NATIONAL INSTITUTE OF OCEANOGRAPHY

WORMLEY, GODALMING, SURREY

Navigation Using V. L. F. Radio Transmissions

An assessment of its potentialities

by

M. J. TUCKER

N.I.O. INTERNAL REPORT No. A 24

FEBRUARY 1966

NATIONAL INSTITUTE OF OCEANOGRAPHY

Wormley, Godalming, Surrey.

NAVIGATION USING V.L.F. RADIO TRANSMISSIONS

An assessment of its potentialities

by

M. J. TUCKER

N.I.O. Internal Report No. A.24

FEBRUARY 1966

C O N T E N T S

Figure Captions

Figure 1 - 2,000 nautical mile range circles from the 6 V.L.F. transmitters, with the 7,000 mile range circle from GBR Rugby, England, and a great circle path from Hawaii to Portugal.

Figure 2 - R.M.S. phase anomalies recorded at Frankfurt, Germany, using the 18 kc/s transmissions from NBA Panama. The phase anomly is the departure from the mean of the values at the same time of day for the whole month. A good month (June) a bad month (April) and a moderate month are shown. Data is from Brady et al. (1963).

Figure 3 - R.M.S. movement of phase pattern between observations separated by time T over all-daylight or all-dark paths, for signals from NBA Panama received at College, Alaska (approximately a 5,000 n. mile path).

A.24

Introduction

In November 1965 the writer was very kindly invited by the Woods Hole Oceanographic Institution to spend ten days aboard the R.V. ATLANTIS II, journeying from Panama to Woods Hole on the last leg of her journey round the world. J. Stanbrough was aboard operating the V.L.F. navigation equipment which he has been developing (Stanbrough and Keily, 1964 and Stanbrough, 1965) and this gave the writer a good opportunity to study the system. At that time the writer was working as a Visiting Scientist at the Massachusetts Institute of Technology, so that on return he was also able to hold very helpful discussions with Professor D.P. Keily of that Institute.

Navigation in areas where the present fully-operational radio aids are not available (and they cover a very small proportion of the world's oceans) remains one of the oceanographers' basic problems. Use of the Satellite radio-navigation system would go a long way to solving this problem, but for security reasons it is not available at the present time, and in any case there is no guarantee that it will be maintained: the cost of maintaining it is, of course, very high indeed. V.L.F. navigation provides one possible answer, and the writer feels that a careful assessment of it is therefore of considerable interest.

Fortunately, a V.L.F. system called Omega (described below) has been under development for some years and has stimulated much research in V.L.F. propagation which is directly applicable to the system under discussion here, so that a reasonably reliable assessment is possible. V.L.F. propagation has also been studied because high-altitude atomic explosions cause effects on V.L.F. propagation which may enable it to be used as a detection system, and because V.L.F. transmissions are used for the transfer of frequency standards.

The situation with respect to V.L.F. navigation is changing so fast that it is difficult to keep up with it. There are at present at least five research and survey ships fitted with experimental installations and at least four more are due to be fitted soon. The U.S. Oceanographic Office alone has about six people working full time on computer programmes, charts, and instrumentation. The author thinks it probable that with the rapidly extending use of the system the transmitting stations will soon have to accept this application as one of their responsibilities, and this would remove one of the most annoying present disadvantages: that the stations go off the air for servicing, regularly for periods of hours, and occasionally for long periods.

This report will discuss principles and limitations of the system, and will only discuss instrumentation in as far as this limits the performance.

It should perhaps be added for the record that the possibility of navigation using the existing V.L.F. transmissions was first pointed out by Balzer (1962) in a preprint of a paper for the 1963 Winter Convention for Military Electronics, Los Angeles, California (1st Feb. 1963).

Though the writer has had the benefit of the advice of many people, the conclusions reached in this report are his own and do not necessarily represent the views of anyone else.

Section 1 : General Discussion

General Principles of the System

A.24. V.L.F. radio waves propagate well over great distances and have long been used for radio telegraphy. A list of the transmitting stations relevant to the present paper is given in Table 1. It will be seen that frequencies are in the region of 20kc/s giving wavelengths in the region of 15 km.

Since the waves are reflected by the ionosphere at a height of about four wavelengths, it is convenient to think in terms of mode propagation in the waveguide formed by the ionosphere and the surface of the earth. For those not familiar with this concept, it may be said that for practical purposes, waves travelling in a given mode may be considered as waves forced to travel along the surface of the earth with a phase velocity slightly different from (and usually less than) the velocity of free electromagnetic waves.

Many modes are generated at the transmitter and the propagation pattern close to the transmitter is complicated: by about 2000 miles, however, all modes except the first have been effectively absorbed and the propagation pattern becomes simple.* At ranges beyond about 7,000 miles the situation may again become complicated by waves which have travelled round the earth in the opposite direction (antipodal paths).

The carrier frequencies of the stations listed in Table 1 now have stabilities of a few parts in 10^{11}. The stabilities are steadily being improved, and should reach a few parts in 10^{12} in the forseeable future. One part in 10^{12} would be effectively absolute stability for all normal navigation purposes. The actual frequencies of the stations (averaged over a day) are monitored continuously, and these figures are available for subsequent correction of navigational fixes if required.**

Assuming for the moment that the transmitters have absolute frequency stability and that the ionosphere remains at constant height, the phase of a signal received at ranges of between 2,000 miles and 7,000 miles therefore remains constant with time and changes uniformly with the great-circle distance from the transmitter. The phase patterns from the various transmitters can be used for navigation in one of two ways.

(1) A highly stable oscillator is carried aboard ship and the phases of the transmissions from two suitably placed stations relative to this local oscillator are measured. Starting from a known point (usually a harbour), the changes in great-circle distances from the transmitters can be calculated and these allow the ship's position to be determined.

(2) If three suitably-placed transmitters are available, the relative phases between them may be measured and this gives the necessary information to calculate changes in the ship's position. The advantage of this system is that it removes dependence on the stability of the oscillator carried by the ship, but because it is necessary to have three transmitters available at widely separated bearings, the geographical coverage is more limited than the system (1) described above (the three transmitter system is almost identical with that of the Omega experimental system described below) and it would not be worthwhile designing equipment specially for this purpose and constructing the necessary charts and tables.

---

* Bates and Albee (1965), however, claim that the 2nd order mode can be important on some paths, particularly at night, out to ranges of at least 5,000 miles. They argue that the large short-term phase fluctuations are due to interference between the first and second modes, and not to solar or geomagnetic effects. This does not affect the general conclusions of this report however.

** Write to: Radio Broadcast Service Section, National Bureau of Standards, Boulder Laboratories, Boulder, Colorado, U.S.A. For U.S. Naval stations: U.S. Naval Observatory, Washington 25, D.C.

However, if system (1) is used, it is worth adding a third receiver since in suitable areas it can then be used in effect as a difference system: all three answers are plotted in the ordinary way and the same time increments are added or substracted from all three until they all cross at the same point. The third receiver is in any case useful since it can often be used to bridge the servicing intervals of one station by using another and this point has been stressed by several authors.

System (2) will not, therefore, be considered further below.

Omega

Omega is the name given to a V.L.F. system of navigation which is under development by the U.S. Navy (Swanson and Tibbals, 1965). The present experimental system uses four transmitters located at Hawaii, Panama, New York State and Wales. Each of these transmits pulses of 10·2kc/s lasting approximately 1 second and interleaved in a 10-second time sequence which enables each to be identified. The carriers are frequency-stable and phase-locked to one another.

The system measures the relative phase between pairs of stations, and thus gives hyperbolic position lines which are only useful when three stations are available with reasonably large angular separation. The geographical coverage is therefore limited at the present time to parts of the North Atlantic, North-East Pacific, and Arctic Oceans. Even in these areas it is doubtful whether it is suitable for general use at the present time. In practice the receivers are very expensive, difficult to get, and the system, being under development, is liable to be changed in such a way as to make them obsolete. The receivers are rather specialised and it would be difficult to adapt other standard equipment.

It is hoped that a system with world-wide coverage and operating with three frequencies to avoid lane ambiguities will be operational by about 1972. Obviously one cannot hold up development of other systems in anticipation of this.

It will be seen that the basic difference in principle between Omega and the system discussed here is that the latter carries a stable oscillator with the receiving system, so that only two suitably placed transmitters are required instead of three, and this extends the geographical coverage very greatly.

Variations in the propagation time

The height of the ionosphere is not, of course, constant as has been assumed above. The most important changes are diurnal. In a daylight path the phase velocity is approximately 0·1% less than the velocity C of free waves, and over a path in darkness it is approximately 0·3% less than C. This means, for example, that at a range of 4,000 miles from the transmitter the phase pattern moves back and forth about 8 miles. This movement can be calculated and allowed for to a first order of accuracy, but comparatively large unpredictable changes in the phase pattern remain.

Measurements of these changes are reported in a series of publications issued by the National Bureau of Standards. The most applicable to the present study is the first of the series (Brady et al, 1963) which reports measurements on signals from NBA Panama as received at Frankfurt, Germany, which is a path of approximately 5,000 n.m. largely over water. The other reports show results which are broadly similar.

Monthly means were subtracted from the measurements and the standard deviation of the anomaly calculated. Values for three months are shown in figure 2. The standard deviations corresponded to changes in the position of the phase pattern

A.24.

varying from approximately 0·15 n.m. in summer over all-daylight paths to as much as 2·0 n.m. in winter over night-time paths. For rather more than 70% of the time the standard deviation was less than 1·0 n.m.

These figures agree well with some quoted by Stanbrough and Keily (1964), and Stanbrough (1965), for example, who made tests on short daytime trips in the vicinity of Woods Hole, Massachusetts, in May and June 1963 and found a maximum error of 0·3 n.m. using GBR, Rugby and NPM, Hawaii at 3,000 and 5,000 n.m. distance respectively.

The rapidity of these variations is significant in connection with the feasibility of the measurement of the drift of a ship on station. Relevant figures are given in the N.B.S. reports. The r.m.s. phase difference between observations separated by time T are calculated for times when the paths are all-daylight or all-dark. This is easier on north-south paths, and so some figures for the NBA, - College, Alaska, path are plotted in figure 3 (from Crary and Murphy 1965, converted to equivalent n. miles of horizontal movement). But note that the method of calculation does not extract systematic daily variation: it assumes that over all-daylight or all-dark paths, there is no systematic variation with time of day, which does not seem to be completely true.

The ship's oscillator

High quality quartz-crystal oscillators are available which are suitable for shipboard use. These vary a little in performance even from the same manufacturer, but the best, after ageing and with careful compensation for the drift rate, change less than 1 part in 10^{11} per day (a change of 1 part in 10^{11} represents a drift in position of approximately 0·14 miles/day.) These oscillators cost typically $3,000 each. However, to achieve this stability requires skilled operation and the total drift over a cruise lasting several weeks may be very serious, so many operators are now using atomic oscillators (rubidium or cesium). For example, cesium-beam frequency standards which are reasonably compact and which have long-term stabilities of 1 part in 10^{11} are available from several manufacturers at costs in the region of $15,000. They also seem to be reasonably reliable.

Hydrogen maser oscillators with even higher stabilities are in an advanced state of development and should be available soon, but their suitability for shipboard use is not known to the present writer.

It will be seen that the station frequencies are all multiples of 100 c/s. The system of comparison of phase is somewhat complicated, but in effect the frequency of the ship's oscillator is divided down to 100 c/s and the received signal is compared with the appropriate harmonic of this 100 c/s reference. The phase change is displayed in terms of microseconds, so that it is convenient also to prepare charts in term of travel time in microseconds.

Geographical coverage

Figure 1 shows the 2,000 mile range circles from the 6 stations of Table 1. The 7,000 mile range circle of GBR is also shown: the rest of these are omitted to avoid confusion, but they are not, in fact, too helpful unless studied on a globe. For example, the great circle path from Hawaii to Lisbon (approx. 7,000 miles) is shown as a dotted line, and illustrates the surprising fact that the stations at Hawaii and Panama could give quite good coverage of the North Eastern Atlantic Ocean, with position lines crossing at obtuse angles. In practice, Seattle would be better than Hawaii in this area because of its shorter range.

Using the first system described above, there is therefore good coverage over most of the world's oceans except for the Indian Ocean and part of the Southern Ocean. A station is being constructed at North West Cape, Australia, with the assistance of the U.S. Navy and this should extend coverage to much of the Indian Ocean, though position lines will cross at rather acute angles in the northern areas. A station in Hong Kong or the Philippines would be better.

A station designed specifically for this application could be comparatively cheap and simple. Because of the very narrow effective bandwidth of the receivers (of the order of 0·01 c/s) they have high sensitivity and it would be necessary to transmit only a few hundred watts of power.

Existing stations can normally be received with adequate signal strengths anywhere in the surface of the earth.

Other considerations

At the present time, most of the stations go off the air at stated times for servicing. These times are shown in Table 2 and represent a major difficulty in the case of the longer servicing intervals. Not only is a position not available during this interval, but the ship's position must be known by other means to within about three miles if there is to be no risk of being one complete phase in error when the station returns to service. For a period of an hour or two on a steady course, extrapolation of the previous rate of change is usually adequate to lock the system into the correct phase when the signal returns. Again, if V.L.F. navigation ever becomes widespread, it would presumably be possible to arrange for servicing shutdowns to be kept short, or even avoided altogether.

The transmission is, of course, interrupted during message keying, but the absolute phase is maintained and the receiving sets are designed to cope with these short interruptions.

The V.L.F. stations are used as frequency standards, and the receiving sets designed for this, which are available commercially, are also suitable for navigation. It is therefore possible to assemble a shipboard navigation system for about $ 13,000 with a negligible amount of special wiring and construction.

Note on Indian Ocean results

Tests on the system were made in the Indian Ocean during the International Indian Ocean Expedition. The results in 1964 and 1965 were on the whole very unsatisfactory. This is hardly surprising since nearly the whole of the Indian Ocean is beyond the recommended range of all stations except GBR, Rugby, and a great deal of trouble was experienced from waves coming the other way round the World (antinodal paths). Also, other than GBR, NBA, Panama is the most suitable of existing stations and should give coverage over the S.W. corner of the Indian Ocean, but this station was off the air for most of the period.

In one sense these tests were unfortunate since they have tended to give the system a bad name, whereas the present author feels that it has real potentialities in more favourable areas where it is still the only available radio aid to navigation.

Section 2 : Assessment

Present capabilities

(1) For position determination

Unpredicatable changes in the position of the phase pattern limit accuracy to about ±0·5 n.m. under the most favourable conditions (summer daytime), and to about ±5·0 n.m. under the least favourable conditions (winter night-time).

Drift in the frequency of the transmitter varies a little from station to station, but in most cases should introduce errors not exceeding about 1 n. mile per day (GBR at the present time seems to be about twice as bad as this).

Drift in the ship's oscillator will cause a position drift of less than 0·15 n. miles per day if an atomic oscillator is used. With a good crystal oscillator the drift rate will be about this value on the first day out from port but will increase steadily as the time from the last calibration increases.

Errors due to our lack of knowledge of the phase velocity, the figure of the earth, etc., should not introduce errors greater than about one mile in 1000 miles.

(2) For drift measurements

The measurement of the drift of an oceanographic vessel on station can give useful information about currents in the water, but requires an accuracy of perhaps 0·2 knots to be useful. It will be seen from figure 3 that such an accuracy cannot be approached at night, but might be marginally obtainable in the summer with propagation over all-daylight paths from favourably-placed transmitters. Stanbrough (private communication) believes that 0·05 knot might be attainable on short daytime cruises in the western North Atlantic.

Future possibilities

With improved frequency stability at the transmitting stations, and with atomic oscillators aboard ship, the time limit should be removed and absolute navigation should be possible over voyages of normal duration.

With experience, it should be possible to improve travel-time calculations to an accuracy of better than one mile over the full range.

It would seem to be within the resources of an institute to set up a temporary transmitting station in, say, Hong Kong, if local co-operation in making a suitable site available, and perhaps with operation, could be obtained, though even a low-efficiency antenna might prove to be rather expensive.

If V.L.F. navigation based on existing stations develops into an important tool, the transmitting stations may be persuaded to accept this function as one of their responsibilities and to reduce the breaks in their transmissions to acceptable lengths.

If these conditions were fulfilled, it should be possible to navigate to within about five miles anywhere on earth.

This accuracy may be improved with increased experience and understanding of the factors governing the variations in propagation.

Practical Problems of Use

If V.L.F. navigation is to be of general use, it will be necessary to have:

(a) Charts available marked with iso-travel-time lines from the most suitable transmitters for the area. The U.S. Navy Oceanographic Office has already prepared a number of such charts for areas in the Indian Ocean, and the author understands that charts are at present in preparation for other areas.

(b) Some convenient way of correcting for diurnal changes must be devised. If this takes the form of tables, it will probably be adequate to have hourly values tabulated for each month for each 10° square. (A specimen of the tables prepared for Omega is shown by Swanson and Tibbals, 1965).

It should perhaps be mentioned that many users believe that it is best to use a digital computer to calculate the diurnal corrections, apply them to the measured time differences, and calculate the ship's position. However, the present author feels that it is likely to be found more generally convenient to use tables and charts, particularly in the present rather experimental state of the system.

Another problem is the "unreliability" of the transmitters. For example, Hawaii and Balboa were recently off the air for a period of many months. "Unreliability" has been put in inverted commas because, of course, navigation is not officially one of the functions of these stations.

The commonly used quartz-crystal shipboard oscillators are being used up to the absolute limit of their accuracy, and to obtain best results have to be adjusted every day by someone who can assess the required drift correction from all the available data (previous history, comparison of V.L.F. fixes with other fixes, etc.). The use of atomic oscillators, though increasing the cost of the system quite considerably, would reduce the skill and time required in its operation and reduce drift errors to almost negligible values.

These considerations largely add up to the fact that it is a system under development, and needs to be operated by someone who understands all the factors involved, and who is prepared to spend quite a lot of time on the equipment.

Section 3 : Summary and Conclusions

Presently operating V.L.F. stations cover nearly all the ocean areas except the Indian Ocean and parts of the Southern Ocean. In these areas, navigation over periods of about a week with maximum errors of about 7 miles should be possible at the present time: considerably higher accuracies are possible at certain times of the year at certain times of day. Within a year or two, improvements in frequency stability should allow this accuracy to be maintained over periods of at least a month.

Useful measurement of the drift of an oceanographic vessel on station does not appear to be possible, except perhaps in favourable locations and at restricted times during the day.

For the system to be convenient in routine use, charts and correction tables must be prepared in advance.

A practical difficulty at the present time is the considerable daily periods during which the transmitters are shut down, though it is usually possible to lock in to the correct phase when they start up again.

Studies using the Omega experimental system have shown an r.m.s. error of about one mile when all predictable corrections have been applied. This is at 10·2 kc/s whereas the system described here works at about twice this frequency, but it is probably still a good measure of the accuracy to be obtained apart from errors due to drift in the ship's oscillator. (The errors are not normally distributed, large errors being more frequent than predicted by a normal distribution.)

R E F E R E N C E S

The following is a selected list of those papers found useful by the present author.

BATES, H.F. & ALBEE, P.R. 1965 General V.L.F. phase variations observed at College, Alaska. J. geophys. Res. 70, 2187-2208.

BLACKBAND, W.T. 1964 Diurnal changes in the time of propagation of V.L.F. waves over single mode paths. Chapter 16 of Propagation of radio waves at frequencies below 300 kc/s. New York: MacMillan & Co.

BRADY, A.H., MURPHY, A.C. & CROMBIE, D.D. 1963 The normal phase variation of the 18 kc/s signals from N.B.A. observed at Frakfurt, Germany. U.S. National Bureau of Standards, Technical Note No. 206-1.

CHILTON, C.J., CROMBIE, D.D. & JEAN, A.G. 1964 Phase variations in V.L.F. propagation. Chapter 19 of Propagation of radio waves at frequencies below 300 kc/s. New York: MacMillan & Co.

CRARY, J.H. & MURPHY, A.C. 1965 The normal phase variations of the 18 kc/s signal from N.B.A. observed at College, Alaska. U.S. National Bureau of Standards, Technical Note No. 206-4.

HAMPTON, D. and HILL, A.S. 1964 The statistical prediction of diurnal phase changes. Chapter 17 of Propagation of radio waves at frequencies below 300 kc/s. New York: MacMillan & Co.

KUEHNEL, R.O. 1964 A very low frequency (V.L.F.) navigation system for ships. Bedford Institute of Oceanography Report, B.I.O. Ref. 64-40. (Unpublished manuscript)

SILVERMAN, M. 1965 Oceanographic application of very low frequency radio navigation in the Indian Ocean. Pp. 320-333 of Ocean science and ocean engineering 1965, Vol. 1. Washington: Marine Technology Society.

STANBROUGH, J.H. 1964 A V.L.F. radio relative navigation system Navigation, Los Ang. 11 417-428.

STANBROUGH, J.H. & KEILY, D.P. 1964 Long-range relative navigation by means of V.L.F. transmissions. Deep-Sea Res. 11, 249-255.

SWANSON, E.R. and TIBBALS, N.L. 1965 The Omega Navigation System. Navigation, Los Ang. 12, 24-35.

Table 1

V.L.F. radio stations useful for navigation (Dec. 1965)

GBR	Rugby, England	16.0 kc/s	52° 21'N	1° 11' W
NPM	Hawaii	26.1 kc/s	21° 25'N	158° 09' W
WWVL	Boulder, Colorado, U.S.A.	20.0 kc/s	40° 41'N	105° 03' W
NSS	Annapolis, Maryland, U.S.A.	21.4 kc/s	38° 59'N	76° 27' W
NBA	Panama	24.0 kc/s	9° 04'N	79° 39' W
NPG	Seattle, Washington, U.S.A.	18.6 kc/s	48° 12'N	121° 55' W

Table 2

Times at which V.L.F. stations shut down for servicing and other purposes (G.M.T. : Dec. 1965).

GBR	1300 - 1500 Daily
NPM	0900 - 1800 Wed. only + hourly 57-60
WWVL	As required + every other Tuesday.
NSS	As required + hourly 57-60
NBA	1200 - 2100 Wed. only + hourly 07-10
NPG	1600 - 2400 Thurs. only + hourly 47-50

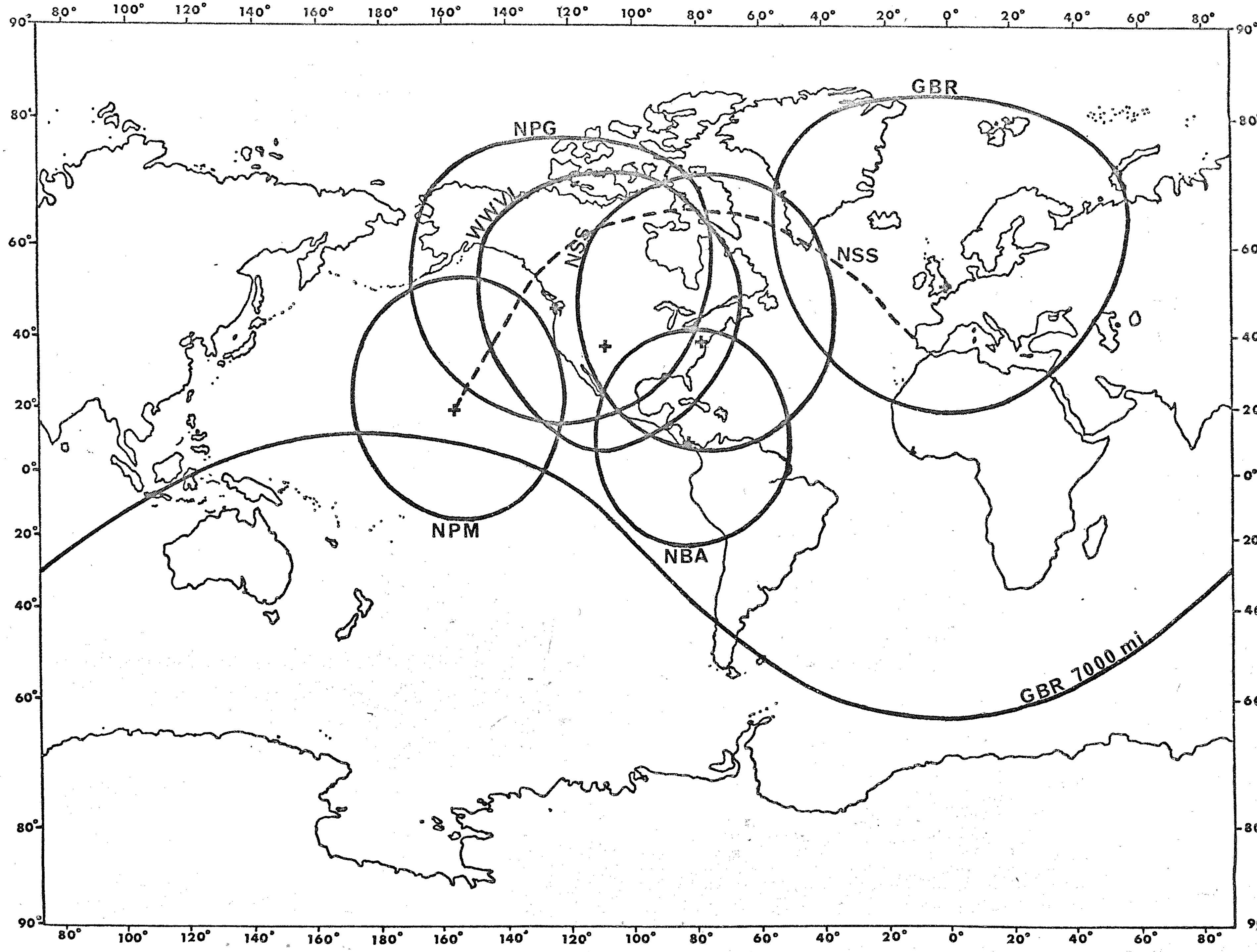
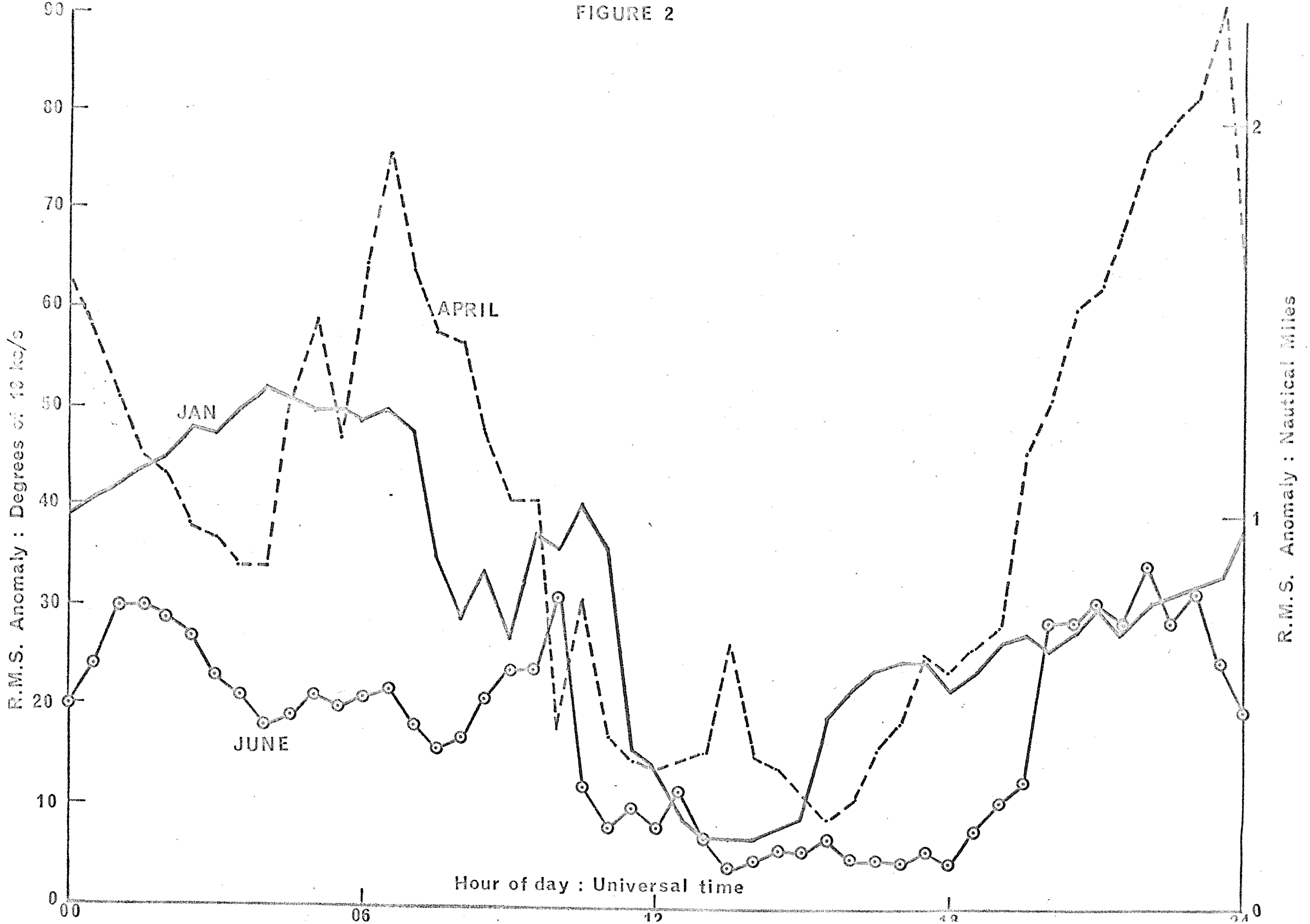
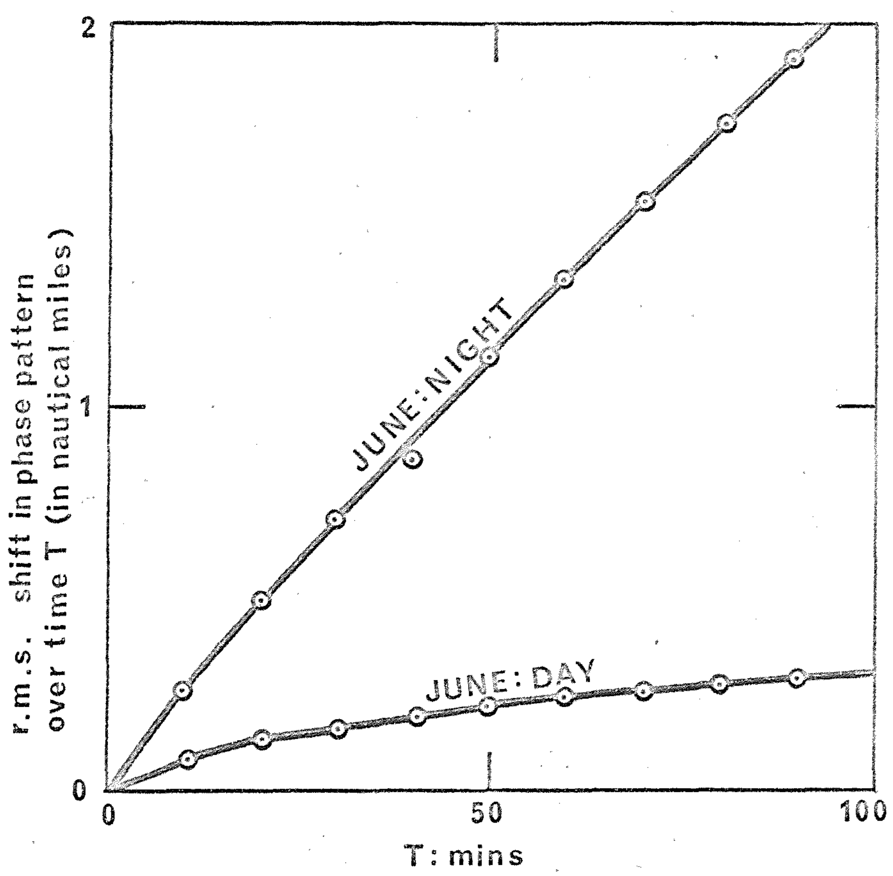


FIGURE 1

FIGURE 2



APRIL
JAN
JUNE
R.M.S. Anomaly : Degrees of 10 kc/s
R.M.S. Anomaly : Nautical Miles
Hour of day : Universal time
0
10
20
30
40
50
60
70
80
90
00
06
12
18
24
0
1
2



r.m.s. shift in phase pattern over time T (in nautical miles)
2
1
0
JUNE: NIGHT
JUNE: DAY
0
50
100
T: mins

FIGURE 3