TWO RADIONAVIGATIONAL SYSTEMS : OMEGA AND DIFFERENTIAL OMEGA

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Editor's Note: The present article formed part of a paper presented at "OCEANEXPO" — the International Colloquium on the Exploitation of the Oceans — held in Bordeaux, France, from 9-12 March 1971.

Although the IHB's Special Publication 39, which was updated in January 1971, contains a more detailed study of the Omega system we have decided to publish the present study of this system by M. SERVEL DE COSMI for readers of the Review who may not be familiar with this particular radio-aid in order to facilitate understanding of the last part of his article where the Differential Omega system is treated.

Indeed, in our opinion the Differential Omega system is likely to prove of immense value to hydrographers in the years to come.

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THE OMEGA RADIONAVIGATIONAL SYSTEM

I. — Principle

Omega is a hyperbolic radionavigational system with a world coverage.

Although designed and developed by the U.S. Navy, Omega is a civil system permanently available to any would-be user. It is, moreover, multinational since many countries — France among them — contribute to its setting up.

World coverage is assured by using VLF frequencies in the 10-14 kHz range which have a very low attenuation (*). These frequencies were only

(*) 3-4 dB per 1 000 km. The ratio of the two powers expressed in decibels is defined by the relation :

$$\frac{W_1}{W_2}\ dB = 10 \log \frac{W_1}{W_2} \cdot$$

3 dB corresponds to a ratio of two between the powers.

adopted after many experiments which proved that their propagation was sufficiently stable and forseeable to enable them to be used for a precise navigational system. World coverage could have been obtained with only six stations, but for reasons of operational safety eight stations will finally be set up.

This is a hyperbolic phase measuring system, and therefore there is lane ambiguity. However, it should be noted that on account of the frequencies used the wavelength is of the order of 30 km. Consequently, to resolve the ambiguity it will suffice that the navigator knows his position to within 15 km. Experiments have shown that in the majority of cases, for civilian vessels in particular, a special channel identification system was not absolutely essential. This system, however, offers the possibility of channel identification at the price of having a slightly more complicated onboard receiver.

It should also be remembered that when the vessel's receiver is permanently tuned in after leaving a known position the variations in phase are recorded and therefore no ambiguity is possible, since the lane number is known.

II. — Technical characteristics

The basic frequency for the system is 10.2 kHz, and all stations in the world network are synchronized. This stability of phase is assured by highly stable atomic cloks (10^{-11} phase per day, i.e. 1 μsec per 10 kHz), and monitoring stations close to the transmitters enable any phase "creeping" to be adjusted.

In view of the range of VLF waves not all the stations can transmit simultaneously, and the eight transmitters accordingly work in a predetermined sequence.

A complete cycle lasts 10 seconds, and each of the stations transmits on four frequencies :

— The basic frequency of 10.2 kHz mentioned above.

— A frequency of 13.6 whose relationship to the basic frequency is :

$$\frac{10.2}{3} = \frac{13.6}{4} = 3.4 \ .$$

Thus by means of beats between these frequencies it will be possible to set up a 3.4 kHz network that is three times wider than the 10.2 kHz basic network. If the moving vessel's position is known to within 45 km, we thus obtain a first resolution of ambiguity.

— A frequency of 11.33 kHz whose relationship to the above two is :

$$\frac{10.2}{9} = \frac{11.33}{10} = \frac{13.6}{12} \ .$$

This frequency allows a third network, even wider than the first two, to be set up by means of beats, and for this it will merely be necessary for the navigator to know his position to within 135 km in order to resolve the ambiguity.

It will be seen that the measurement accuracy on frequencies 13.6 and 11.33 kHz need not be very great, since in order to resolve ambiguity it will suffice to be able to know the lane of the basic network in which the ship is navigating. It is only within this basic network that accuracy of positioning will be obtained.

— Finally the stations each transmit on a distinctive frequency which enables them to be identified.

All frequencies in the system are sub-multiples of 48 kHz. Each of the three frequencies 10.2, 11.33 and 13.6 kHz is transmitted for a duration varying between 0.9 and 1.2 sec according to the station. There is an interval of 0.2 second between each frequency to allow time for switching.

The diagram below shows the signal formats for the eight stations. Each distinctive frequency is transmitted for approximately 7 seconds. The sequence itself, i.e. the relative duration of each of the transmissions, also makes identification of the transmitting station possible.

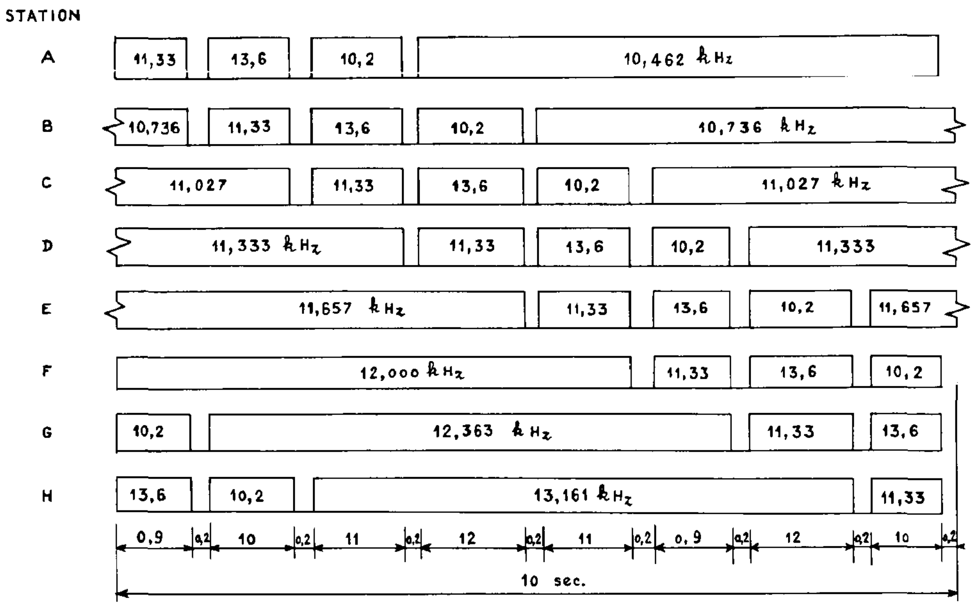

FIG. 1. — Omega signal format.

III. — **Operational characteristics**

Accuracy of the Omega system

A radionavigational system's principal operational characteristic is its accuracy. It should however be remembered that accuracy can only be defined in terms of probability. To say that a navigational system is accurate to within 1 km signifies nothing unless the probability of obtaining this degree of accuracy is also mentioned.

The two most generally used notions are the circle of uncertainty (probable error at n %) and the standard deviation σ where the law of probability is known.

If f_n is the radius of the circle of uncertainty with a PE of n % this this simply signifies that for a given measurement to fall within a circle of radius r_n the probability will be n%.

For a gaussian law, if measured points are to be less than σ from the true point the probability is 68%.

For a gaussian law of probability — and if the mean value is at the same time the true value — the following are the relations between the radii r_n of the circle of uncertainty, PE n%, and :

$$r_{68} = \sigma$$

$$r_{95} = 2\sigma$$

$$r_{50} = \frac{2}{3}\ r_{68} = \frac{2}{3}\ \sigma \qquad r_{99} = 1.25\ r_{95} = 2.5\sigma$$

The user who only makes discontinuous measurements will obviously have only scattered points and will find only 50% of the points within the circle of 50% PE. However in the case of permanent measurements — those for instance of radionavigational receivers — a certain smoothing of the results is evident, and the reading gives in fact a mean value. Thus we may say that the accuracy defined by a 50% PE reflects a margin of error that a navigator can normally expect to find in a system that is permanently in operation (except during sizeable radioelectric disturbances of long duration). These then are the conditions under which we shall be defining the accuracy of the Omega system and also that of the Differential Omega system.

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When the Omega system becomes globally operational in 1973 the accuracy (50% PE) will always be to within 2 km. By day it will be even better, of the order of 1 km.

This accuracy can however only be achieved by using annually edited correction tables which give the corrections to be made to the phasemeters in relation to their position and both the date and the time. The tables are computer calculated from a wave propagation mathematic model. The model was drawn up from wave phase measurements carried out over a number of years by many countries. France has been collaborating with the U.S.A. since 1965.

In point of fact the system's accuracy is restricted by the accuracy of the predictions of fluctuations in propagation conditions. It is precisely by using accurate predictions that in the differential Omega system the positioning accuracy in certain areas can be very considerably improved.

It should also be noted that in the hyperbolic system the accuracy varies within the coverage. Firstly, the hyperbola which are very close together on the baseline diverge when the navigator moves away from it. Thus, for one and the same relative degree of accuracy of phase the absolute accuracy is less in the field itself. Secondly, for purely geometric reasons the area of best accuracy is found where the two hyperbolic networks required for fixing a position intersect roughly orthogonally.

These questions have very little importance in the Omega system : the divergence of the hyperbola remains in point of fact small in view of the length of the baselines (of the order of 8 000 km). Moreover, whereas six stations would have been sufficient for obtaining world coverage, the eight stations of the projected system will allow the best choice to be made for the two pairs of stations that are needed for positioning. In this way, it is always possible to be in an optimum position, both as regards the spacing of the hyperbolae as well as for their angle of intersection, and the accuracy obtained is almost identical for any point on the globe.

Finally, it should be noted that these arrangements mean that the system remains fully usable even in the case of a breakdown of one or even two of the transmitting stations. In the former case there will only be about a 15% loss in accuracy : in the latter about 50%.

IV. — **Equipment**

Transmitters

Omega stations are essentially VLF transmitting stations, and are therefore characterised by the size of their aerials. At the very low frequencies used, i.e. 10 kHz for a wavelength of 30 km, the aerials must have a height of several hundred metres in order to obtain satisfactory radiation.

Even in these conditions efficiency is only about 10%, and the transmitter power must therefore be 100 kW for radiating the 10 kW required.

There is special equipment for working out the signals according to the scheme mentioned earlier, as well as for phase and frequency control, and this is triplicated at each station to permit intercomparison and to allow for breakdowns.

The stations are fundamentally distinguished by their type of aerial, and this also has a very large bearing on their cost.

The most economical stations — costing about 50 000 000 Francs — are those benefiting from a natural geographic position, i.e. a deep, narrow valley, a fjord, etc., where the aerial cables can be hung at a sufficient distance from the ground, that is at about 700 to 1 000 m in this particular case.

If this possibility does not exist it is then necessary to erect pylons of more than 300 m in height. The cost of a station is then of the order of 80 000 000 Francs.

Receivers

The complexity of the format of the Omega signals makes it possible to construct various types of receivers adapted to the needs of a great number of users. The equipment is primarily made up of a device for reconstituting the format of the Omega signals and of a VLF unit for receiving the transmitted waves.

The first operation consists of synchronising the receiver's time base with the format of the transmitted signal, and secondly to recognize the pairs of transmitting stations which the user has chosen in relation to his position.

Once these operations have been carried out the measurements of the phase differences can be started. As the stations transmit sequentially the receiver must be able to retain the phase of one station in memory while waiting for the second.

The measurements of the phase difference having been done in this way, the results can be shown on either an oscilloscope or on dials since the processing of this information may be done by either analogue or digital methods. The latter method allows other equipment, such as computers for transforming the coordinates, to be linked in. It will, however, be simpler if the information for the track plotter is transmitted in analogue form.

Resolving the ambiguity is a process done in the same way as a phase comparison at 10.2 kHz, but with less accuracy, and thus the receiver should be capable of receiving a frequency of 13.6 kHz and even possibly 11.33 kHz.

For marine navigational uses the receiver need only be of one frequency as the resolution of ambiguity is not an absolute necessity. It should be automatically synchronized and it must be possible to read the phase differences direct on dials. The price, as one of a series, would be about 20 000 Francs plus Tax.

To make his fix with these results the operator must first use correction tables and then enter the corrected values on a special chart overprinted with the Omega hyperbolae.

It would take too long to list the possible forms of receiver. It will, however, be of interest to note that it will also be possible for aircraft to use the Omega system, although a plane's speed poses special problems because the aircraft flies a considerable distance during the seconds that the measurement sequence lasts.

Before carrying out a phase comparison it will therefore be necessary to reduce all the measurements artificially to the same point. Thus the receiver for an ultra-rapid craft must take account of the distance run, and will naturally be a little more complex, but the idea is sound and experiments have proved the validity of this navigational method.

THE DIFFERENTIAL OMEGA SYSTEM

I. — Principle

With the Omega system it is possible to fix a craft's position by measuring the difference of phase between two signals. From an analysis of the causes of inaccuracy in this phase measurement we shall see that it will be quite easy to devise a sub-system which in a limited area will give considerably better performances than the basic system.

There are two causes of inaccuracy — the wave propagation, and the instruments themselves.

Inaccuracies due to the instruments are actually very small. The station synchronization characteristics have been noted above, and nowadays it is possible to measure phase differences with extremely good accuracy. It is not therefore to these components that we should look if we wish to increase the system's performance considerably.

On the other hand in radio-electric waves the speed of propagation and the phase vary considerably. A range of 10-14 kHz was adopted for the Omega system because both the propagation and the phase of these frequencies are sufficiently stable for them to be used for radionavigational purposes. However, as we have noted, it is necessary to make corrections for the variations in characteristics that are due to geographic reasons (wave paths over land or over sea) as well as for the radioelectric conditions in the atmosphere (height and density of the ionized layers).

The factors for the geographic correction are fixed, and only a calibration is needed to determine them. On the other hand ionospheric propagation conditions are essentially variable. They depend on the amount of atmospheric ionization and thus on the sun's activity, the season and the time of day. They are, however, to some extent forecastable and are the subject of correction tables which are issued annually as predictions.

Long term forecasting only gives the general aspect of the phenomena and is obviously lacking in refinement. Certain "accidental" occurrences, such as solar eruption, cannot in any case be predicted.

If the variations in propagational conditions were perfectly known the system's accuracy would merely be a function of the quality of its component instruments. A receiver having a phase difference sensitivity of one degree would thus lead to an accuracy of about 50 m on the baseline.

Accurate knowledge of such variations is possible if, for a point of known coordinates, the phase differences are compared with their theoretical difference and if this information is immediately transmitted to all navigators in the neighbourhood.

Two receivers placed in the same position thus give identical Omega indications, instrumental errors apart, and the corrections to be made to them in order to obtain true values are at all times equal. If the two receivers are placed slightly apart it is seen that the differences in propagation between two neighbouring points are similar in a particular area, and that by correcting the mobile receiver B (close to receiver A) for the discrepancy between the theoretic and the instrumental value we should obtain a much improved accuracy of positioning for mobile B.

It is thus possible to set up a sub-system, provided of course that the gain in accuracy is appreciable and that the area (where the relative variations in propagation conditions are of the second order in relation to the absolute variations) is large enough to justify the setting up of the necessary additional equipment.

The numerous trials undertaken have demonstrated the soundness of this method — one in which the accuracy can be improved by a factor of at least four within a radius of about 500 km of the reference point.

II. — Technical characteristics

Let A be a fixed point with known coordinates, and for which the theoretic value of the phase difference in an Omega network is p_a. At time t, the value read on the receiver's phasemeter will in fact be p'_a.

The correction given by the monthly tables is c_a, and this gives the value $p''_a = p'_a - c_a$ for point A, which is not the same as p_a. The accuracy (50% PE) for this correction is such that 50% of the fixes lie within a radius of 2 km around point A.

The instantaneous correction to be made to measurement p'_a to cancel the error is $d_a = p'_a - p_a$. If the same correction is applied to another receiver located in the same place the true position, instrumental errors apart, is obtained with an accuracy of several tens of metres.

Let B be a point, close to A, at which is placed an Omega receiver which will give the phase difference p'_b for the same network, whereas the theoretic value is p_b.

The correction c_b can be applied to p_b. In the tables $p''_b = p'_b - c_b$, and thus a positioning accuracy of within 2 km is found for mobile B.

If the correction $d_a = p'_a - p_a$ is then applied $p'''_b = p'_b - d_a$ is obtained. If B is less than 500 km from A the position given by p'''_b is accurate within approximately 500 m.

It would have been possible to think of applying the correction $d'_a = p''_a - p_a$ to the already corrected p''_b to obtain the point $p''''_b = p''_b - d'_a$ but experience has shown that hardly any gain in accuracy resulted, and it seemed simpler merely to apply the correction d_a which can be done automatically in the receiver, whereas it would be difficult to make the c_b correction unless there were a computer on board.

Possible applications

The sole means of transmitting the corrections that make it possible for users everywhere to benefit from the Differential Omega's accuracy is to broadcast this information continuously over the radio. Many countries have given much thought to this problem. In France, at the Ministry of Defence the "Direction des Recherches et Moyens d'Essais" has requested SERCEL (*) to study the practical applications of a Differential Omega system.

Before making any arrangements for such broadcasts it is essential to

(*) "Société d'Etudes, Recherches et Constructions Electriques". A subsidiary of the "Compagnie Générale de Géophysique" which worked out the Toran radionavigational system and which builds Omega receivers.

know the extent of the area to be covered and the amount of information to be transmitted. An investigation at present being undertaken has revealed that a relatively small amount of information is concerned, of the order of 10 bauds only, since propagation conditions change fairly slowly with time. It thus appears possible to build up a system using that part of the HF range reserved for radionavigation (i.e. around 1.6 MHz) for retransmission of the necessary corrections and by using a very narrow spectrum of frequencies of less than 100 Hz.

Since at this frequency the waves have limited range it is possible to use the same frequency at points more than 2 000 km apart. Moreover, as the spectrum for each station is very narrow, a single frequency may be used for about ten stations in any one area. As the frequency is the same for all stations the world over the Differential Omega receiver can be very simple. Only one HF terminal is therefore necessary, as simple switchable filters can be used for channel separation at each station.

In order that the users may find the system still more advantageous it would seem desirable that the corrections be made automatically within the receiver and that the corrected value be the one shown on the phasemeters.

For a reasonable price such a possibility exists, and models on this basis are to be constructed as part of the study mentioned above. These will permit a full operational evaluation of the principle of the Differential Omega system.

As the ordinary Omega system is a world system it seems most desirable that Differential Omega should also be determined at world level, so that the same receiver can be used in any of the world oceans. The research carried out in France is only at the exploratory stage, and we shall need to rely on a system of international cooperation to define the exact details of this sub-system.

III. — Operational characteristics

The accuracy of the Differential Omega system is known as a result of the many experiments carried out by various countries. By its very

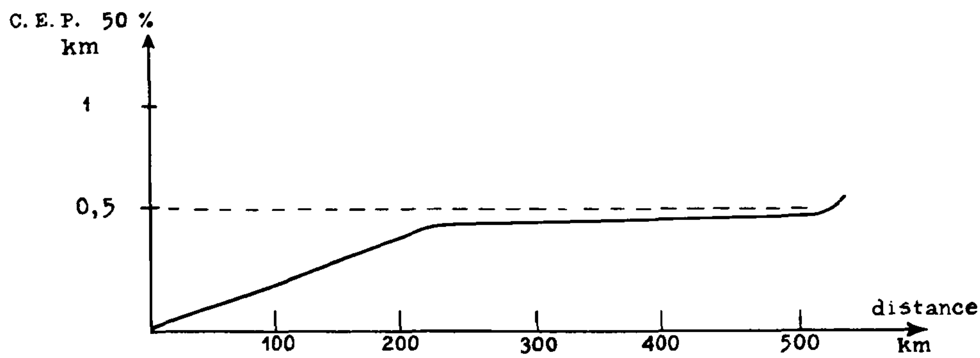

Fig. 2

principle the accuracy should be to some extent proportional to the distance to the point where the corrections are being transmitted.

The results confirm this. Up to 200 km the accuracy is proportional to the distance, but at greater distances remains nearly constant. Beyond 500 km the gain in accuracy as compared with the ordinary Omega rapidly diminishes.

Thus in relation to the basic Omega system at 100 km the Differential Omega system is 10 times more accurate, and at the area's outer limits, i.e. at 500 km, it is still four times as accurate.

Thus over 24 hours the accuracy is :

200 m at 100 km
400 m at 200 km
500 m at 500 km

As in the case of the basic Omega system, the daylight accuracy is about twice as good.

It should also be noted that the accuracy of the Differential Omega system is better in the N-S direction than in the E-W direction which is normal because all points of the ionosphere on the same meridian have the same degree of ionisation since all are equally affected by the photons radiated by the sun.

IV. — **Equipment**

Shore Station

A Differential Omega station for transmitting the necessary corrections to the Omega information for a given area is made up as follows :

— An Omega receiver.
— A phase comparator.
— A coder.
— An HF transmitter of about 100 W.

None of this equipment is very costly, and the price of such a station, with all the equipment duplicated so as to ensure uninterrupted service on a 24 hour basis, will amount to about 300 000 Francs.

The installation is not bulky, and the transmitter aerial itself can be a simple whip. The stations might therefore be set up in signal stations or in lighthouses. Thus it would seem that conditions for setting up shore stations will be very satisfactory.

Onboard equipment

Differential Omega receivers can quite easily be adapted from an ordinary Omega receiver by the addition of an unit that includes :

— a single frequency HF receiver;
— a signal decoder.

The HF received corrections are then applied to the Omega receiver's phase measurements and the corrected values are shown directly on the phasemeters.

An ordinary Omega receiver costs about 20 000 Francs, and it is estimated that the price of a Differential Omega will be around 30 000 Francs.

For areas outside the Differential Omega coverage the receiver can naturally be used as an ordinary Omega receiver. Thus a single set can cover all navigational needs.

The phasemeter information can be routed to a track plotter, and this will make it possible to follow a predetermined course as well as to monitor the area around. The cost of a track plotter is of the order of 30 000 Francs.

V. — Planned developments

As has already been said, it seems very desirable that the Differential Omega's signal format be internationally approved so that one and the same receiver can be used everywhere in the world's oceans. Thus a universal radio navigation system will have been set up.

Many users were quick to realize right from the outset of the Omega system's development the possibilities afforded by differential measurements.

The first application envisaged was for the case where two vessels have to meet. When both vessels have the Omega coordinates of the meeting place, if the system's absolute error is 2 km (probably somewhat larger without correction tables), then both have the certitude of finding themselves in close proximity to one another. This application will naturally always be possible, and it enables two fishing vessels, for example, to fix their rendezvous in a very simple manner.

Almost at the same time a start was made — first by the Americans, followed fairly closely by the British and the French — on evaluating the differential errors. Although at that time the accuracy of the basic system had not yet reached the expected values, the results actually obtained with differential measurements were proving very interesting. It was seen, for instance, that up to a distance of about 300 km only very little gain in accuracy results from the use of correction tables.

The principle of the Differential Omega system was thus established. To date, however, there have to my knowledge been no developments in equipment. There is nothing unusual in this, since the Omega system will not become operational until 1973. It should, however, be noted that the system could be put into operation in the North Atlantic as early as the end of 1971.

Thus it might be envisaged to set up the Differential Omega system on Europe's West Coasts as from that date, although the geometry of the hyperbolic network would not be optimal in this zone until the Indian Ocean station is put into operation.

For several years now the authorities in France have been seeking a solution to both navigation and positioning problems on the continental margin. A CNEXO-inspired (*) Working Group composed of many operators has been seeking the best means of resolving this problem. The setting up of the Differential Omega system might supply a very satisfactory solution from both an operational as well as a financial point of view for certain of these problems, and in particular for fishing vessels.

In France the Ministry of Defence has initiated a study on both the Omega and the Differential Omega systems. The prospects of their civil uses have encouraged the Ministry of Equipment and Housing (Lighthouse and Beaconage Service) and the Ministry of Transport (the General Secretariat of the Merchant Marine) to take an interest in these studies and to participate in the development of the Differential Omega.

The experiments on models — making it possible to investigate the operational possibilities of an automatic differential system on the terrain itself — will thus be undertaken in a far wider context than its military uses. As part of the Sixth Plan, the civil Ministries concerned have requested the necessary funds for perfecting these developments and for setting up shore stations. The need in the Bay of Biscay is in fact pressing.

CONCLUSIONS

A comparison of the characteristics of the basic Omega and the Differential Omega systems with those of an ideal navigational aid shows that considerable advance has been made towards the creation of a universal system.

The system is available at all points on the globe, thanks to the use of VLF waves. Moreover, the Differential Omega stations when set up will increase positioning accuracy in certain zones where the navigational need is felt. The accuracies expected of these two complementary systems are entirely compatible with navigational needs and the requirements of the majority of operators.

Other expressed wishes of the operators regarding bulk, cost, ease of use, etc., appear to have been catered for satisfactorily. The basic Omega and the Differential Omega thus appear to be the systems of the future for all kinds of marine navigation, and their use can even be foreseen in other domains, for air navigation in particular.

The systems are in the development stage : it is only in 1972 that the Omega system will come into operational use, and we may anticipate that the Differential Omega system will follow hot on its heels, at least in certain specified areas.

(*) CNEXO — France's "Centre national pour l'Exploitation des Océans".

All the characteristics claimed are therefore merely prudent estimates. It should however be noted that from a mass of information gathered over more than 10 years it is possible to affirm that the basic Omega's performances will be of the standard expected of it. Certain operators are already using the system. In the neighbourhood of the French coasts, however, in view of the present status of operational stations and the low power they radiate the accuracy actually obtained sometimes differs considerably from the expected value. These passing difficulties, which are inherent in the system's state of advancement, must not be allowed to discourage these pioneers who have faith — and rightly so — in this new navigational system.

In the case of Differential Omega much additional evaluation remains necessary, for up to the present no campaign of operational evaluation has been undertaken.

In view of the system's advantages — for Differential Omega is a natural and very interesting complement to the basic Omega system — the French authorities have decided to pursue Research and Development in this field. Thus we may envisage seeing Differential Omega stations set up in the very near future all along the coasts of France in order to resolve the numerous navigational problems encountered there.

To speak of a system in its development stage risks leading to misinterpretations. Although it is necessary to announce the characteristics expected of a system fairly early in its development, there is a risk the first users may draw hasty conclusions about a still incomplete and therefore imperfectly realised system. Their experiences are however essential, for it is thanks to their observations and criticisms that the system can be perfected in the most complete and quickest possible way.

The object of the present article is not to convince potential users but rather to call their attention to the important possibilities of this universal radionavigational system which with a single receiver meets most navigational needs the world over.

The present evolution already seems irreversible. In several years we shall no longer imagine a ship without an Omega receiver, just as today there is no sizeable ship which is not radio-equipped.

Let us therefore hope that the Omega and the Differential Omega systems can be fully and finally developed in the very near future.