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A NOTE ON PHASE VELOCITIES FOR VLF NAVIGATION

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S U M M A R Y

The accuracy of long range VLF navigation systems depends ultimately on the development of phase propagation corrections which will allow for the geophysical variability of VLF phase velocity. Some preliminary estimates of phase velocities likely to be relevant to Omega users in and around Australia are presented, as gleaned from the literature. Some likely areas of investigation which may lead to improvements in these values are described.

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1. INTRODUCTION

Interest in VLF navigation has increased in recent years with the approaching completion of the Omega transmitter network. The main advantage of the Omega system lies in its world wide availability for such diverse forms of transport as army vehicles and aircraft, ships, and submarines.

VLF navigation relies on a natural resource, namely the earth-ionosphere waveguide. It is fundamentally propagation limited by the stability of that waveguide and the accuracy with which natural variations in phase velocity within that waveguide can be predicted. The variation of phase velocity from day to night presents the most obvious need for phase propagation corrections but other more subtle geophysical dependencies are also significant.

At the VLF frequencies of interest (10-24 kHz), the wavelength of the propagating waves varies from 30 to 12.5 km and thus is comparable to the width of the earth-ionosphere waveguide (70-90 km). In these circumstances, long distance reception is most usefully described by a waveguide-mode theory of propagation. At short distances (eg. less than 1000 km) it is sometimes profitable to consider the alternative approach of a suitably modified ray theory involving a ground wave and reflected skywaves. However, it is just in this region of maximum multiple interference that VLF navigation is least satisfactory. Accordingly, all subsequent discussion in this paper is framed in terms of propagating waveguide modes (analogous to the waveguide modes of microwave theory).

For the modes of interest, the cut-off frequencies lie below 10 kHz. Thus as the frequency of transmission decreases, the parameters of the propagating modes tend to diverge in value. In particular, the attenuation rates increase rapidly with mode number at the lower VLF frequencies resulting effectively in single mode propagation at some distance from the transmitter. The Omega frequencies are at the bottom end of the currently used band and thus reduce the radius of the multimode interference zone in the vicinity of the transmitter to some 1000-2000 km.

Beyond this region, the propagating field is essentially that of one mode, consequently the phase of the propagating radio wave varies linearly with distance and is thus suitable for navigation purposes.

The phase velocity of the dominant waveguide mode increases with decreasing frequency as the waveguide mode cut-off is approached. The propagation is thus dispersive. The curvature of the waveguide results in an increase in phase velocity with height, consequently the phase velocities given in this review refer to the ground level values. The phase velocity of the dominant waveguide mode can either be calculated from theory or experimentally measured. Each method has its limitations. The theoretical calculation requires a complete knowledge of the waveguide boundary characteristics. In particular, the variation with height of all relevant ionospheric parameters such as electron density, collision frequency, ion species and magnetic field components. The mathematical difficulties in computing propagation parameters for a curved waveguide with at least one diffuse boundary have resulted in approximations being made. At the time of writing, the more sophisticated waveguide models appear to have reduced the mathematical approximations to the point where they can be neglected in comparison with the uncertainties in the ionospheric parameters. As a consequence of these latter uncertainties, it is usual to do the calculations for a range of possible ionospheric models and then try to fix the most appropriate model by comparing calculated with measured field observables.

A direct measurement of phase velocity, on the other hand, is necessarily of limited accuracy and often contains unresolved variations over the path concerned. The extrapolation of such data to other geographic circumstance must be made with caution. It is evident that some feedback between theory and measurement is necessary in order to optimise either.

The review of phase velocities given in this paper is mainly directed towards the Omega frequencies and is necessarily limited in scope. It is hoped that this review will provide some reference to values likely to be met in developing Differential Omega navigation under Australian conditions and act as a point of departure for further investigations.

2. THE DIURNAL PHASE VARIATION

The variation in D region electron density from day to night produces an increase in the effective height of the earth-ionosphere waveguide at VLF frequencies. The subsequent reduction in phase velocity results in the phase path between transmitter and receiver being longer at night than in daytime. By measuring the phase of an incoming VLF signal against the phase of a local frequency standard (as is typically done with a VLF phase tracking receiver), a regular diurnal phase variation is observed which, if uncorrected, would result in an apparent movement in the position of a VLF navigator at a fixed site. To correct for this effect, the navigator must have time varying predicted propagation corrections (PPCs). The derivation of the official Omega PPCs is described in ref.1 and is discussed in subsequent sections.

Forms of diurnal phase variation likely to be encountered in Australia are shown in figure 1 for transmission paths from Omega Japan, Omega Reunion and Omega Hawaii to DRCS. (The unit of phase variation in these examples is the centicycle (cec)). For a given path, the duration of a sunrise or sunset transition varies continuously throughout the year, the magnitude of the variation increasing with path latitude. PPCs thus have to be found for each individual day. Of note in these diagrams is the high level of phase and amplitude fluctuation at night compared to day and the regular variation of phase with path illumination during the day.

Examining the north-south path from Omega Japan to DRCS, the sunrise and sunset phase transitions are seen to be relatively abrupt. On the other hand, for the paths from Omega Reunion and Omega Hawaii to DRCS, the sunrise and sunset transitions are of comparable duration to the periods when the path is entirely in darkness or in daylight. In practical terms this means that a navigator using the Omega system will commonly be using propagation paths which are in various stages of sunrise or sunset transition. Thus the successful modelling of the phase variation during such transitions is of the utmost importance. The simplest way of modelling a transition is to calculate the position of the effective sunrise or sunset line on the path (a value of solar zenith angle of $\chi = 94^{\circ}$ would be suitable to define the terminator). The relative proportion of diurnal phase shift can then be calculated from the proportion of path in darkness. As discussed in section 3.5, the Omega propagation correction algorithm takes this procedure a stage further by calculating the actual solar zenith angle of points along the path and solving a differential equation in which the observed phase is the response to a zenith-angle dependent illumination function. The phase response is then integrated along the path.

The regular phase steps and accompanying amplitude fading visible in the sunrise transition patterns of Omega Reunion and Hawaii arise from mode conversion at the sunrise line. This is a well understood phenomenon (cf.Lynn ref.2), readily modelled, but is not currently considered to produce deviations of sufficient magnitude at Omega frequencies to warrant inclusion as a navigational correction. Mode conversion effects increase in magnitude with increasing VLF frequency and regularly produce phase cycle slips at frequencies of some 20 kHz and above (ref.2).

The phase pattern of Omega Hawaii in figure 1 exhibits an abrupt reversal in the direction of phase movement during the sunrise transition and an equivalent but minor variation during the sunset transition. This phase discontinuity is associated with the traversal of the sunrise or sunset line through the magnetically equatorial section of the path(ref.3). This type of transequatorial propagation effect is of magneto-ionic origin and is observed only for westward propagation near the magnetic equator. The form of the resultant diurnal pattern can not at present be theoretically derived and no attempt is made to model phase path corrections under these conditions in the current official Omega propagation correction algorithms(ref.1).

3. PHASE VELOCITY MODELLING

This paper follows the treatment of the Omega propagation corrections report (ref.1) in assuming that the normalised phase velocity v/c can be represented as a linear summation of the form

$$v/c = v_0/c + F_1 + F_2 + F_3 + F_4 + E \qquad (1)$$

where v_0/c = reference phase velocity
F_1 = ground conductivity correction
F_2 = latitude correction
F_3 = azimuthal correction
F_4 = solar zenith-angle correction
E = bias error in adding corrections

Undoubtedly the interaction between variables is complex so that the F parameters are not actually independent as suggested by equation 1. However this is the simplest way of approaching the problem and currently appears capable of giving practical results. Relative variations in phase velocity are usually known with greater accuracy than absolute values, consequently the accumulated bias error E may be quite significant.

The theoretical phase velocity calculations which are the basis for many of the algorithms given in reference 1 derive from the computer VLF waveguide program developed by R.A. Pappert and his colleagues at the Naval Electronics Laboratory centre, San Diego. The most recent update of this program appears to be that given in reference 4.

3.1 Basic phase velocities

Early measurements of VLF phase velocities (pre 1965) are given by Watt (ref.5), Wait and Spies(ref.6), Burgess(ref.7). All three references appear to be describing essentially the same collection of experimental observations which are shown in figure 2 (taken from ref.7). Discussions of various methods used in making experimental measurements of phase velocity are given in references 2, 3, and 5. In figure 2, theoretical curves are also shown based on the Wait and Spies(ref.3) theoretical models defined by an effective waveguide height h = 75 km (day), h = 90 km (night) with corresponding ionospheric exponential gradient parameters β = 0.3/km (day) and β = 0.5/km (night). Numerical data for these models is given in the numerical supplement to(ref.6).

These theoretical models do not include the directional effect of the earth's magnetic field. The experimental values apparently have the directional variation averaged out and are thus representative of probable north-south values at middle latitudes.

In reference 6, Swanson is quoted as stating that later measurements gave v/c = 1.0034 as the best 10.2 kHz value for middle latitude propagation over sea water with the directional effect averaged out. Interpolating from the data of figure 2, the day and night base phase velocities for these conditions are given in Table 1 for the main VLF transmissions of likely interest. The day value is for an overhead sun. The accuracy of these values is less at night than for day and decreases with increasing frequency. In this paper, the values of v/c given in Table 1 are taken as the reference values for equation 1.

For single mode propagation, the total phase change from day to night $\Delta\theta$ (i.e. the diurnal phase shift) is given in radians by:

$$\Delta\theta = \arg(\Lambda^D/\Lambda^N) + 2\pi f\,(1/v_1^N - 1/v_1^D)d \qquad (2)$$

where Λ = modal excitation factor

f = frequency

d = propagation path length

so that

$$\Delta\theta/d \doteq (f/3\mathrm{x}10^2)(v_1^D/c - v_1^N/c) \text{ cycles/1000 km} \qquad (3)$$

The diurnal phase shift is an easily measured parameter from which the night phase velocity may be deduced if the day value is known. At frequencies above some 17 kHz, the diurnal phase shift is usually disturbed by the presence of higher order modes at night (cf. ref.10). This may render useless direct attempts to measure phase velocity. The night phase velocities above this frequency in Table 1 consequently rely heavily on extrapolation using a theoretical curve which fits the lower frequency data.

In preparing Omega navigation charts on which lines of position or transmitter distances (in wavelengths) are drawn, a reference phase velocity must be chosen. At 10.2 kHz, this velocity is taken as c/0.9974 (i.e. v/c = 1.00261). The official Omega propagation corrections are thus calculated with respect to this "standard" velocity which lies somewhat below the "absolute" day value of 1.0034 given in Table 1 but is probably closer to an "average" value for a real middle latitude path under actual conditions of solar illumination.

3.2 Ground conductivity correction

For day conditions in Australia, the ground conductivity correction is the most significant which must be applied to the sea water values of Table 1. The variation of phase velocity with ground conductivity has been experimentally measured with results given by Swanson(ref.13) and quoted in the Omega propagation corrections report(ref.1). The agreement between theory and experiment appears to be satisfactory down to the low values of conductivity associated with ice, at which point a major change in the form of the dependence is theoretically predicted with phase velocity increasing rapidly for subsequent reductions in conductivity.

The reduction in daytime phase velocity with decreasing ground conductivity is shown in figure 3. The corresponding corrected phase velocities are given for 10.2 and 13.6 kHz in Table 2.

At night, the situation is not as satisfactory. Both theory and experiment(ref.9) indicate that the ground conductivity effect will be less than for day. However, the night corrections of the Omega propagation corrections report(ref.1) appear to carry over a bias of unknown origin in an experimental determination of Swanson and consequently are not obviously reliable. This bias has been removed to give the night data of figure 3 and Table 2.

The single mode diurnal phase variation may be expected to be less over land because of the differences in the effect of ground conductivity on day and night phase velocity values.

Within Australia, the conductivity map of reference 1 classes most of the interior as of conductivity 10^{-3} increasing to 3.2×10^{-3} near the Great Divide and 10^{-2} along the eastern coastal plains. Since the skin depth at 10.2 kHz varies from 50 to 500 m over the 10^{-2} - 10^{-3} mho/m conductivity range, it is the average conductivity of the ground to a considerable depth which determines the phase velocity.

3.3 Latitude correction

The main causes of latitude variation in VLF phase velocities are first, the sensitivity of the reflecting process to the dip angle and strength of the earth's magnetic field(ref.11) and second, the actual physical variation in the reflecting electron density profile with latitude(ref.5). The latter effect is commonly attributed to a decrease in cosmic ray ionisation towards the equator produced by the shielding effect of the earth's magnetic field. (The change in insolation with latitude is, hopefully, taken into account by the solar zenith-angle correction). References often do not distinguish clearly between the different causes of latitude variation. However, it would appear that the physical variation in the ionospheric profile is the larger factor. Fortunately, both the magnetic field and ionospheric variations work in the same sense so that there is general agreement that phase velocities decrease towards the equator. The magnitude of this effect still appears to be controversial. The Omega propagation corrections report(ref.1) indicates the presence of a small latitudinal dependence in daytime whose magnitude increases significantly at night. However, the subsequent update(ref.12) increases the magnitude of the day variation by some 500% resulting in values which seem physically unreasonable. These discrepancies are discussed further in section 6. Until this situation is clarified it would seem preferable to stick to the middle latitude data of Table 1 for phase velocities at Australian latitudes.

There is apparently an increase in VLF phase velocity within the auroral zone as measured by Rothmuller (quoted in ref.1). The auroral zone here is roughly defined as extending from 60° to 80° geomagnetic latitude. This increase is physically ascribed to the constant precipitation of ionizing particles at these latitudes from the magnetospheric radiation belts. The Omega propagation correction report(ref.1) also shows an abrupt decrease in phase velocity at higher latitudes still (80° geomagnetic). No physical explanation or reference for this effect is given.

3.4 Azimuthal correction

As previously noted, the ionospheric reflection process at VLF is sensitive to the orientation of the VLF electric field of the propagating wave with respect to the earth's magnetic field. This interaction is brought about by the free electrons in the ionosphere whose forced motion by the VLF electric field is modified by the presence of the earth's magnetic field. As one consequence, the attentuation rates for VLF waves are less for propagation to the east than to the west. As another, the phase velocity is found to alter with path orientation. These azimuthal effects increase in magnitude towards the magnetic equator.

Early theory (cf. ref.5 and 6) suggested that the phase velocity would vary in a simple sinusoidal fashion with path azimuth, producing maximum values for propagation to the west and minimum values for propagation to the east. Recent theory based on the NELC VLF waveguide program predicts more complex and assymmetric patterns as are shown in figure 4, (taken from ref.13 and also shown in ref.1).

Gallenburger and Swanson(ref.13) suggest that these results may be modelled by an algorithm of the form:

$$v/c = v_0/c + g_1 + g_2 \sin\theta + g_3 \cos 2\theta \qquad (4)$$

where g_1, g_2, g_3 are latitude dependent coefficients and θ is the magnetic azimuth angle (measured clockwise from due north). Such an algorithm is adopted in the Omega propagation corrections report with some higher order terms added.

From figure 4 it will be noted that the azimuthal variation is quite small in daytime at middle and higher latitudes and consequently can be initially neglected for propagation within Australia. At night, however, the azimuthal variation increases considerably and can no longer be ignored except at latitudes above some 50°. Examining the night-time azimuthal dependence on latitude, it is evident by extrapolation that the variation could be incredibly high at the magnetic equator for propagation to the west. Actually the waveguide solutions tend to "blow up" at this point and the theoretical results are currently of unknown validity. Experimentally, there is little evidence of latitude variation for propagation to the east; however for propagation to the west, a strong latitude variation is seen reaching an extreme of currently unknown magnitude at the magnetic equator (Lynn ref.14, Meara ref.15).

In summary then, for propagation within Australia, the azimuthal variation can probably be ignored in daytime and for propagation to the east at night. For westward propagation it would seem that the phase velocities of Tables 1 and 2 may require lowering by up to 20-40 parts in 10^4. It is interesting and cautionary to note that this azimuthal variation is in the opposite sense to that given by the older theory of reference 5.

A change in the magnitude of the azimuthal dependence from day to night necessarily makes the magnitude of the diurnal phase shift a function of the direction of propagation. If the models of figure 4 are to be believed, the diurnal phase shift for west-east propagation will be smaller than for east-west. This is in the opposite sense to the dependence suggested in the older data of reference 5. There appears to be no reliable experimental measurement in the literature which directly relates to this question.

3.5 Solar zenith-angle correction

VLF waves "reflect" from the base of the ionosphere. In daytime, the electron density profile changes gradually with height over the relevant range (60-80 km) and is quite complicated in structure. The latter characteristic arises from the number of contributing sources of ionisation (solar Lyman alpha, solar x-rays, cosmic rays), their height dependence, and the height dependence of the chemical constituents which they affect. Moreover, the free electrons which interact with the radio wave are not in simple equilibrium with the ionising radiation but rather exist as the difference between the number of positive and negative ions. An acceptable theory for this complex photochemical system has yet to be found. It is hardly surprising therefore that the VLF reflecting properties of the lower ionosphere in daytime vary continuously with changing solar zenith-angle, are not symmetric with respect to morning and afternoon, and cannot be accurately calculated from theory alone.

Over long VLF paths, the solar zenith-angle will vary greatly along the path with a consequent averaging effect. However, over north-south paths at low latitudes, the solar zenith-angle dependence can be directly seen at times when the path is parallel to the sunrise or sunset line. DRCS is well placed for such observations, being nearly due south of the Omega transmitter in Japan on 10.2, 111/3 and 13.6 kHz as well as the U.S. Navy transmitter NDT on 17.4 kHz at Yosami. Regrettably, accurate measurements have so far only been made at DRCS on the NDT transmissions. It is hoped to rectify this situation as suitable equipment becomes available. The dates of main interest are around 7 April and 6 September for sunrise observations of Omega Japan and 4 March, 10 October for sunset observations.

The variation in phase velocity as observed for the VLF transmitter NDT (17.4 kHz) at DRCS is shown in figure 5. The form of the solar zenith angle dependence is in agreement with observations made elsewhere. The major features are the lack of symmetry between morning and afternoon and the substantial temporary increase in phase velocity subsequent to sunrise which supposedly arises from the release of electrons from negative ions by the sun's illumination. This effectively adds an additional electron "source" at this time of day to those previously mentioned, thus lowering the effective reflection height. The magnitude of the phase velocity variation with solar zenith-angle increases with decreasing VLF frequency and consequently will be greater at Omega frequencies than that shown.

In daytime, the time constant of the VLF reflecting region to changes in ionising radiation is believed to be measured in minutes (4 minutes for overhead sun according to ref.1), increasing to possibly 50 minutes at night. Consequently the night-time phase velocity is not immediately achieved after ionospheric sunset.

The "sluggishness" of the ionospheric response means that phase velocity depends on the rate-of-change of solar zenith-angle as well as on solar zenith-angle. To overcome this problem, the Omega propagation corrections report(ref.1) follows the work of Swanson and Bradford(ref.14) in finding the solar zenith-angle correction by solving a differential equation of the form:

$$d\varphi/dt = S(t)/\tau \quad - \varphi \;/\tau \qquad (5)$$

where φ is related to phase velocity, S represents the changing "source" function and τ is the ionospheric time constant, functionally related to S. Whilst this equation is based on current opinions of ionospheric dynamics, the actual models for S and τ used in reference 1 appear somewhat artificial and this would seem to be an area where further research is needed.

For low and middle latitude areas such as are relevant to Australia, it is possible that a simple model may suffice in which phase velocity is taken as proportional to solar zenith-angle.

It will be noted that the diurnal phase shift can be calculated entirely in terms of a model of solar zenith-angle dependence. The definition of the solar zenith-angles at which sunrise and sunset effectively commence are thus of particular importance. Little detailed work in this area appears to have been done. However measurements based on Brisbane data suggest that sunrise commences at a solar zenith-angle which is related to the path sunrise-line angle and consequently varies continuously throughout the year.

The magnitude of the diurnal phase shift is known to vary over the year in a regular manner by some 25%. This is currently ascribed to a variation in stellar x-ray flux at night produced by the uneven distribution of significant x-ray stars. Variations of this time scale are not currently allowed for in the Omega propagation corrections report and are likely be a considerable source of error in the date base.

4. PHASE VELOCITY ERROR

In daytime, the phase of a VLF signal received over a 6000 km path is usually repeatable from day-to-day to within 1 μs. The limit in phase velocity fluctuation which this implies can be found from the relation:

$$\delta v/v = -v/(fd)\delta\varphi \qquad (6)$$

where d is the distance, v the phase velocity, f the frequency and $\delta\varphi$ is the phase fluctuation at the receiver in cycles. The above example at 10 kHz gives $\delta v/v = 0.5 \times 10^{-4}$. The natural fluctuation at night could well be five times this value giving $\delta v/v = 2.5 \times 10^{-4}$. In terms of fluctuation in apparent position, these values correspond to 0.3 km in daytime and 1.5 km at night.

The figures given above should be compared with the magnitude of the phase velocity corrections discussed in previous sections. Whilst it is difficult to arrive at exact figures for the accuracies of the various corrections, it would seem that present phase velocity predictions can be at least an order of magnitude poorer in accuracy than the actual stability limit of the propagation medium. There is thus considerable room for improvement.

5. GEOPHYSICAL DISTURBANCES

Omega phase velocities are subject to transitory and often unpredictable variations of geophysical origin. These include the Sudden Ionospheric Disturbance (SID) effects of solar x-ray bursts, stellar x-ray bursts (controversial) and charged particle precipitation at high latitudes, as well as solar eclipse effects and some minor atmospheric tidal and meteorological variations.

Of these, the solar x-ray bursts(ref.17) are the most significant, producing an increase in phase velocity over the illuminated portion of the earth and a subsequent phase deviation known as an SPA (Sudden Phase Anomaly). SPA occurrence follows the 11 year sunspot cycle, with SPAs being almost non-existent for several years at sunspot minimum. At sunspot maximum (next in 1979-1981), particularly strong flare activity associated with active sunspots may occasionally result in a continuous and variable increase in phase velocity over the normal day value, whenever the sun illuminates the propagation path.

A typical solar x-ray flare will have a rise time shorter than the fall time, both of several minutes duration, though bursts lasting for tens of minutes are occasionally seen. The sluggishness of the ionospheric response results in a time lag of some four minutes in the maximum phase deviation and an approximately exponential recovery with a time constant of some 35 minutes. The largest SPAs observed have been produced by increases in phase velocity of some 20-30 parts in 10^{-4}; i.e. comparable to the diurnal variation (though in the opposite sense). The occurrence of SPAs decreases with increasing SPA magnitude. As might be expected, the magnitude of SPAs and their associated amplitude deviations are strongly dependent on solar zenith-angle.

While SPAs are a serious source of error in VLF navigation, they have some positive uses. As with solar eclipses, their effective source function is often accurately known. Consequently they can be used to investigate the temporal response of the ionosphere, so necessary to the successful modelling of diurnal phase shifts and to an understanding of the photochemistry involved.

PCA (Polar Cap Absorption) associated phase deviations(ref.18) are also solar cycle dependent. The source is the injection of fast solar protons into the solar wind, this proton cloud arriving at the earth some hours later. The heavy dumping of protons at auroral latitudes at such times produces a depression of the lower ionosphere and a consequent increase in VLF phase velocity which may take several days to recover(ref.18).

Electron precipitation also produces phase velocity increases at high latitudes. This less important effect produces phase velocity changes of considerable irregularity apparently defying simple classification.

6. DISCUSSION

In ascertaining the phase velocity corrections necessary to obtain the ultimate accuracy from the Omega navigation system, two possible approaches could be made. The first would involve a complete physical understanding of all the phenomena involved with a consequent ability to theoretically calculate the effective phase velocity over any given path. In the present state of scientific knowledge this is not possible, though the situation appears to be improving. The second approach would be, to show no interest in understanding the physical mechanisms, but to rely on a force fitting of as many experimental phase measurements as possible in order to derive mathematical algorithms which will fit the observed situation. The difficulty here lies in the great geophysical complexity of the problem and the comparatively restricted amount of experimental data which can be practically obtained. The Omega propagation corrections report endeavours to steer a middle course in which physically based algorithms are taken and the coefficients thereto modified by fitting the algorithms to experimental phase observations. These latter observations appear to consist of lines-of-position (lop) data which involve the difference in the received phase of transmissions from two locations.

A comparison of the original algorithm coefficients in reference 1 with the later values derived in reference 12 give some grounds for disquiet. The original coefficients were derived from mainly North American data and were subsequently found to yield substantial errors when applied to reception in the European area. The new coefficients reduced total error and improved the European results with, however, some degradation of accuracy elsewhere. For an initially well chosen set of algorithms, the solutions to such a process of fitting data should result in an improved geophysical content. However, the new coefficients appear to have resulted in bearing and azimuthal corrections which diverge from the physically reasonable. When it is remembered that data from many parts of the world, in particular, the southern hemisphere, Asia and low latitudes have yet to be considered, it would seem that there is a need for further research into the physical basis of the algorithms.

7. CONCLUSIONS AND RECOMMENDATIONS

The user accuracy of the Omega navigation system is dependent amongst over things on phase velocity correction algorithms which attempt to compensate for the known regular variations in VLF phase velocity. The relevant geophysical parameters include solar zenith angle, magnetic latitude, magnetic azimuth and ground conductivity. The algorithms are most accurate for daytime propagation over sea water at middle latitudes. They are least accurate near the magnetic equator at night for westward propagation, over ground of poor conductivity, during sunrise and sunset transitions, and at auroral latitudes.

Within Australia, the solar zenith-angle and ground conductivity corrections are of greatest significance, with magnetic azimuth becoming of increasing importance as the magnetic equator is approached. The current algorithms are entirely unsatisfactory for westward propagation across the magnetic equator at night. Present Omega policy appears to involve side-stepping this problem by not recommending the use of such transmissions. In Australian terms, the relevant transmissions are those from Omega Hawaii received in the south-west Pacific and Australian mainland, and Omega Japan received in the Indian Ocean. This policy requires the use of Omega Argentina at night in the multimode interference zone of Omega Australia. For these transmissions, auroral and polar corrections will be of great importance.

Whilst a good deal of effort has gone into the official Omega phase velocity correction algorithms, the data base on which they rest is currently biased towards the northern hemisphere. However, an increase in the geographic range of the data base will not automatically result in significant improvements in accuracy if there are fundamental weaknesses in the geophysical structure of the algorithms. Such weaknesses do appear to exist, some in areas in which Australia is geographically well placed for investigation. Moreover a solution to these problems would be of direct benefit to the Australian user.

The following topics spring to mind.

1. Transequatorial propagation at night

   Observations of Omega Hawaii can be made over a considerable range of distances and azimuths within Australian territory. Observations of Omega Japan at Perth and DRCS indicate that the transition to an anomalous transequatorial condition occurs at magnetic azimuths observable within Western Australia. Observations of Omega Japan at Cocos Island are also feasible and would indicate whether the Hawaiian observations can be safely generalised.

2. Solar zenith angle dependence

   DRCS lies nearly due south of the Japanese Omega transmitter and is thus perfectly placed for an investigation into the solar zenith-angle dependence of VLF phase velocity. Twice a year the path becomes parallel to the sunrise or sunset line, producing uniform solar angles over the path at the high values where the deviation in phase velocity is greatest, thus allowing direct measurements to be made.

   Such observations also allow the time lag between peak path illumination and maximum phase velocity to be measured. This ionospheric "sluggishness" is a vital parameter in the differential equation used to calculate the dynamic variation of phase velocity with solar zenith-angle. The current Omega model employs a differential equation in which the phase velocity parameter is linearly related to the ionospheric production function. There are some doubts as to the form which this relation takes. Observations over paths with the necessary range of solar zenith-angles are readily available at DRCS to investigate this matter.

3. Auroral zone effects

   The propagation path from Omega Argentina to DRCS passes through the southern auroral zone where observations up to now are distinguished mainly by their absence. This path would afford an opportunity to test the effectiveness of the existing auroral-zone model (based on northern hemispheric observation) in a region of greater relevance to Australia.

4. Transitory disturbances

   Geophysical disturbances of solar origin will increase significantly as the current sun-spot cycle develops and will prove a major source of navigational error. Such errors can be removed with the aid of corrections from base stations monitoring the event. For maximum success, this requires the user to translate the measured phase deviations to paths of differing length, azimuth and solar zenith angle. Currently this area of research has received little attention. Propagation paths which can be monitored at DRCS are suitable for such an investigation.

5. Differential Omega

Differential Omega obviates the need for phase velocity algorithms by supplying measured variations in relative phase velocity applicable to users within some 300 km of a fixed monitoring site. Equipment for the application of Differential Omega is currently being developed at DRCS. If frequency standards of high accuracy are available (i.e. atomic frequency standards), observations between known locations with such equipment will allow direct measurement of VLF phase velocity, including the variations with solar zenith-angle, direction of propagation and ground conductivity. Such direct measurements, applicable to Australia, are to be recommended.

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TABLE 1. SEAWATER REFERENCE PHASE VELOCITIES AT MIDDLE LATITUDES

Frequency (kHz)	tx.	v/c day	v/c night
10.2	OMEGA	1.0034	0.9996
11.33	OMEGA	1.0021	0.9988
11.8	OMEGA	1.0016	0.9985
13.6	OMEGA	1.0003	0.9976
16.0	GBR	0.9992	0.9968
17.4	NDT	0.9988	0.9964
17.8	NAA	0.9987	0.9963
18.6	NLK	0.9985	0.9961
22.3	NWC	0.9978	0.9952
23.4	NPM	0.9975	0.9949

TABLE 2. OMEGA REFERENCE PHASE VELOCITIES CORRECTED FOR GROUND CONDUCTIVITY

Conductivity	Day		Night	
	v/c (10.2 kHz)	v/c (13.6 kHz)	v/c (10.2 kHz)	v/c (13.6 kHz)
4.0 x 10	1.0034	1.0003	0.9996	0.9976
1.0×10^{-2}	1.0030	1.0000	0.9994	0.9974
3.2×10^{-3}	1.0027	0.9998	0.9991	0.9972
1.0×10^{-3}	1.0021	0.9994	0.9988	0.9970
3.2×10^{-4}	1.0014	0.9987	0.9982	0.9967
1.0×10^{-4}	1.0004	0.9979	0.9975	0.9963
3.2×10^{-5}	0.9992	0.9993		

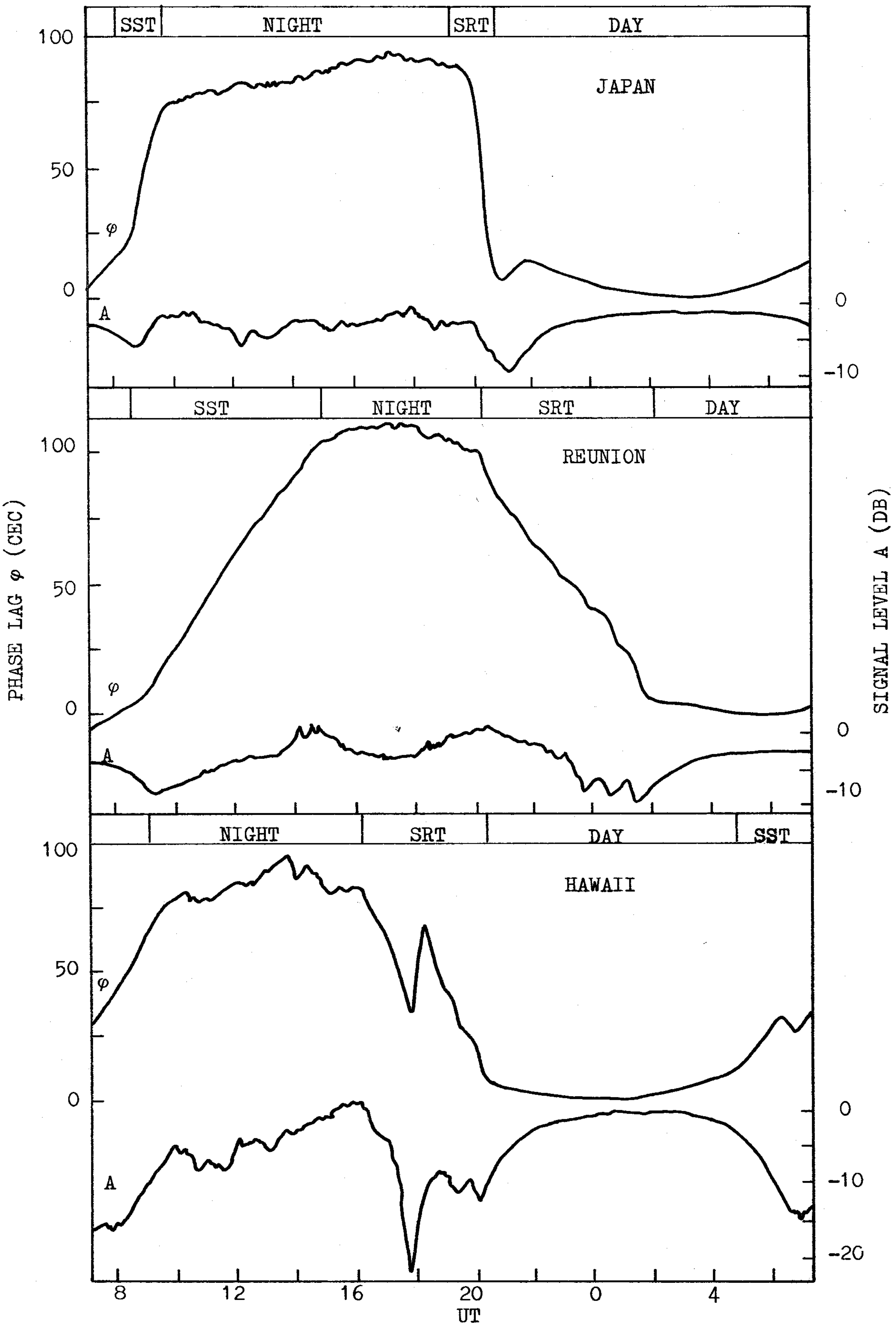

Figure 1. Diurnal phase and amplitude patterns for Omega (13.6 kHz) transmissions from Japan, Reunion and Hawaii received at DRCS.

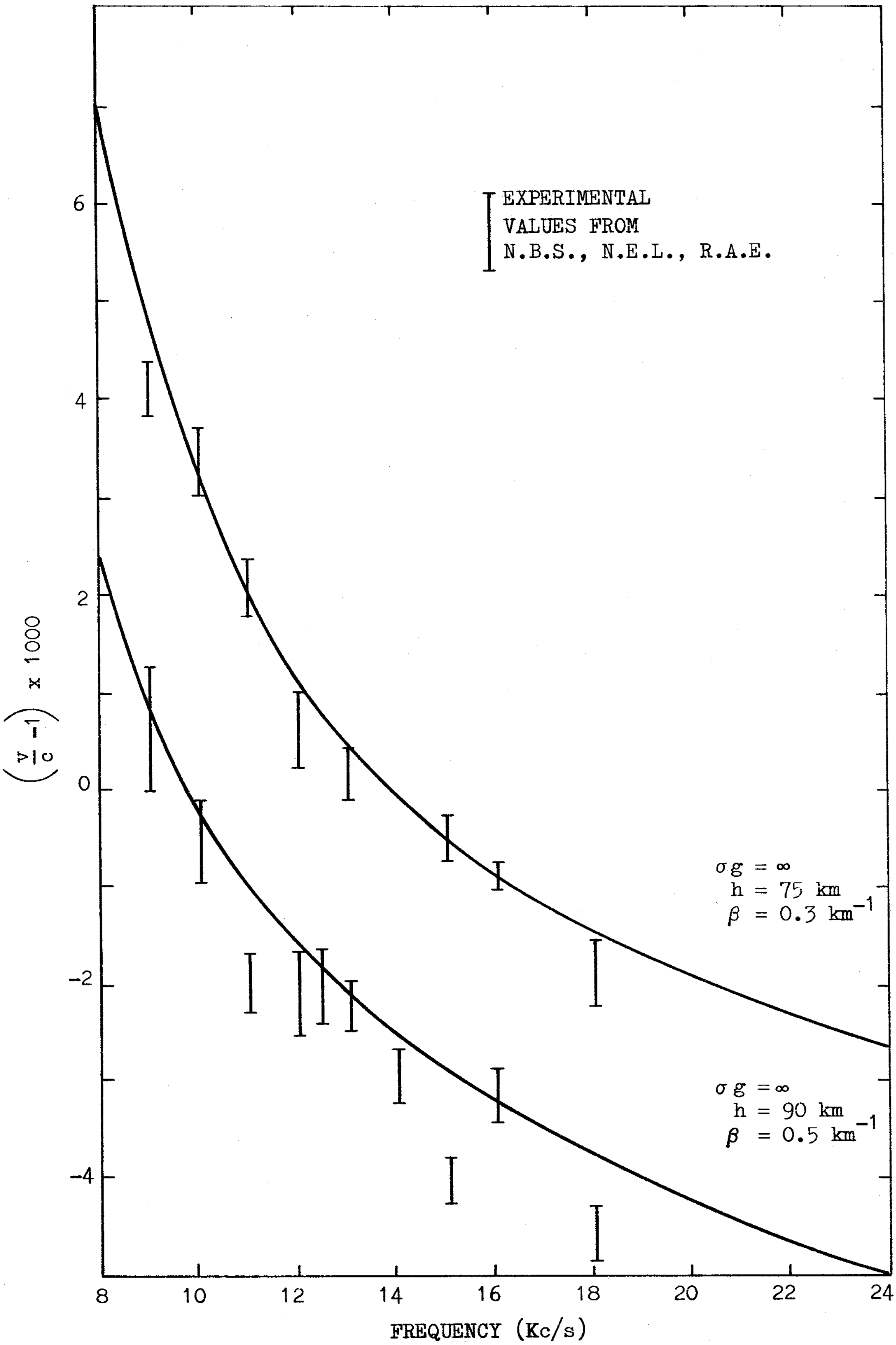

Figure 2. Experimental and theoretical values of VLF phase velocity for day and night conditions(ref.7).

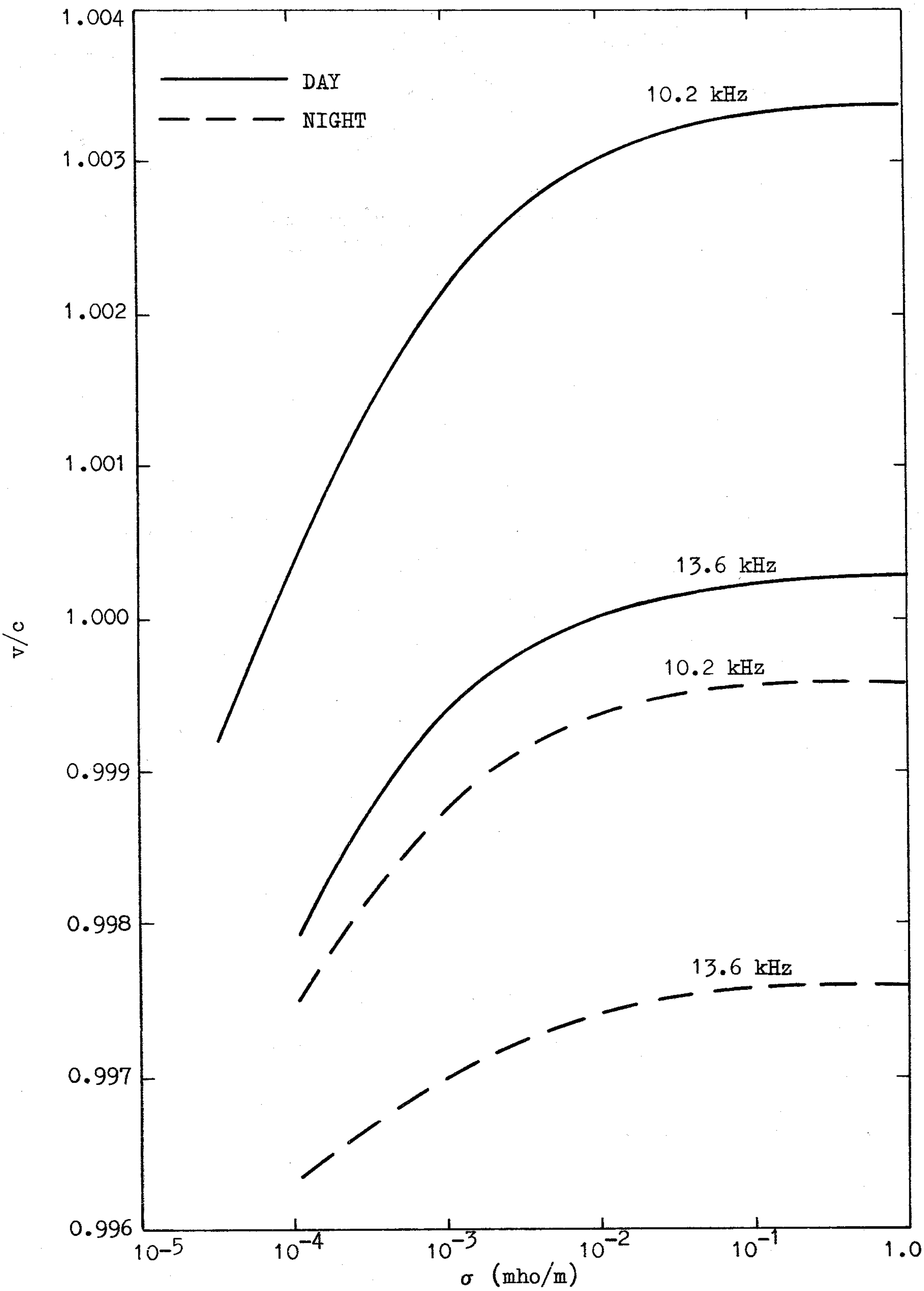

Figure 3. Omega phase velocity as a function of ground conductivity. (data from ref.1)

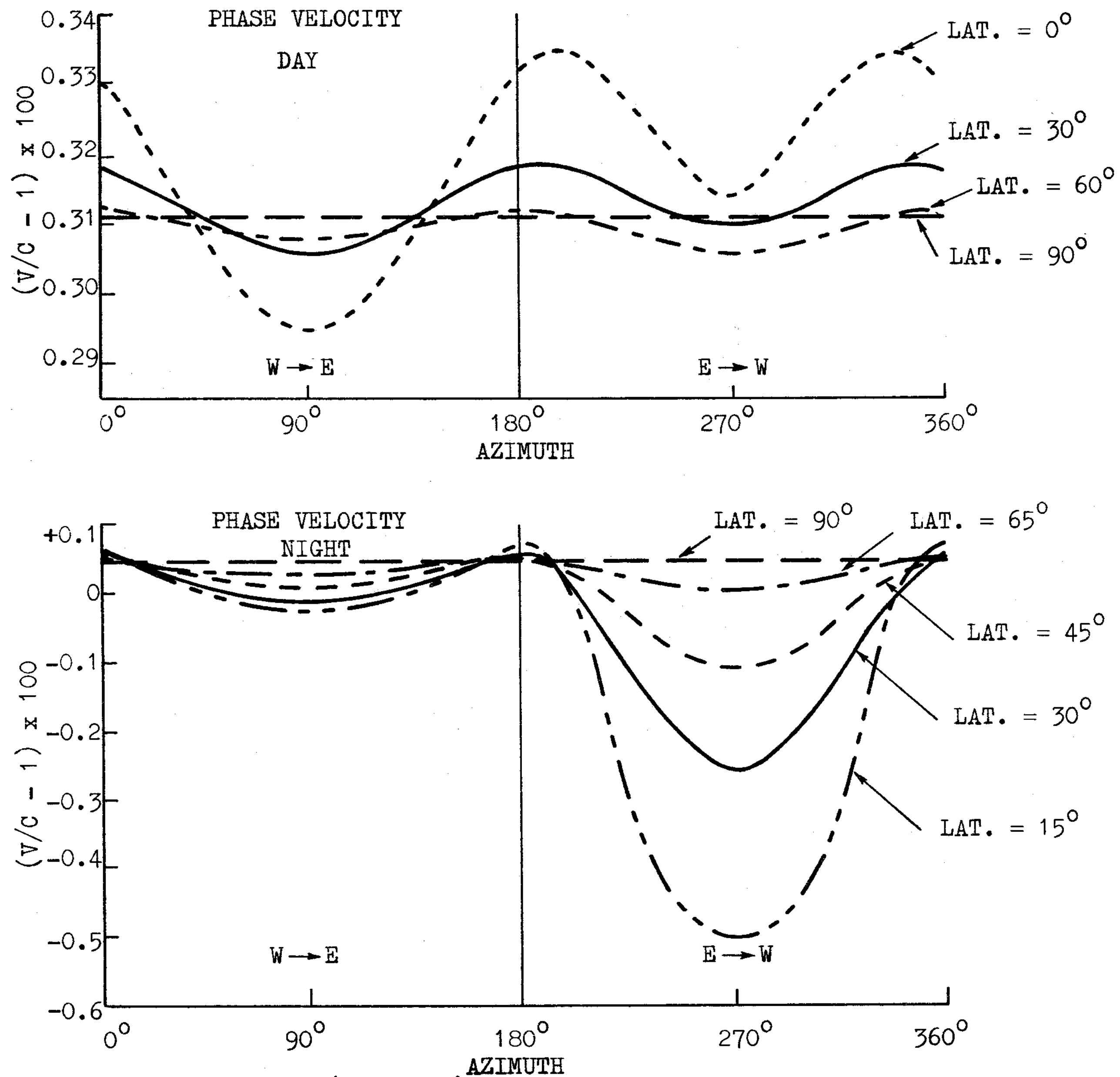

Figure 4. Omega (10.2 kHz) phase velocity as a function of magnetic azimuth for day and night(ref.13).

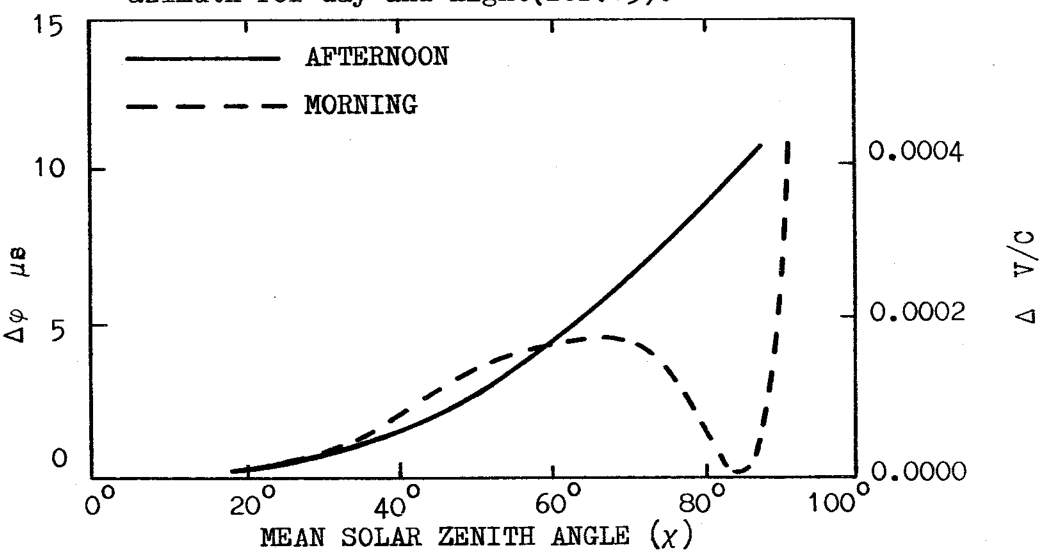

Figure 5. Dependence of phase velocity on solar zenith angle for NDT (17.4 kHz) received at DRCS.

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The accuracy of long range VLF navigation systems depends ultimately on the development of phase propagation correction which will allow for the geophysical variability of VLF phase velocity. Some preliminary estimates of phase velocities likely to be relevant to Omega users in and around Australia are presented, as gleaned from the literature. Some likely areas of investigation which may lead to improvements in these values are described.

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