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TECHNICAL REPORT

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THE TOTAL SOLAR ECLIPSE OF 23 OCTOBER 1976 OBSERVED AT VLF

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S U M M A R Y

VLF transmissions at 13.6 and 22.3 kHz from Omega Reunion, Omega Japan, and NWC were monitored at Melbourne during the total solar eclipse of 23 October 1976. The solar obscuration function for each path was calculated and compared with the phase deviation observed experimentally. The phase response was found to be a non-linear function of solar obscuration with a maximum phase deviation which was less than expected when compared with the normal diurnal phase variation. A differential equation was developed to model the observations. The effective time constant of ionospheric response was found to be 4.3 ± 1.5 min and independent of reflection height.

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1. INTRODUCTION

The Omega navigation system is made possible by the long range and excellent phase stability of VLF radio propagation. The phase velocity of the propagating wave is, however, sensitive to the effective height of the earth-ionosphere waveguide. In daytime reflection occurs at D-region heights of around 75 km. At night, recombination and attachment remove the free electrons in the D-region causing the reflection height to increase by some 15 km. To obtain the maximum accuracy from a VLF navigation system such as Omega, an algorithm is commonly employed to correct for the resultant diurnal change in phase velocity. The algorithm in current use by the U.S. Coast Guard(ref.1) involves a differential equation in which a model of solar illumination provides the driving function. A parameter of importance is the assumed time constant of ionospheric response. The exact form taken by this differential equation (which attempts a simple modelling of ionospheric dynamics) is a matter of some conjecture since a satisfactory understanding of the formation of the D-region has yet to be achieved.

On 23 October 1976, a total eclipse of the sun, visible from the coast of Africa through the Indian Ocean to the south-east corner of Australia, occurred. The effects of this eclipse on VLF phase path were observed at Melbourne(within the path of totality) on transmissions from Omega Reunion and Omega Japan at 13.6 kHz and from the U.S. Navy transmitter NWC in Western Australia at 22.3 kHz. These measurements provided a rare opportunity for investigating the phase response of a VLF path to a major change in solar illumination of known time variation. In this paper, the eclipse measurements are described and compared with predictions based on the current Omega diurnal correction model of reference 1.

2. EXPERIMENTAL DETAILS

2.1 The observations and their reduction

VLF signals from Omega 13.6 kHz transmitters in Japan, Reunion, Hawaii and Argentina as well as the U.S. Navy transmitters NWC (22.3 kHz) and NLK (18.6 kHz) were monitored in Melbourne. The NWC transmitter normally operated on MSK (Minimum Shift Keying), a format which would not allow the phase of the signal to be tracked by the receivers concerned. In order to assist eclipse observations, NWC reverted to a transmission format which could be phase tracked for a period of eight hours spanning the eclipse.

The location of the propagation paths with respect to the eclipse area and the path of totality is shown in figure 1. The paths from Omega Japan, Omega Reunion and NWC lay entirely in daylight for the duration of the solar eclipse. The paths from NLK, Omega Hawaii and Omega Argentina, on the other hand, were well into the sunset transition so that the eclipse phase deviations were superimposed on the normal diurnal phase change.

Examination of the records obtained during the eclipse showed phase deviations on all records except, perhaps, the path from Hawaii for which the signal-to-noise ratio was particularly bad. Comparison of records obtained on days prior and subsequent to the eclipse on the paths from Hawaii, Argentina and NLK showed that the normal phase pattern at the eclipse time was too variable to extract the time variation of the eclipse with any accuracy, consequently these observations were not pursued further. Attention was directed to the observations from Japan, Reunion and NWC.

Because of differences in quality and duration, the data from the three paths were treated differently. The Omega Reunion observations were processed by averaging records taken two days prior and two days subsequent to the eclipse day and subtracting this average from the eclipse record to obtain the eclipse phase deviation. (All receivers used a local caesium atomic frequency standard as phase reference and phase drift from this source was negligible.) The effective phase tracking time constant of the four channel navigation receiver employed was some 50 s.

Phase displacements accompanied by signal dropouts occurred in the Omega Reunion record around the time of the maximum eclipse effect. This was followed by a period of some 10 min (as given by the USNC Time Bulletin No. 111) when the transmitter went off the air. Examination of concurrent Omega Reunion records taken at Perth and Brisbane (Dr J. Crouchley, private communication) confirmed that the transmitter was the source of these disturbances.

The record of Omega Japan was taken from a single channel receiver with a phase tracking time constant of 5 s which resulted in an effective time constant of 50 s when the commutated nature of the signal was taken into account. Because of the poor signal-to-noise ratio, this data was smoothed with a 4 min running mean adjusted to prevent the introduction of a time shift. Once again an average phase record derived from the two days prior and subsequent to the eclipse day was subtracted from the eclipse record to obtain the phase deviation as a function of time.

The NWC signal was recorded with a 5 s receiver time constant which, because of the high transmitted power and short sunlit path, gave a record of excellent phase stability. Because of the transmitter keying format, no records from days prior or subsequent to the eclipse day were available. Examination of the phase before and after the eclipse effect on the day in question showed no measurable change so that this value was subtracted from the eclipse record to yield the eclipse phase deviation.

The reduction of the phase records and the receiver time constants have been described at some length because they are crucial to the credibility of such records for time comparison purposes.

Signal strength records were available only from the Omega Reunion receiver which was running near saturation. Whilst the receiver was not accurately calibrated in this region, the maximum increase in signal strength associated with the eclipse appeared to exceed 3 db.

2.2 The calculation of changes in path illumination

To find the change in total path illumination during the eclipse, it was necessary to calculate the degree of solar obscuration S at points along each path as a function of time. The solar obscuration parameter S discussed here is the ratio of the obscured area of the solar disc to the total area and is thus a measure of the reduction in illumination during the eclipse. Following the detailed eclipse calculations in the explanatory text of The Astronomical Ephemeris, a program was written to calculate solar obscuration at any given location using the tabulated Besselian elements for the eclipse taken from the appropriate Astronomical Ephemeris. Linear interpolation of the table was used to give greater time discrimination and the appropriate correction from ephemeris to universal time was made. The resultant computer program was successfully tested for observations at ground level against the calculated times of total eclipse given for specific locations in the USNO eclipse circular of Fiala and Duncombe(ref.2). Subsequent calculations for comparison with the VLF observations were made at a height of 80 km above the earth's surface.

The great circle path from each transmitter to Melbourne was found as were the latitudes and longitudes of 30 equally spaced points along each path. At successive times during the eclipse, the degree of solar obscuration S at each path point was calculated and a numerical integration performed to give the average value of solar obscuration $\bar{S}$ over the whole path i.e.

$$\bar{S} = 1/L \int_0^L S \, dl \tag{1}$$

Thus $\bar{S}$=0 corresponds to an absence of any eclipse effect whilst $\bar{S}$=1 corresponds to totality over the whole path (a physical impossibility for long propagation paths).

3. EXPERIMENTAL RESULTS

The eclipse phase deviations ($\Delta\phi_E$) observed over the paths from Omega Reunion, NWC and Omega Japan to Melbourne are shown in figure 2 along with the calculated solar obscuration functions $\bar{S}$. The two sets of data have been normalised to a peak value of one to facilitate comparison. The values of maximum eclipse phase deviation $\Delta\phi'_E$ and solar obscuration $\bar{S}'$ are listed in Table 1 along with the times t_E and t_S when they occurred. (Note that primed quantities in this paper represent the maximum value of the variable in question). The t_E value for the path from Reunion was derived from the shape of the experimental data before and after the interruptions to the signal described in Section 2.

Examination of figure 2 shows the duration of the eclipse phase effect to have varied over the three paths, being 4.3 h for the Omega Reunion transmissions, 2.0 h for NWC and 1.7 h for Omega Japan. Eclipse totality intersected the Melbourne terminal of the propagation paths at 6h41 m UT. The maximum eclipse phase deviation occurred seventeen minutes before Melbourne totality for the Omega Reunion path, at the same time for the NWC path and nine minutes subsequent to totality for the path from Omega Japan. The times t_S of maximum path solar obscuration $\bar{S}'$ also differred from the time of totality at Melbourne but always occurred before the corresponding maximum phase deviation. The time difference (t_E - t_S) showed considerable variation from path to path (Table 1). As shown from the $\bar{S}'$ values in Table 1, the reduction in illumination was the greatest over the path from NWC whereas the largest phase deviation occurred over the longer path from Omega Reunion.

In figure 2, the magnitude of the phase deviation is clearly not linearly related to the changing obscuration function (with or without the introduction of a time shift) since at low levels of solar obscuration, the phase deviation is relatively less than at high levels of solar obscuration. This effect is particularly evident over the path from Omega Reunion where a period of relatively slow convergence between the path of totality and the propagation path resulted in an unusual form of eclipse time variation.

The reduction in illumination produced by a solar eclipse has some similarity with that occurring at sunset and it is thus of interest to compare the ratio of eclipse deviation to the normal phase variation from day to night (i.e. the diurnal phase variation $\Delta\phi_D$) with the maximum value of solar obscuration. These two values should be comparable if the phase deviation is linearly related to the reduction in illumination. The diurnal phase change ϕ for each path was therefore measured using data from days adjacent to the eclipse date. In the case of NWC, a calculated first mode diurnal phase value had to be used in the absence of appropriate experimental data (cf.reference 14). The ratio $\Delta\phi'_E/\Delta\phi_D$ (Table 1) proved to be much less than the corresponding reduction in illumination, once again suggestive of a non-linear relationship.

3.1 Eclipse modelling

VLF navigation systems require correction for changes in the phase velocity of the received signals. The most significant correction allows for the solar control of D-region electron density and thus VLF reflection height and phase velocity. Modelling of this diurnal phase change has been attempted by Swanson(ref.3) in terms of a differential equation relating a phase parameter G(t) to a source function F(t) which changes with solar zenith angle. The equation is of the form

$$\frac{dG(t)}{dt} = \frac{F(t)}{\tau} - \frac{G(t)}{\tau} \qquad (2)$$

where τ is the relaxation time or 'sluggishness' of the ionosphere and is given by

$$\tau = \tau_D + (\tau_N - \tau_D)\ F(t) \qquad (3)$$

where

$$\tau_D = \text{minimum day value } (\chi=0^{\circ})$$

$$\tau_N = \text{night value } (\chi > 90^{\circ}).$$

The functions in equation (2) have been normalised so that at midday when $dG/dt=0$, $F=G\doteqdot 0$. At night when $dG/dt=0$, then $F=G=1$. The actual phase deviation from the midday value ($\Delta\phi$) is then given by averaging G over the propagation path and multiplying the resultant mean $\bar{G}$ by the observed diurnal phase variation $\Delta\phi_D$.

Equation (2) derives the phase parameter G(t) from the solar illumination function F(t), bypassing the intermediate details of changing electron density and VLF reflection height. Similarly equation (3) relates the effective time constant directly to the illumination function F. Since reflection height varies with changing illumination, equation (3) also indicates that τ is a minimum at the low values of reflection height (about 75 km) corresponding to midday and a maximum at night when the reflection height moves towards 90 km.

The experimental basis for the assumed variation in the ionospheric time constant rests on two kinds of measurement. First is the observed time lag between maximum VLF phase change and maximum solar illumination over the path. (This kind of measurement is similar to the original derivation of ionospheric 'sluggishness' given by Appleton, reference 4). The second measurement is the apparently continuing recovery of VLF phase after the sun has set on the night reflection level. From such measurements, Swanson, as reported by Morris and Cha(ref.1), deduced values of τ_D = 7.5 min and τ_N = 67.5 min.

Since an eclipse should correspond in some ways to a mini-diurnal change in path illumination, testing the ability of equation (2) to reproduce the observed eclipse effect is of both practical and theoretical interest.

In order to evaluate equation (2), the form of F(t) must be established. Since an eclipse produces a relatively slow variation in illumination, dG/dt is small compared to the other terms. Thus to a first approximation, the phase parameter G(t) can be taken as proportional to F(t). In order to introduce the observed non-linearity between changing illumination and phase deviation, F(t) was assumed to vary as S^n. The average value $\overline{S^n}$ over each path was found as a function of time in the manner described in Section 2.2. For $2<n<3$, the $\overline{S^n}$ curves thus derived were found to closely approximate the form of the observed phase deviations. The time delay (Δt) between the maximum value of $\overline{S^n}$ and the maximum phase deviation was found to decrease rapidly as n increased for the path from Omega Reunion, less so for the path from NWC and not noticeably for the path from Omega Japan. The range of n which gave the best fit between F(t) and the observed phase deviations was found to reduce the time differences between F maximum and the maximum phase deviations over the various paths to a common value in the range 3-5 min. This corresponds to a time delay between source function and phase response equal to the probable pre-eclipse ionospheric time constant.

The above investigation suggested that a suitable differential equation for describing VLF phase response to an eclipse would take the form

$$\frac{dG(t)}{dt} = \frac{(aS)^n}{\tau} - \frac{G(t)}{\tau} \qquad (4)$$

where tau is independent of S and thus the reflection height.

Equation (4) was solved numerically as a function of time at successive points along each propagation path (30 points for Reunion and Japan, 20 for the NWC path) and the average path value $\bar{G}$ as a function of time was found. In these calculations, the parameter a allows the magnitude of the source function to be adjusted so that the modelled phase deviation $\Delta\phi_M$ for the path is given by

$$\Delta\phi_M(t) = \bar{G}(t)\,\Delta\phi_D \qquad (5)$$

The values of a, n and τ which produced the best fit with observation are listed in Table 2 and the resultant match between model and experimental values can be seen in figure 2. The differences in the values listed in Table 2 are commensurate with the errors of experimental measurement and thus may have no physical significance.

During the calculations described, the solar zenith angle was also found as a function of time along each path. These calculations showed that the path from Reunion to Melbourne was the only one with an eclipse effect of sufficient duration for changing solar zenith angle to be a factor in shaping the VLF response. The zenith angle correction estimated was less than the experimental error of measurement and consequently was not considered worth adding to the model.

4. DISCUSSION

The obscuration function for an eclipse observed at a particular geographic location normally has a considerable degree of symmetry. Under these conditions, calculations show that equation (4) will always result in a time delay between maximum solar obscuration and maximum phase deviation which is equal to the ionospheric time constant (assuming of course that the time constant is small compared to the eclipse duration). This result is essentially independent of the non-linearity parameter n. Over a long propagation path, the solar obscuration function and resultant phase deviation are the sum of such localised responses. The non-linearity of the phase deviation under these conditions may result in a time delay between the maximum path obscuration function and maximum phase path phase deviation differing considerably from that at any one path point. This was most evident for the path from Omega Reunion to Melbourne where the unusual path-eclipse geometry resulted in minimum path illumination occurring much earlier than the time of path intersection with the line of totality. The path from Omega Japan, on the other hand, lay approximately at right angles to the line of totality so that the time of maximum reduction in path illumination corresponded closely to the time of intersection with the line of totality and the overall delay in phase response had practically no sensitivity to the non-linearity term. Thus, in the absence of detailed eclipse calculations, it can be dangerous to assume the equivalence of the experimental time delay and the ionospheric time constant over long VLF paths.

4.1 Eclipse time delays

Skywave propagation over short VLF paths can be considered in terms of a single hop which reflects from an ionospheric area of finite extent (related to the dimensions of the first Fresnel zone) midway between the transmitter and receiver. Measurements of the time variation in phase path can thus be directly related to changing ionospheric conditions in the reflection area if contamination from the ground wave can be avoided. From eclipse measurements made over such paths, values of 0-6, 1-2 and 6 min have been reported by Weekes(ref.6), Crary and Schneible(ref.7) and Sales(ref.8) respectively, for the time delay Δt between maximum obscuration and maximum phase deviation. A possible non-linearity in the phase response may be indicated by the data of Crary and Schneible(ref.7), since the percentage eclipse deviation of the normal diurnal phase variation fell from 68% for total obscuration over one path to 43% for 88% obscuration over another.

Over long VLF propagation paths, time delays of 4 min between the passage of totality across the path and peak phase deviation have been found by Noonkester and Sailors(ref.5) and Swanson and Kugel (as reported by Noonkester and Sailors(ref.5). As discussed above, time delays may depend on the orientation of the path relative to the eclipse region. Since the line of totality crossed the propagation paths concerned centrally and at high angles, the values quoted are probably good approximations to a corrected time response. VLF observations from previous solar eclipses are thus consistent with those found here and indicate that there is a 3-5 min time delay between the maximum solar obscuration and the maximum deviation in VLF reflection height. The observed time delay is inconsistent with the increase in D-region time response for decreasing solar illumination suggested by Swanson(ref.3). (This conclusion was further tested by re-calculating equation (4) over the propagation paths with τ effectively increasing with height as given by equation (3). The resultant increased time delay greatly exceeded the observed value). The lack of variation in the eclipse ionospheric time constant suggests that either the ionospheric photo-chemistry during sunset differs markedly from that present during a solar eclipse or the observed slow recovery of VLF phase during and after apparent ionospheric sunset is not a true time constant effect but results from an actual slow decay of a 'source'.

It is interesting to note that the value of 4-5 min for the time delay between eclipse maximum and the associated VLF phase deviation is the same as that between the peak x-ray intensity of an impulsive solar x-ray burst and the maximum phase deviation of the corresponding SPA (Sudden Phase Anomaly) observed at VLF (Mitra, reference 9: Hudson et al, reference 10). The recovery of an SPA is, however, significantly different with an apparent time constant of some 35 min. This slow recovery of the ionosphere produces the typically asymmetric appearance of an SPA which contrasts with the symmetry of the eclipse response. Rowe et al(ref.11) have suggested that the x-ray burst produces a change in ionospheric ion chemistry which results in a reduction in the effective recombination rate.

4.2 Eclipse phase deviations

In equation (4), the parameter a was introduced to reduce the effective source function in order to match the small phase change observed. In consequence, the phase deviation given by equation (4) only reaches some 50-60 % of the normal diurnal phase change for steady night conditions of $S=1$ and $d\phi/dt=0$ (as approached at totality). This could be taken as indicating the presence of a significant 'source' of electron production still acting at eclipse totality. Measurement indicates that some Lyman and solar x-ray flux is indeed present at this time (SMITH, reference 12; Accardo et al, reference 13) but not apparently of sufficient magnitude to produce the effect observed here. Another possibility is that the change in electron density gradient during the eclipse opposed the effect of increasing reflection height thus resulting in a diminished phase response. A detailed examination of this question would require a knowledge of the actual change in the electron density profile during an eclipse and the resultant effects on both VLF signal level and phase velocity. Such eclipse electron density profiles have been calculated on theoretical grounds by Noonkester and Sailors(ref.5) and appear to have produced VLF phase and amplitude deviations of satisfactory magnitude with the propagation model used. The actual profiles developed were not shown and consequently can not be discussed further.

To check whether the relatively small VLF response to the Melbourne eclipse was consistent with previous observations, VLF phase deviations for the annular solar eclipse of 19 September 1969 were examined. The path of this eclipse lay between Hawaii and the American mainland. The propagation paths concerned and values of maximum phase deviations observed are listed in Table 3. The measurements for Aztec, Arizona were taken from reference 5 whilst the values for Deal, New Jersey were obtained as a private communication from Dr F. Reder (Fort Monmouth, N.J.). Equation (4) was evaluated for the paths listed using the average parameter values $a = 0.85$, $n = 2.5$ and $\tau = 4.3$ min derived from Table 2 along with the appropriate Bessellian Elements for the eclipse. Values of diurnal phase variation for these paths were estimated using a single mode day-night phase shift of 9.2 μs/Mm at 12.2 kHz and 8.3 μs/Mm at 23.4 kHz (cf reference 14). The diurnal phase variations $\Delta\phi_D$ thus found are listed in Table 3. Also listed are the estimated phase deviations $\Delta\phi'_S$ found by multiplying the maximum average solar obscuration factor $\bar{S}'$ by the diurnal phase variation, $\Delta\phi_D$ together with the phase deviations $\Delta\phi'_M$ given by the model of equation (4). The experimental eclipse phase deviations $\Delta\phi'_E$ are seen to be less than those calculated ($\Delta\phi'_S$) from the degree of solar obscuration but consistent with the values calculated from the model. There are thus some grounds for believing the results of the present study have general validity for eclipse observations over long VLF paths.

4.3 Navigational relevance

When deriving propagation corrections for VLF navigation systems, the use of a model of diurnal phase change involving a differential equation is based on the belief that the effective time constant of the ionosphere is height dependent and can assume large values. If the eclipse observations are indeed relevant to conditions at sunrise and sunset, then they suggest that the effective time constant of the ionospheric response to changing illumination for VLF reflection heights is small and consequently can possibly be neglected. A model based on this approach would give phase velocities directly as a function of solar zenith angle and would simplify considerably the task of programming diurnal propagation corrections into VLF navigation systems. The possible effectiveness of this alternative procedure would seem to warrant further investigation.

5. CONCLUSIONS

Observations of VLF phase over three long VLF paths were made during the total solar eclipse of the 23 October 1976. The propagation paths terminated within the path of totality at Melbourne. A comparison of the observed phase deviations with the calculated changes in path illumination showed that:

(1) The VLF phase response was proportional to S^n where S is the solar obscuration function and $2<n<3$.

(2) The apparent time constant of ionospheric response was 4.3 min and independent of the ionospheric reflection height.

(3) The maximum phase deviation was less than expected in comparison with the normal diurnal phase change.

The current method of calculating VLF phase as a function of solar illumination in the official Omega propagation correction report(ref.1) was found to be unsuccessful in predicting a VLF phase response to an eclipse. Whilst the connection between eclipse changes in illumination and those occurring at sunrise and sunset is not clear, the present study suggests that other approaches to the problem of deriving the diurnal phase variation may be worth examining.

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TABLE 1. PARAMETERS ASSOCIATED WITH THE ECLIPSE

TX	Freq (kHz)	Dist (Mm)	$\Delta\phi'_E$ (μs)	t_E (UT)	t_S (UT)	$\bar{S}$	$\Delta\phi_D$ (μs)	$\Delta\phi'_E/\Delta\phi_D$	t_E-t_S (min)
NWC	22.3	3.43	5.7	6h41	6h34	0.68	28	0.21	7
Omega R	13.6	8.57	9.3	6h24	6h08	0.36	74	0.13	16
Omega J	13.6	8.20	4.2	6h50	6h44	0.19	53	0.08	6

TABLE 2. ECLIPSE MODEL PARAMETERS

TX	a	n	τ
NWC	0.80	3.0	5
Omega R	0.80	2.5	3
Omega J	0.96	2.0	5

TABLE 3. TEST OF MODEL AGAINST THE ECLIPSE OF 19 SEPTEMBER 1969

Path	Freq (kHz)	Dist (Mm)	$\Delta\phi_D$ (μs)	$\bar{S}$	$\Delta\phi'_S$ (μs)	$\Delta\phi'_M$ (μs)	$\Delta\phi'_E$ (μs)
NPM-Deal	23.4	8.00	67	0.36	24	8.1	6.6
Ω H-Deal	12.2	7.98	73	0.36	26	8.9	8.5
Ω H-Aztec	12.2	4.67	42	0.57	24	5.7	6.8

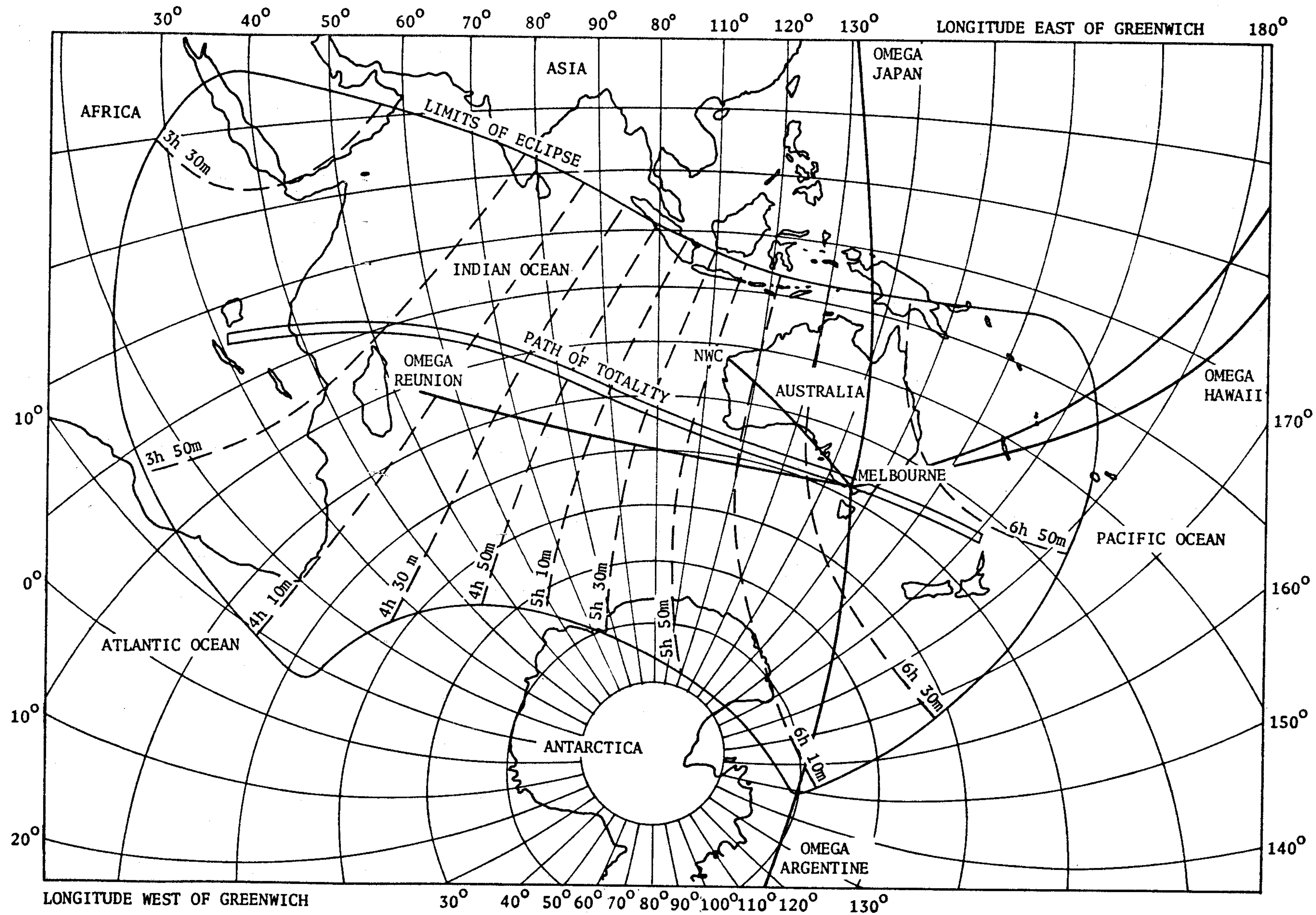

Figure 1. VLF paths monitored in Melbourne are shown in relation to the path of totality and the eclipse limits for the total solar eclipse of 23 October 1976

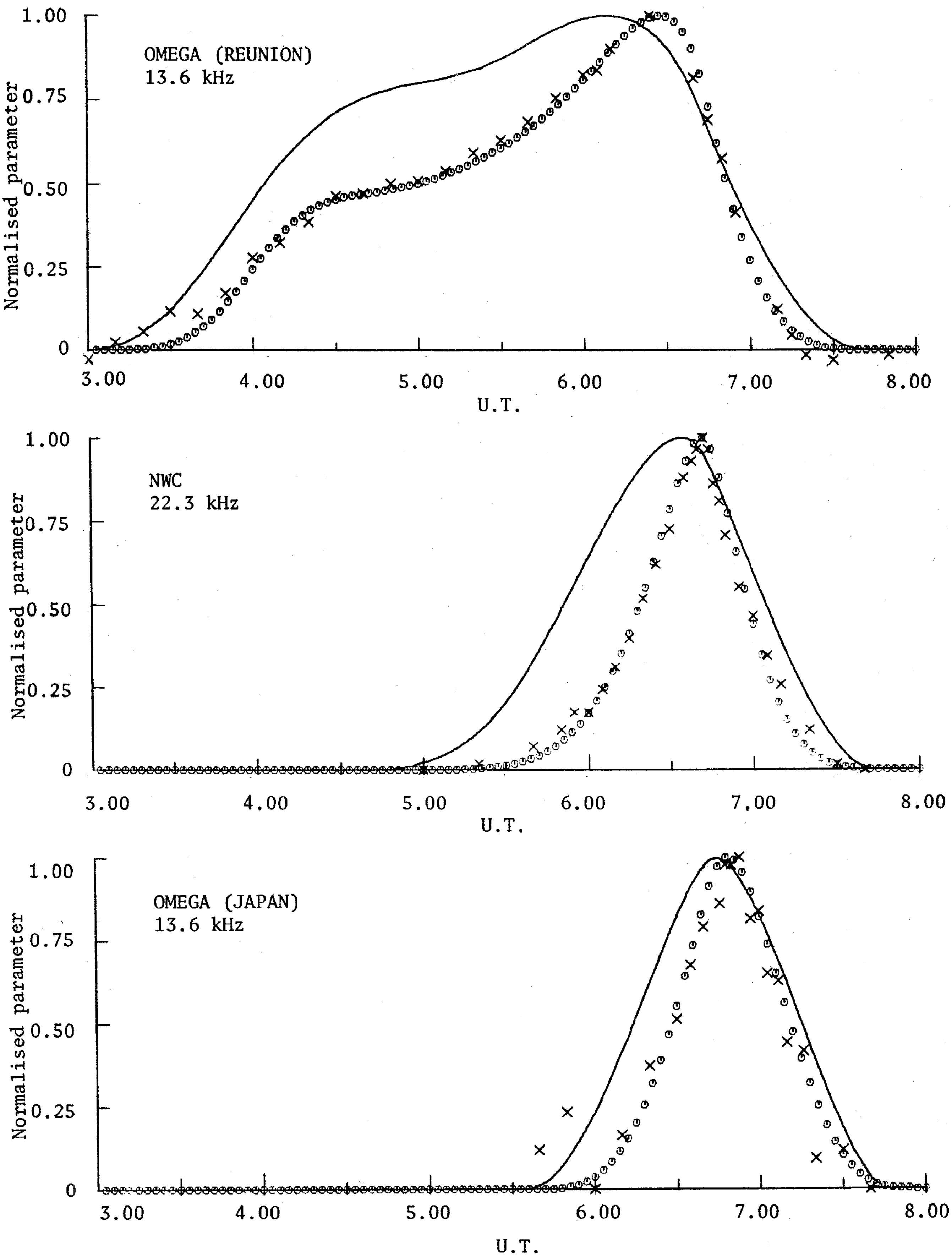

Figure 2. The average path obscuration $\bar{S}$ (full line), experimental phase deviation $\Delta\phi_E$ (crosses) and modelled phase deviation $\Delta\phi_M$ (circles) are shown as a function of universal time. The curves have been normalised to a maximum value of one to facilitate comparison between the obscuration curve and the resultant observed and modelled response

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