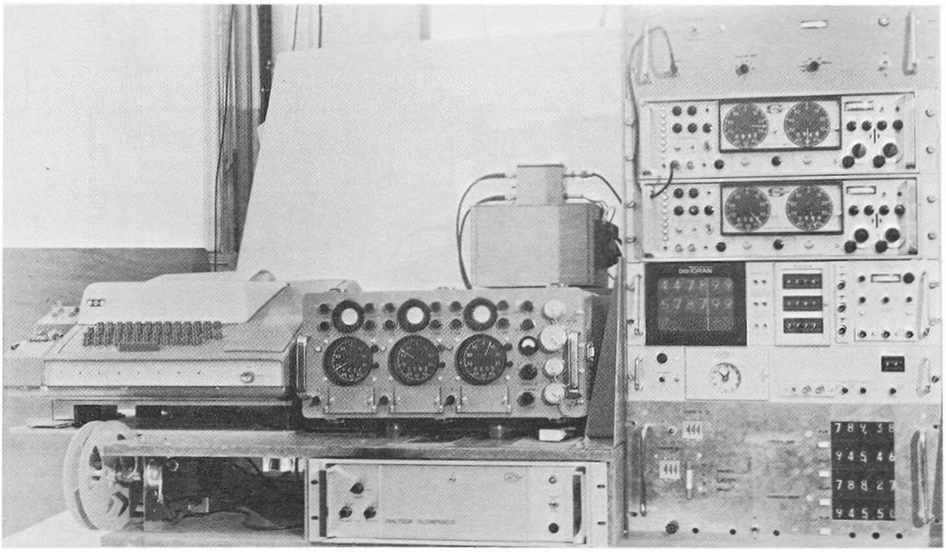


FIG. 4. — Mobile station for Differential Omega recording.

DESCRIPTION OF EQUIPMENT USED DURING THE TRIALS

Correction transmitter (See figure 5).

This is comprised of :

— An Omega receiving antenna including a 1-metre whip and its tuning box mounted atop a 8-metre braced mast erected over a spider-type wire network on the ground. A coaxial cable approximately 100 metres long is used to connect the antenna tuning box with the Omega receiver.

— An Omega receiver, model M2.
The LF signals representing the phases from the four Omega stations A through D are taken from this receiver and applied to the encoder via a cable. Model M2 dimensions are three 19-inch standard units.

— An encoder unit.
Here the LF signals taken from the receiver and corresponding to actual phases (as read) are phase shifted by a quantity equal to the theoretical Omega phase values calculated from the geographical position of the receiving antenna (theoretical phase values). Phase shifting is obtained by means of phase shifters at front panel of encoder unit. The signals thus phase shifted carry the phase correction : φ cor = φ read — φ theor. for each of the stations.
Segments A, B, C, D and H, also taken from the internal sequencer

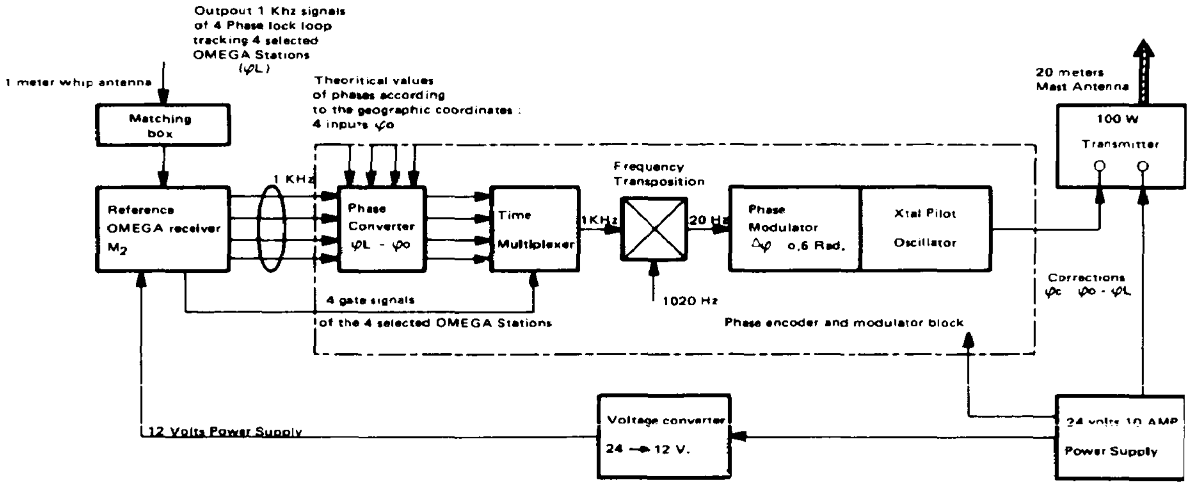


FIG. 5. — Omega corrections transmitting station.

in the receiver, are used to control a multiplexer which thus segregates in a single output all four correction signals for stations A, B, C and D, and the internal 1 kHz signal selected by segment H. At this point, the signals representing the respective correction values appear at the same rate as the Omega format : they are then reduced to 20 Hz by a simple frequency converting process.

The 1607.5 Hz signal from a crystal standard is phase modulated by the multiplexed 20 Hz signal. The phase modulator is of special design : it permits a .8 modulation index being obtained with excellent linearity. The phase modulated signal is then routed to the transmitter via a coaxial cable.

This encoder/modulator unit has dimensions of four 19-inch units.

— A 100-watt transmitter.

This is the type commonly used in Toran radiolocation chains. It is housed in the same room with the Omega receiver and the correction encoder, and contains all necessary adjustment means for tuning and adaptation to the transmitter antenna. Its dimensions are five 19-inch standard units.

— A transmitter antenna, 20-metres high, with a terminal capacitance fitted to its upper braces. Total weight of the assembly : 70 kg.

— 24-volt batteries charged from the 22 V, 50-cycle line supply power to the station. Total power consumption is 300 VA.

Experimental mobile receiver station.

This was constituted by the equipment to be tested, i.e., the Omega receiver, the correction receiver, and all the instruments necessary for measurement calibration and recording.

Figure 6 shows the arrangement of the Omega and correction units.

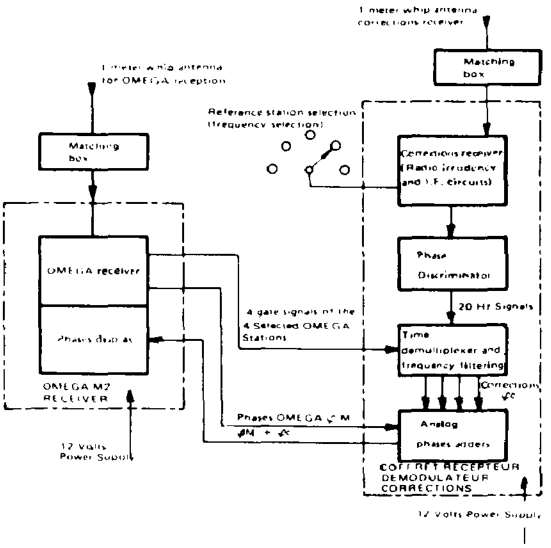


FIG. 6. — Mobile station for Differential Omega reception.

— The Omega receiver also is a model M2. The LF signals corresponding to the four stations used, and the segments corresponding to the internal standard, are taken from this receiver and carried over a cable connecting with the correction receiver. This same cable carries the LF signals back to the Omega unit after phase shifting by a value equal to the correction.

— The correction receiver is housed in a cabinet having dimensions of four 19-inch standard units. It contains :
  - — A double superheterodyne section;
  - — A local oscillator/synthesizer;
  - — A discriminator and a 20 Hz filter;
  - — Four demodulators/phase-shifters.

— Two antennas are fitted :
  - — One for the Omega signals constituted by a 1-metre whip with coaxial cable adaptor;
  - — One for correction signals, also comprised of a 1-metre whip with adaptor box (100 mm × 80 mm × 50 mm).

Both antennas are mounted atop an 8-metre braced mast when the station is used for experiments at a land position. They are preferably erected clear of power transmission lines and/or large metallic structures. By the same token antennas used aboard ships should be erected clear of obstructions, preferably at or near the top of a mast.

Monitoring and recording instruments.

For best results in phase information acquisition and calibration the following equipment was used during the tests (see figure 7).

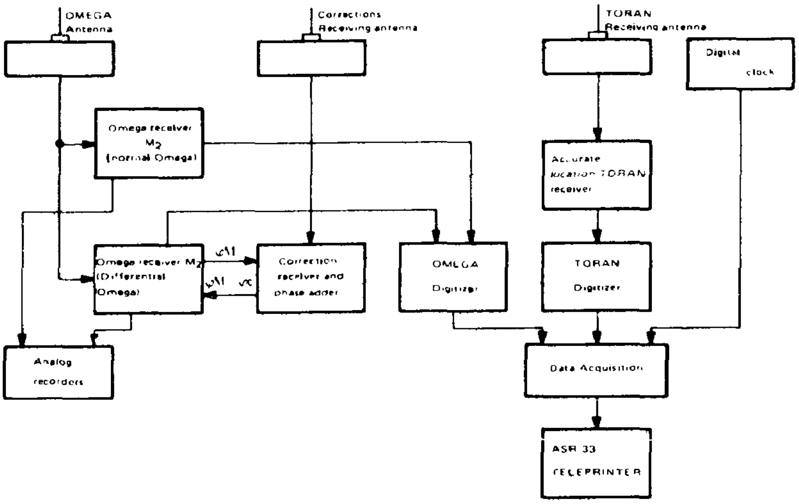


Fig. 7. — Mobile station for Omega and Differential Omega data recording.

- A further model M2 Omega receiver for recording conventional Omega readings. This unit was connected to the same antenna as the differential Omega receiver.
- A digitizer for the Omega phases, containing :
  - Four numerical phasemeters with associated continuous hyperbolic lane counters;
  - A dual input section for the corrections to be applied to the conventional Omega receiver readings (in the computer program);
  - A serializer arranged to handle all Omega information, both conventional and differential;
- A Toran radiolocation receiver used for accurate calibration of the measurements. This was made up of two units : a receiver unit and a display unit (with electromechanical phasemeters and monitoring scopes). This Toran receiver had its own antenna.
- A digitizer for the phases and hyperbolic lane counters picked up by the Toran receiver. This unit contained buffer memories and serializers.
- A digital clock, also fitted with serializers, was used for giving hours and minutes.
- Recorders. These were of three different types, viz. :
  - A track plotter, model T5, directly connected with the Toran receiver, for continuous monitoring of the ship's course. The scale was 1 mm on the plot for approx. 10 metres travelled by the ship. This unit thus makes it possible to detect any loss of continuity in holding the position given by the Toran receiver;
  - Graphic recorders for differential Omega phases and, if applicable, conventional Omega phases. These recorders, calibrated from 0 to 100 CEC, were each connected with a pot coupled with the shaft of a phasemeter in the Omega receiver. These recorders were mostly used when operating at a land-based location;
  - A numerical recorder. This was an ASR 33 teleprinter used to simultaneously print out results and to prepare a perforated band for

later processing in a computer. This teleprinter was associated with a data logger capable of scanning each unit at one-minute intervals (the scanning rate could have been faster. However, this would have been of little interest as the information from the Omega receivers was correlated over a period of time close to one minute).

All the above equipment was powered from batteries, with or without intermediate voltage converters, so that line fluctuations, if any, could not impair the quality of the measurements.

DETAIL OF TEST PROGRAM

After a comprehensive series of shop tests aimed at ascertaining inherent equipment accuracy, field testing could be envisaged with a degree of confidence.

Preliminary tests were first conducted by locating the transmitter quite close (50 metres) to the receiver, with a very low transmission power being used. These tests have shown that the whole equipment was operating satisfactorily, with discrepancies consistently less than .5 CEC at any time of day or night, under all sorts of receiving conditions.

A comprehensive series of land tests with the receiving equipment installed in an automobile has subsequently been carried out. These tests, usually of 48 hours' duration at each position, were conducted with the car at a standstill. A 6-metre antenna was erected clear of obstructions, power being supplied by batteries. Only analog recordings on paper tape were made as digital recording equipment has an excessively high power consumption implying considerable complexity of operation.

Land tests have been conducted over transmitter-to-receiver distances of 10, 50, 100 and 200 km. For the 10 km tests a very low (3-watt) radiated power was used. For all other tests transmission was at 100 watts, with the correction transmitter installed on the Ile d'Yeu in the Bay of Biscay (position : 46° 43′ N — 2° 23′ W).

At-sea tests were carried out using the permanent Biscay Toran chain for calibration. This chain comprises two station pairs, each generating a separate hyperbolic grid.

The first pair has a 240 km baseline, the transmitters being located as follows :

— A : 46° 41′ 30″ N — 2° 17′ 10″ W;
— A′ : 44° 40′ 35″ N — 1° 15′ 17″ W.

The second pair has a 295 km baseline, the transmitters being located as follows :

— B : 46° 2′ 48″ N — 1° 24′ 34″ W;
— B′ : 43° 23′ 28″ N — 1° 41′ 54″ W.

Practical coverage with this chain reaches from 1° to 7° W and 43° 30′ to 46° 30′ N. Average position location accuracy is 10 to 50 metres rms.

Two series of tests have been conducted at sea :

1. With the light convoy escort vessel *Le Savoyard* from 21-25 September 1971;
2. With the missile recovery vessel *Henri Poincaré* from 18-23 October 1971.

In both cases, the ships have been steaming at distances of 50 to 300 km from the reference station on the Ile d'Yeu. During both trips a great number of digital recordings was made at the rate of one every minute. SWC corrections taken from USNOO tables were introduced manually every 15th minute by means of the figure wheels. In addition they were recorded by the teleprinter.

Digital records on perforated tape, therefore, contain the following information (see figure 12).

	Characters
· Toran pair AA′	6
· Toran pair BB′	6
· Time, hours	2
· Time, minutes	2
· Conventional Omega and USNOO SWC corrections, phases A – D	6
· Conventional Omega and USNOO SWC corrections, Corr. phases A – D with sign	3
· Phases B – D	6
· Corrections, phases B – D with sign	3
· Differential Omega, phases A – D	6
· Differential Omega, phases B – D	6
	Total 46 characters

Recording time totalled approx. 5 seconds every minute.

ANALYSIS OF RESULTS

Analog recordings, land positions. Referring to the tabulated results shown below :

— *Column 1 : RMS value of absolute phase error, pair A-D*

— Column 2 : RMS value of absolute phase error, pair B-D

— Column 3 : RMS value of position error in metres for present-day geometry on western coast of France, i.e. a lane width of 23 km for A-D and 44 km for B-D, with a crossing angle of 60°.

— Column 4 : RMS value of position error in metres that would be obtained with the final Omega system configuration. Lane width 25 km. Crossing angle 80°.

In all the results shown in these tabulations, whether from analog or digital records, the RMS values listed include not only the observed variations, but also local distortions where applicable, constant errors in instrument calibration, etc. The results presented in this manner are thus similar to what the commercial user would observe in practice.

First Land Test, transmission distance 11 km, 2 July 1971 (see figure 8).

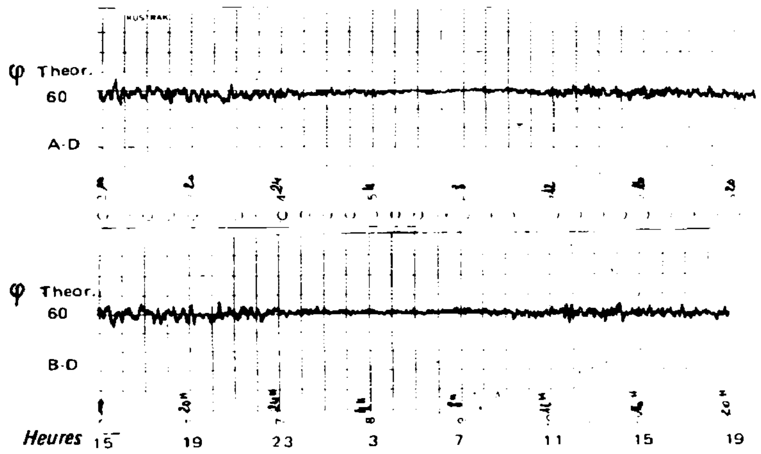


FIG. 8. — Differential Omega at 11 km. (July 2/71). — La Guilinière-Beausoleil (land path).

The 11 km path is entirely overland. Transmission power is only 3 watts and the transmitter antenna only 7 metres high.

The noise level observed was variable : rather high from 1500 to 2300 hours GMT on the first day, low from 2300 hours on the first day to 1100 hours on the second day, and medium afterwards. This record gives a good idea of the deterioration in performance due to the weakness of the D (Forestport) signal. Measurement fluctuations in Differential Omega mode show an amplitude that substantially correlates with the diurnal attenuation of signals received from Forestport.

Phase errors due to system transmission noise are not observed because of the very high signal-to-noise ratio over this short distance.

The table below gives the errors observed for the 11 km separation distance. Note that the first part of the recording reflects disturbances due to stormy conditions.

Period	σ(A − D) CEC	σ(B − D) CEC	σd, with Lane A − D = 23 km Lane B − D = 44 km and crossing angle = 60°	σd, with Lane 1 = 25 km Lane 2 = 25 km and crossing angle = 80°
1500 to 2300	3.2	2.8	1 450 metres	1 050 metres
2300 to 1100	1.0	0.8	420 metres	300 metres
1100 to 1900	2.3	2.0	1 050 metres	650 metres

Second Land Test, transmission distance 50 km, 8-9 August 1971 (see figure 9).

The reference station is on the Ile d'Yeu and the receiving unit 50 km off that island to the North-Northwest. Oversea path. Noise was more uniform, although some increase was observed between 1600 and 2300 hours. Transmission power was 100 watts and the transmission signal-to-noise ratio was large enough to preclude phase disturbances (if transmission noise had been present it would show rather conspicuously on the records since its pseudo-period is approximately 20 times that of the Omega receiver internal noise owing to the difference in bandwidth). Discrepancies in RMS values likely to be caused by poor correlation of ionospheric disturbances imposed on Omega operation do not yet appear on that comparatively short distance.

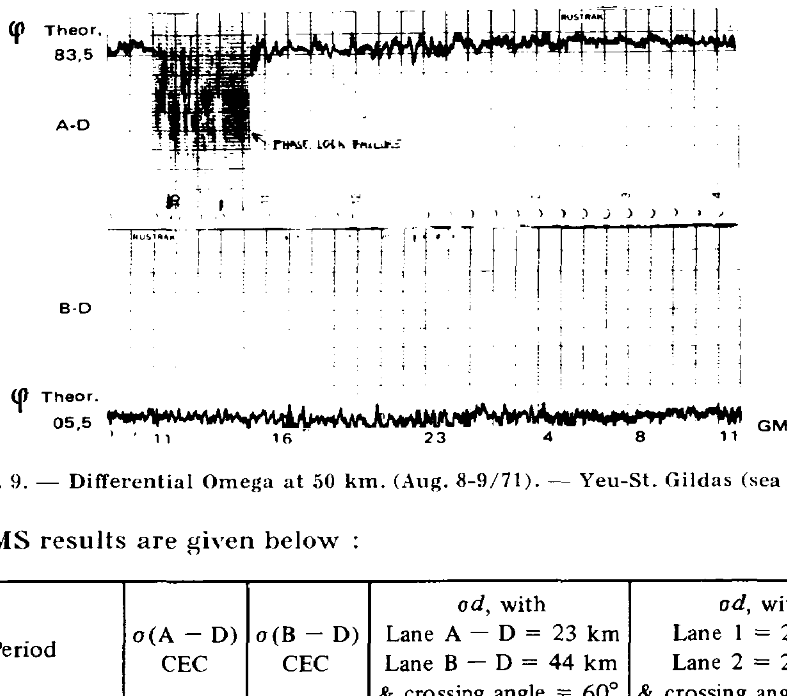


FIG. 9. — Differential Omega at 50 km. (Aug. 8-9/71). — Yeu-St. Gildas (sea path).

RMS results are given below :

Period	σ(A − D) CEC	σ(B − D) CEC	σd, with Lane A − D = 23 km Lane B − D = 44 km & crossing angle = 60°	σd, with Lane 1 = 25 km Lane 2 = 25 km & crossing angle = 80°
Round the clock	2.2	1.5	850 metres	580 metres

Third Test, transmission distance 95 km (see figure 10).

The transmitter is again on the Ile d'Yeu and the receiving unit at Nantes, 95 km to the North-East of that island. The transmission path is 30 km oversea and 65 km overland. In this figure 10 is also shown a record of A-D in conventional Omega mode; this offers the possibility of comparing the results.

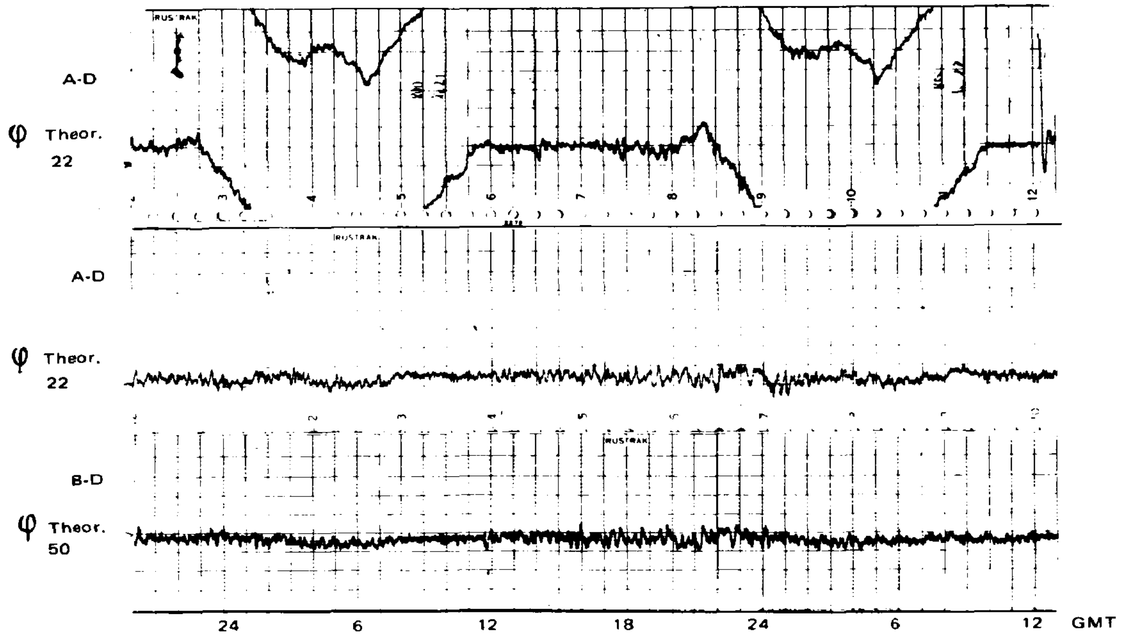


FIG. 10. — Omega A-D and Differential Omega A-D and B-D at 95 km. (Yeu-Carquefou). 30 km sea and 65 km land path (Aug. 20/71).

While the A-D trace exhibits a 60 CEC excursion in conventional mode, the variation observed in differential mode for the same pair reduces to approximately 3 CEC, RMS value, over the same period of time. This variation which is chiefly observed between 2400 and 0600 hours GMT corresponds to the loss of correlation in ionospheric variations. This lack of correlation is less apparent for B-D where the variation is only 1 to 2 CEC.

A definite drift in RMS value, which reaches 2 CEC for A-D and almost 3 CEC for B-D is apparent from these records. This may be due to local distortions, as the test was conducted in an industrialized area with very large metallic structures. No short period noise can be observed that could be ascribed to the transmission system.

Tabulated results are as follows :

Period	σ(A − D) CEC	σ(B − D) CEC	σd, with lane A − D = 23 km lane B − D = 44 km and crossing angle = 60°	σd, with lane 1 = 25 km d, lane 2 = 25 km and crossing angle = 80°
36 hrs	3.5	2.8	1 700 metres	1 050 metres

Fourth test, distance 260 km (refer to figure No. 11).

Transmitter again on Ile d'Yeu; receiver unit at Cap Ferret, 260 km to the south-south-east. Transmission path entirely oversea, with the

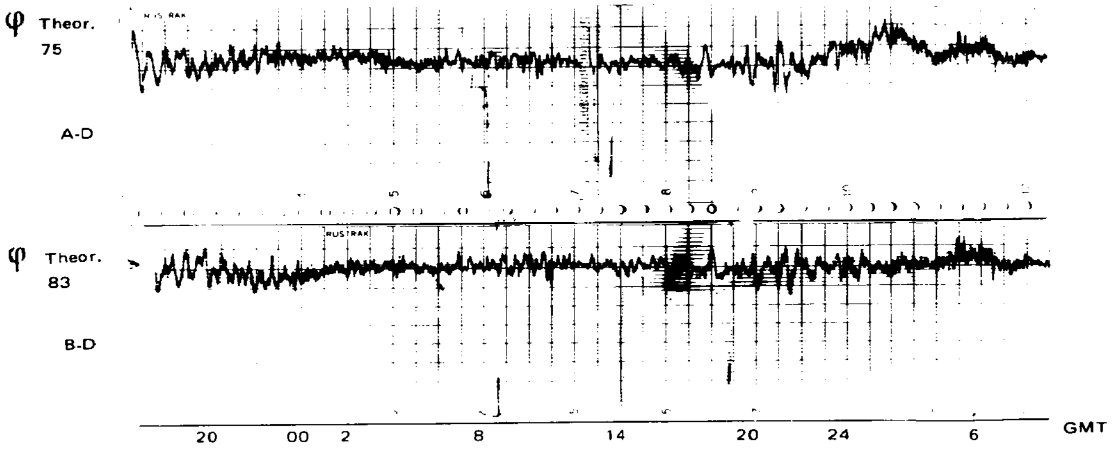


FIG. 11. — Differential Omega at 260 km. (Aug. 10/71). — Yeu-Cap Ferret (sea path).

last part of it a tangent to the coastline. Receiving equipment installed on sand dunes on the outskirts of a pine wood in an area well known for its poor radio wave propagation conditions. This record was made over a period of 30 hours in stormy weather which caused a marked deterioration of Omega signal reception, in particular from station D, as shown by the clear noise correlation in the two records.

Apparent from these records is a more marked loss of correlation of ionospheric variations resulting in a slow drift of the RMS value synchronized with the large peaks in conventional Omega variation (in particular between 2400 and 0600 hours GMT). These variations reached 10 CEC, a rather unusual value, at 0200 GMT for A-D and 5 CEC for B-D.

Further, a quick noise exhibiting a $\sigma \simeq 4$ CEC will be observed between 0000 and 0600 GMT. This noise is due to a decrease in the signal-to-transmission noise ratio which begins to appear in this record.

If the rather marked correlation loss which appears between 2400 and 0600 hours on A-D and between 2200 and 0200 hours on B-D is taken into account it becomes easy to descry the daytime error from 0600 to 2200 hours and the nighttime error from 2200 to 0600 hours.

Tabulated results are as follows :

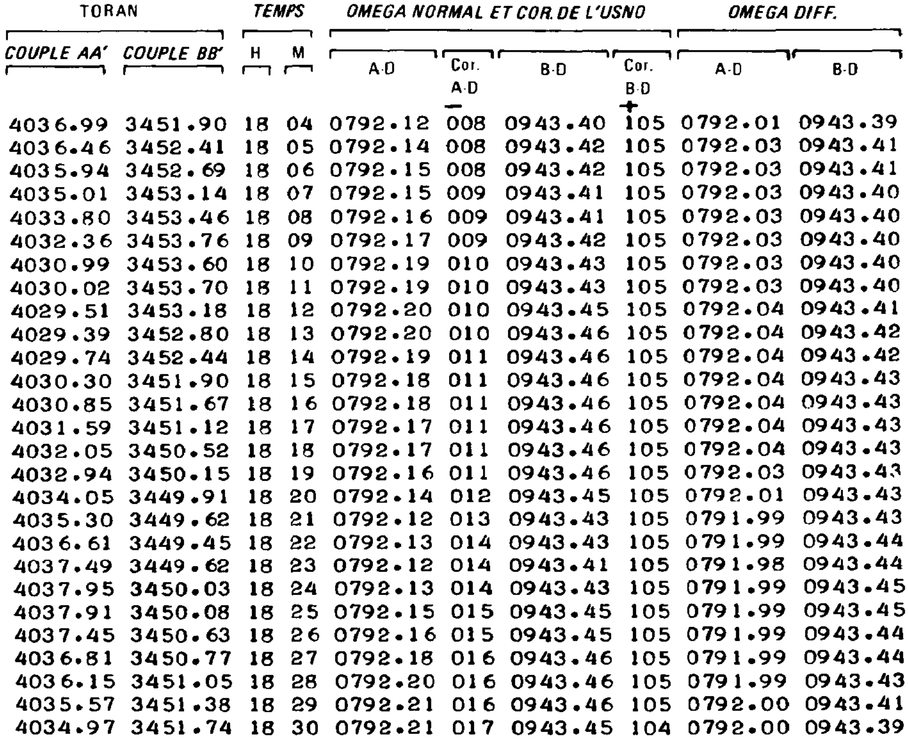
Period	σ(A — D) CEC	σ(B — D) CEC	σd, with lane A — D = 23 km lane B — D = 44 km and crossing angle = 60°	σd, with lane 1 = 25 km lane 2 = 25 km and crossing angle = 80°
0600 to 2200	2.6	2.4	1 500 metres	900 metres
2200 to 0600	5.8	3.5	2 200 metres	1 450 metres

At-sea tests aboard " Le Savoyard ".

The first part of this test series was seriously disturbed by heavy storms, September 21, 22. On this occasion (as already observed elsewhere) with a poor signal-to-noise ratio the accuracy normally obtained in Differential Omega mode deteriorates materially and tends toward that obtained in conventional Omega mode, and may even become inferior when approaching the reception limit. This, incidentally, is in accordance with theory. These drawbacks which are now present over an average 5-10 per cent of the time will disappear completely when the transmitters radiate their final operational power.

As conditions practically returned to normal September 23-24 it became possible to make use of the measurements taken and recorded over 30 consecutive hours in an area located between 200 and 300 km to the south-south-west of the transmitter, i.e., approximately 44° N and 4° W, in open sea with 100 per cent over water paths.

The data recorded under these conditions were in accordance with the format shown in figure 12 (reference position given by Toran phases, time, phases and corrections in conventional Omega mode, and phases in Differential Omega mode). These results were analysed using an EMR 6135 computer.



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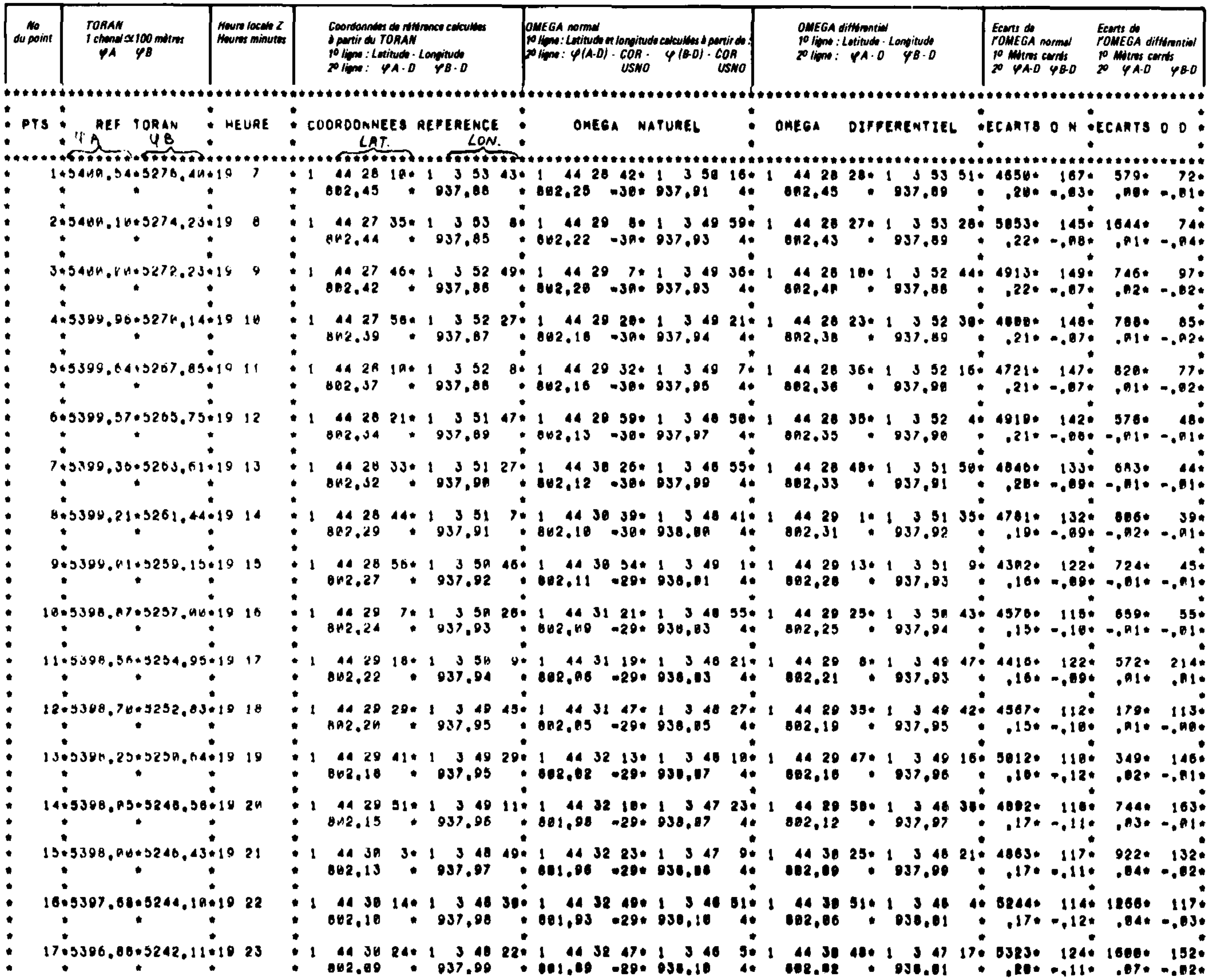
      TORAN          TEMPS    OMEGA NORMAL ET COR.DE L'USNO          OMEGA DIFF.
COUPLE AA' COUPLE BB'  H  M     A-D    Cor.    B-D    Cor.      A-D       B-D
                                       A-D            B-D
                                        —              +
4036.99 3451.90 18 04 0792.12 008 0943.40 105 0792.01 0943.39
4036.46 3452.41 18 05 0792.14 008 0943.42 105 0792.03 0943.41
4035.94 3452.69 18 06 0792.15 008 0943.42 105 0792.03 0943.41
4035.01 3453.14 18 07 0792.15 009 0943.41 105 0792.03 0943.40
4033.80 3453.46 18 08 0792.16 009 0943.41 105 0792.03 0943.40
4032.36 3453.76 18 09 0792.17 009 0943.42 105 0792.03 0943.40
4030.99 3453.60 18 10 0792.19 010 0943.43 105 0792.03 0943.40
4030.02 3453.70 18 11 0792.19 010 0943.43 105 0792.03 0943.40
4029.51 3453.18 18 12 0792.20 010 0943.45 105 0792.04 0943.41
4029.39 3452.80 18 13 0792.20 010 0943.46 105 0792.04 0943.42
4029.74 3452.44 18 14 0792.19 011 0943.46 105 0792.04 0943.42
4030.30 3451.90 18 15 0792.18 011 0943.46 105 0792.04 0943.43
4030.85 3451.67 18 16 0792.18 011 0943.46 105 0792.04 0943.43
4031.59 3451.12 18 17 0792.17 011 0943.46 105 0792.04 0943.43
4032.05 3450.52 18 18 0792.17 011 0943.46 105 0792.04 0943.43
4032.94 3450.15 18 19 0792.16 011 0943.46 105 0792.03 0943.43
4034.05 3449.91 18 20 0792.14 012 0943.45 105 0792.01 0943.43
4035.30 3449.62 18 21 0792.12 013 0943.43 105 0791.99 0943.43
4036.61 3449.45 18 22 0792.13 014 0943.43 105 0791.99 0943.44
4037.49 3449.62 18 23 0792.12 014 0943.41 105 0791.98 0943.44
4037.95 3450.03 18 24 0792.13 014 0943.43 105 0791.99 0943.45
4037.91 3450.08 18 25 0792.15 015 0943.45 105 0791.99 0943.45
4037.45 3450.63 18 26 0792.16 015 0943.45 105 0791.99 0943.44
4036.81 3450.77 18 27 0792.18 016 0943.46 105 0791.99 0943.44
4036.15 3451.05 18 28 0792.20 016 0943.46 105 0791.99 0943.43
4035.57 3451.38 18 29 0792.21 016 0943.46 105 0792.00 0943.41
4034.97 3451.74 18 30 0792.21 017 0943.45 104 0792.00 0943.39
```

FIG. 12. — Sample of teleprinter record.

A sample output listing for this specially programmed computer is shown in figure 13.

Computation procedure was as follows :

- Compute position in longitude and latitude from Toran readings (accuracy better than 1 second of great circle arc);



No du point	TORAN 1 chenal ≃ 100 mètres φA φB	Heure locale Z Heures minutes	Coordonnées de référence calculées à partir du TORAN 1º ligne : Latitude - Longitude 2º ligne : φA - D φB - D	OMEGA normal 1º ligne : Latitude et longitude calculées à partir de : 2º ligne : φ(A-D) - COR - USNO φ(B-D) - COR USNO	OMEGA différentiel 1º ligne : Latitude - Longitude 2º ligne : φA - D φB - D	Ecarts de l'OMEGA normal 1º Mètres carrés 2º φA-D φB-D	Ecarts de l'OMEGA différentiel 1º Mètres carrés 2º φA-D φB-D

```
******************************************************************************************************************
*      *                    *         *                           *                           *                            *              *              *
* PTS  *     REF TORAN      * HEURE   * COORDONNEES REFERENCE     *     OMEGA  NATUREL        * OMEGA   DIFFERENTIEL       *ECARTS O N    *ECARTS O D    *
*      *  φA         φB     *         *       LAT.       LON.     *                           *                            *              *              *
******************************************************************************************************************
*      1*5400,54*5276,40*19  7  * 1  44 28 10* 1  3 53 43* 1  44 28 42* 1  3 50 16* 1  44 28 28* 1  3 53 51* 4650*  167*  579*   72*
*      *       *       *        *    802,45  *  937,88  * 802,25  -30* 937,91   4*   802,45  *  937,89  *  ,20* -,03*  ,00* -,01*
*      *               *        *                        *                         *              *              *
*      2*5400,10*5274,23*19  8  * 1  44 27 35* 1  3 53  8* 1  44 29  8* 1  3 49 59* 1  44 28 27* 1  3 53 28* 5053*  145* 1644*   74*
*      *       *       *        *    802,44  *  937,85  * 802,22  -30* 937,93   4*   802,43  *  937,89  *  ,22* -,08*  ,01* -,04*
*      *               *        *                        *                         *              *              *
*      3*5400,00*5272,23*19  9  * 1  44 27 46* 1  3 52 49* 1  44 29  7* 1  3 49 36* 1  44 28 10* 1  3 52 44* 4913*  149*  746*   97*
*      *       *       *        *    802,42  *  937,86  * 802,20  -30* 937,93   4*   802,40  *  937,88  *  ,22* -,07*  ,02* -,02*
*      *               *        *                        *                         *              *              *
*      4*5399,96*5270,14*19 10  * 1  44 27 58* 1  3 52 27* 1  44 29 20* 1  3 49 21* 1  44 28 23* 1  3 52 30* 4808*  148*  788*   85*
*      *       *       *        *    802,39  *  937,87  * 802,18  -30* 937,94   4*   802,38  *  937,89  *  ,21* -,07*  ,01* -,02*
*      *               *        *                        *                         *              *              *
*      5*5399,64*5267,85*19 11  * 1  44 28 10* 1  3 52  8* 1  44 29 32* 1  3 49  7* 1  44 28 36* 1  3 52 16* 4721*  147*  820*   77*
*      *       *       *        *    802,37  *  937,88  * 802,16  -30* 937,96   4*   802,36  *  937,90  *  ,21* -,07*  ,01* -,02*
*      *               *        *                        *                         *              *              *
*      6*5399,57*5265,75*19 12  * 1  44 28 21* 1  3 51 47* 1  44 29 59* 1  3 48 50* 1  44 28 35* 1  3 52  4* 4919*  142*  576*   48*
*      *       *       *        *    802,34  *  937,89  * 802,13  -30* 937,97   4*   802,35  *  937,90  *  ,21* -,08* -,01* -,01*
*      *               *        *                        *                         *              *              *
*      7*5399,36*5263,61*19 13  * 1  44 28 33* 1  3 51 27* 1  44 30 26* 1  3 48 55* 1  44 28 48* 1  3 51 50* 4840*  133*  683*   44*
*      *       *       *        *    802,32  *  937,90  * 802,12  -30* 937,99   4*   802,33  *  937,91  *  ,20* -,09* -,01* -,01*
*      *               *        *                        *                         *              *              *
*      8*5399,21*5261,44*19 14  * 1  44 28 44* 1  3 51  7* 1  44 30 39* 1  3 48 41* 1  44 29  1* 1  3 51 35* 4781*  132*  806*   39*
*      *       *       *        *    802,29  *  937,91  * 802,10  -30* 938,00   4*   802,31  *  937,92  *  ,19* -,09* -,02* -,01*
*      *               *        *                        *                         *              *              *
*      9*5399,01*5259,15*19 15  * 1  44 28 56* 1  3 50 46* 1  44 30 54* 1  3 49  1* 1  44 29 13* 1  3 51  9* 4302*  122*  724*   45*
*      *       *       *        *    802,27  *  937,92  * 802,11  -29* 938,01   4*   802,28  *  937,93  *  ,16* -,09* -,01* -,01*
*      *               *        *                        *                         *              *              *
*     10*5398,87*5257,00*19 16  * 1  44 29  7* 1  3 50 26* 1  44 31 21* 1  3 48 55* 1  44 29 25* 1  3 50 43* 4576*  115*  659*   55*
*      *       *       *        *    802,24  *  937,93  * 802,09  -29* 938,03   4*   802,25  *  937,94  *  ,15* -,10* -,01* -,01*
*      *               *        *                        *                         *              *              *
*     11*5398,56*5254,95*19 17  * 1  44 29 18* 1  3 50  9* 1  44 31 19* 1  3 48 21* 1  44 29  8* 1  3 49 47* 4416*  122*  572*  214*
*      *       *       *        *    802,22  *  937,94  * 802,06  -29* 938,03   4*   802,21  *  937,93  *  ,16* -,09*  ,01*  ,01*
*      *               *        *                        *                         *              *              *
*     12*5398,70*5252,83*19 18  * 1  44 29 29* 1  3 49 45* 1  44 31 47* 1  3 48 27* 1  44 29 35* 1  3 49 42* 4567*  112*  179*  113*
*      *       *       *        *    802,20  *  937,95  * 802,05  -29* 938,05   4*   802,19  *  937,95  *  ,15* -,10*  ,01* -,00*
*      *               *        *                        *                         *              *              *
*     13*5398,25*5250,64*19 19  * 1  44 29 41* 1  3 49 29* 1  44 32 13* 1  3 48 10* 1  44 29 47* 1  3 49 16* 5012*  110*  349*  146*
*      *       *       *        *    802,18  *  937,95  * 802,02  -29* 938,07   4*   802,16  *  937,96  *  ,10* -,12*  ,02* -,01*
*      *               *        *                        *                         *              *              *
*     14*5398,05*5248,58*19 20  * 1  44 29 51* 1  3 49 11* 1  44 32 10* 1  3 47 23* 1  44 29 58* 1  3 48 38* 4802*  118*  744*  163*
*      *       *       *        *    802,15  *  937,96  * 801,98  -29* 938,07   4*   802,12  *  937,97  *  ,17* -,11*  ,03* -,01*
*      *               *        *                        *                         *              *              *
*     15*5398,00*5246,43*19 21  * 1  44 30  3* 1  3 48 49* 1  44 32 23* 1  3 47  9* 1  44 30 25* 1  3 48 21* 4863*  117*  922*  132*
*      *       *       *        *    802,13  *  937,97  * 801,96  -29* 938,08   4*   802,09  *  937,99  *  ,17* -,11*  ,04* -,02*
*      *               *        *                        *                         *              *              *
*     16*5397,68*5244,10*19 22  * 1  44 30 14* 1  3 48 30* 1  44 32 40* 1  3 46 51* 1  44 30 51* 1  3 48  4* 5244*  114* 1268*  117*
*      *       *       *        *    802,10  *  937,98  * 801,93  -29* 938,10   4*   802,06  *  938,01  *  ,17* -,12*  ,04* -,03*
*      *               *        *                        *                         *              *              *
*     17*5396,88*5242,11*19 23  * 1  44 30 24* 1  3 48 22* 1  44 32 47* 1  3 46  5* 1  44 30 48* 1  3 47 17* 5323*  124* 1600*  152*
*      *       *       *        *    802,09  *  937,99  * 801,89  -29* 938,10   4*   802,02  *  938,01  *  ,20* -,11*  ,07* -,02*
```

FIG. 13. — Computer listing (sample).

- Compute theoretical Omega phase values from the reference latitudes and longitudes given by the Toran (subprogram Omega, Fisher's ellipsoid);
- Compute corrected conventional Omega phase values, and conventional Omega errors minus reference, and Differential Omega minus reference;
- Compute position, in longitude and latitude, conventional Omega;
- Compute position, in longitude and latitude, Differential Omega;
- Compute magnitude and direction of vectorial error between conventional Omega position and reference position, and between Differential Omega position and reference position.

A total of 1508 positions determined at one minute intervals were thus processed and the list of results subsequently sorted for computing the rms values of the absolute phase errors for A-D and B-D in Differential Omega mode, as well as the rms values of the vectorial error in both conventional and Differential Omega modes. A tabulation of the results obtained from these 1508 positions is given below.

Time	$\sigma\varphi(A-D)$	$\sigma\varphi(B-D)$	σd, Differential Omega	σd, Conventional Omega
For 1 508 positions from 0500 hrs on 9.23.71 to 0800 hrs on 9.24.71	2.8	2.15	1 340	4 900

If the above phase measurements had been made with a hyperbolic grid geometry such that a uniform lane width of 25 km and a crossing angle of 80° obtained, then the σd values would have been as follows:

$\sigma d = 700$ metres in Differential Omega mode

and

$\sigma d = 2600$ metres in Conventional Omega mode.

The results from the measurements taken on board the *Henri Poincaré* have not been processed in time for the author to use them in this paper. Further series of land and at-sea tests are planned so that a better knowledge of the system may be acquired.

BEHAVIOUR OF DIFFERENTIAL OMEGA UNDER EFFECT OF SUDDEN IONOSPHERIC DISTURBANCES

Omega signal transmission is sometimes adversely affected by sudden ionospheric disturbances (S.I.D.). These S.I.D.s are caused by rapid increases in solar activity which have very rapid repercussions on the ionization of the upper atmosphere and, consequently, on the speed with which Omega waves are propagated. These disturbances may arise about once every two months in calm periods, but several times per month during a period of solar activity.

In practice these S.I.D.s lead to sharp variations of phase in the Omega receiver. This variation in amplitude often amounts over several seconds to from 50 to 60 %. The phase then returns to its normal value in an interval that can vary from some tens of minutes up to three hours.

These unforecastable phenomena thus have a distinctly adverse effect on the accuracy of Omega when it is used in its conventional form.

Over long distances the effects of these disturbances are very fortunately strongly correlated in space. Consequently the S.I.D. effect is either cancelled out or considerably reduced in Differential Omega.

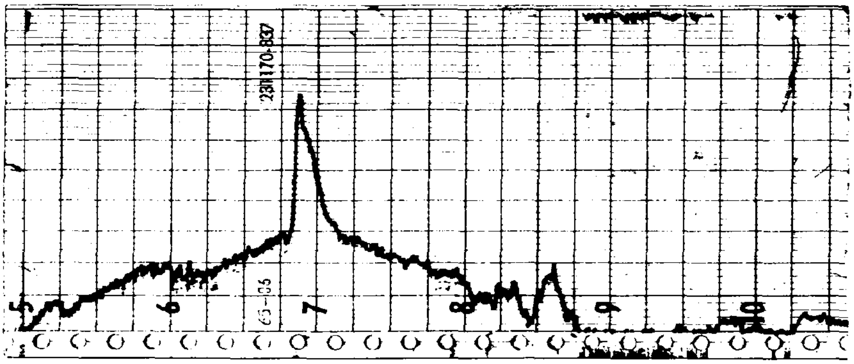


Fig. 14a. — Conventional Omega. A-D Conventional. At Nantes.

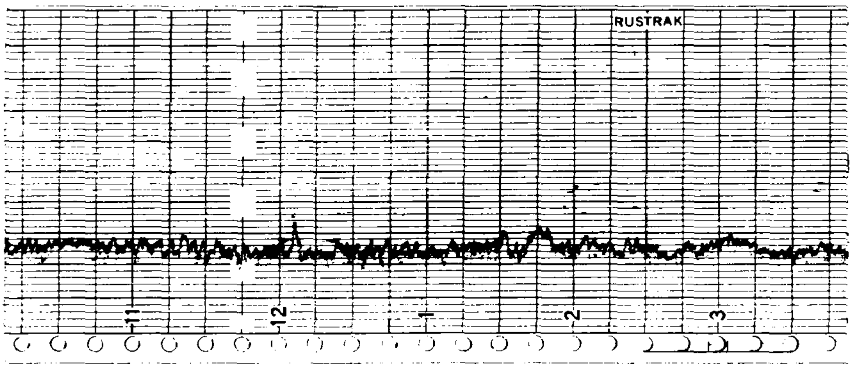


Fig. 14b. — A-D Differential. At Nantes, retransmitting station at Yeu.

This is well brought out in figures 14A and 14B where the A-D station couple phase recordings plotted against time are shown. The time scale is 1 cm per hour. On the upper recording, which is of conventional Omega, there is a large variation in phase. The lower recording, which is of Differential Omega, shows a residual about 8 times less, and of very short duration. This measurement was effected at Nantes, the retransmitting station being on the Ile d'Yeu about 90 km away.

This very interesting trial showed very clearly how reliable Differential Omega can be for accurate coastal navigation in comparison with results obtained with conventional Omega alone.

CONCLUSION

It can be said that the whole system developed for phase correction transmission in association with Omega receiving equipment has operated according to expectations. As far as Differential Omega results are concerned the conclusions to be drawn are as follows :

1. Omega signal to VLF noise ratio.

If satisfactory results are to be obtained in Differential Omega mode it is essential that the signal-to-VLF noise ratio be high for all Omega stations received, both at the correction transmitter receiver and at the mobile receivers operating around that transmitter.

The required signal-to-noise ratio is dependent upon the degree of correlation of the VLF noise at the various receivers. It can be said that, on an average, a signal-to-noise ratio of at least 20 to 25 dB should obtain at the point of phase measurement in the receivers. This is generally true at present on western Europe coasts for stations A and B, but this figure is far from being reached for stations C and D.

The accuracy deterioration currently due to the low signal-to-noise ratio for station D is in the order of 200-1000 metres. This loss should, however, be reduced to 50-250 metres when stations A, B and D operate at their ultimate power, and even to 50-150 metres when all stations are in operation at full power.

2. Equipment calibration.

Equipment calibration errors, for a complete transmission chain, will not be markedly lower than ± 0.5 CEC, which corresponds with present-day geometry off western European coasts to 250 metres. This will be reduced to approx. 150 metres with the ultimate configuration.

3. Accuracy deterioration due to transmission system.

Apart from the calibration errors mentioned above, the signal-to-noise ratio of the transmission system proper results in an accuracy deterioration which varies with transmission distance. This loss of accuracy results in mean values as shown in the table below.

Correction transmitter to receiver distance	0 to 250 km	250-400 km	400-800 km
Present geometry	0	30-50 m	50-200 m
Ultimate geometry	0	20-30 m	30-150 m

4. Errors due to loss of correlation of ionospheric effects.

The loss of accuracy due to this cause is dependent upon distance and time of day. This error will be predominant when the Omega system is fully operational, for a user determined to do away completely with the boresome task of entering corrections taken from tables.

It is difficult at present to state with any degree of precision the final values that will be obtained, as this implies that results from Differential Omega recordings made over at least one to two years at several positions located at different distances and orientation transmitter be available.

However, the observations made over the last few months make it possible to put forward figures that should not be too far off the mark, provided due regard be given to factors likely to affect the error values, viz., distance, night or day, present versus future configuration. This would give the following tabulation.

Distance from correction transmitter		0-250 km	250-400 km	400-800 km
Present configuration	Daytime	0	0	200-500 km
	Nighttime		800-1 200 m	1 200-2 000 m
Ultimate configuration	Daytime	0	0	100-250 m
	Nighttime	0	500-700 m	700-1 100 m

The main facts of interest to the future user of Differential Omega off western European coasts are the present mean accuracy reached with this navigational mode and the trend to be expected from the two important steps planned in Omega system operation.

— Step 1 : Present status, figure 15.
Station A, Aldra : 2 kW; Station B, Trinidad : 1 kW; Station D, Forestport : 200 W.

— Step 2 : During 1973, figure 16.
Station A, Aldra : 10 kW; Station B, Trinidad : 10 kW; Station D, North Dakota : 10 kW.

— Step 3 : 1974-1975 status, figure 17.
All Omega stations : 10 kW.

Differential Omega could be found of interest as early as the latter part of 1973 off western European coasts. This could be extended all over the world at little cost from 1974-75.

As early as 1973 the use of a correction transmitter constructed along the above described lines, i.e., light in weight and low in operating costs, capable of being installed in a few hours by two men only, could be of great value, in some areas lacking even medium accuracy navigation systems, to solve the problems associated with the operation of research and/or exploration parties working on a short time basis. This applies to fishing vessels, geophysical exploration, and various reconnaissance work.

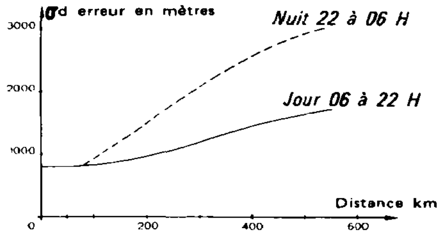


Fig. 15. — Accuracy of Differential Omega versus distance, at present time (Oct. 71) (West European coasts).

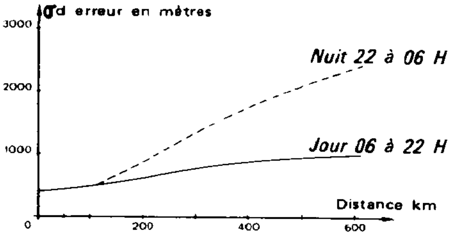


Fig. 16. — Accuracy of Differential Omega, expected for the end of 1973, on West European coasts (A, B and D stations at full power).

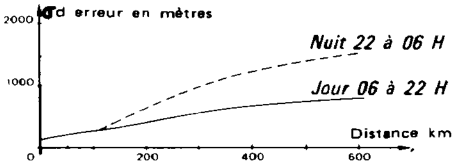


Fig. 17. — Accuracy of Differential Omega, expected for 1974-1975, for all the world (A to H stations at full power).

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He also wishes to extend his thanks to the Direction des Recherches et Moyens d'Essais who sponsored this program both technically and financially, encouraged and stimulated the efforts of all concerned, and gave permission to publish the results of the tests.

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