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Effect of the Ionosphere on Space Systems and Communications

Editor

John M. Goodman

Based on

Ionosphere Effects Symposium

Held in

Crystal City, Arlington, Va.
January 20-22, 1975

NAVAL RESEARCH LABORATORY
Washington, D.C. 20375

For sale by the Superintendent of Documents, U.S. Government Printing Office
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Stock Number 008-051-00064-0

RAY TRACING THROUGH REALISTIC IONOSPHERE GRAVITY WAVE MODELS : A COMPARISON WITH EXPERIMENTAL DATA FROM SEVERAL DIFFERENT TECHNIQUES.

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ABSTRACT

Model ionospheres using experimentally measured parameters are constructed from a realistic medium scale ionospheric gravity wave model. The ray tracing technique is then employed to simulate the results of the original experimental measurements from the model ionospheres. The technique is found to be limited by the gravity wave model which uses only one gravity wave period in the construction of the ionospheric model whereas realistic ionospheres contain in general a spectrum of medium scale gravity waves.

1. INTRODUCTION

Travelling ionospheric disturbances (TIDs) have been observed by a large number of workers using many different techniques since the pioneering work of Munro (1958). However it was not until the theoretical work of Hines (1960) and Hooke (1968) that the nature of these disturbances was interpreted successfully as wave like fluctuations of the electron density induced by gravity waves in the neutral atmosphere. There are two major classes of TIDs, large scale and medium scale. (Georges, 1968). The large scale waves are generally associated with magnetic storms whereas the medium scale waves occur much more frequently, their sources being uncertain.

Many techniques have been used in the past and are being used to detect the presence of these TIDs. Depending on the technique and the ionospheric parameter measured, various properties of the TIDs can be determined. The intent of this paper is to report the results of a simulation of the results of some of these techniques using ray tracing techniques. The experimental techniques to be simulated include high frequency doppler, group and phase paths at oblique incidence, vertical incidence ionograms, total electron content measurements using the Faraday rotation of the plane of polarization of a signal from a VHF beacon, and the refraction of a signal from a VHF beacon on a geostationary satellite.

Before the ray tracing studies can be performed a suitable ionospheric model of TIDs is required. This is provided by the medium scale TID model as described by Francis (1973). Experimentally measured TID parameters were inserted in the model and a time varying ionospheric model generated for the ray tracing program.

2. SIMULATION METHOD

(a) Travelling Ionospheric Disturbance Model

The Francis (1973) TID model was used to simulate a realistic ionosphere. This model differs from previous models by including dissipation (viscosity and thermal conductivity) and by using a realistic sound speed profile throughout the thermosphere. The model assumes that the wave dependence on the time t and horizontal co-ordinate x is a sinusoidal function of $\omega t - k_x x$. It derives the vertical profile by solving the coupled Navier-Stokes and electron continuity equations. The basic inputs to the model are the wavelength, period, amplitude and azimuth of propagation of the neutral gravity wave underlying the TID which is to be modelled. The ambient ionosphere, specified by an α Chapman profile (unless otherwise indicated) is used to compute the electron density as a function of space and time for the TID perturbed ionosphere.

(b) Ray Tracing Program

The three dimensional ray tracing computer program developed by Jones (1968) was used in this work. Previous ray tracing simulation of HF radio measurements of ionospheric disturbances have been made by Detert (1968). He used a two dimensional Snell's Law digital computer ray tracing program to simulate the effects of large travelling ionospheric disturbances on oblique incidence high frequency radio transmissions. He calculated the phase and group paths, the received elevation angle of arrival and the Doppler shift variations produced by the passage of representative disturbance models through the transmission paths.

The Jones ray tracing program has been used by Georges (1969) in an attempt to simulate Doppler results from a model of ionospheric disturbances. However the electron density contours were constructed by introducing a wavelike model irregularity into the profile. The results presented in this paper use a realistic gravity wave model of the neutral atmosphere with coupling to the ionized medium.

(c) Experimental Data

The aim of the ray tracing was to simulate experimentally measured ionospheric data using a realistic ionospheric TID model. To this end data from several experiments operating on two winter days in 1969 when TIDs were present were selected. The dates and times were 13 January 1969 15-19UT and 15 November 1969 16-20UT. The experimental details and results are described in another paper by Essex (1974). Briefly the experimental results to be used here were obtained from high frequency Doppler observations on 7.335 MHz at oblique incidence from the transmitter at Ottawa (geographic co-ordinates 45°18'N, 75°20'W) to a receiver at Bedford (geographic co-ordinates 42°27'30"N, 71°20'W), three spaced vertical incidence ionosondes at Hanover (geographic co-ordinates 45°41'30"N, 72°11'18"W), Highgate Springs (geographic co-ordinates 45°00'47"N, 73°05'11"W) and Errol (geographic co-ordinates 44°47'30"N, 71°07'30"W) total electron content measurements at Sagamore Hill from the geostationary satellite ATS-3, the four hundred and twenty kilometer subionospheric point being 38°42'N, 29°70'W on January 13 1969, and 38°36'N, 67°12'W on November 15 1969, geographic co-ordinates, and the refraction of the VHF beacon as measured by a 10 km long baseline interferometer at Sagamore Hill (geographic co-ordinates 42°36'N, 70°48'W). See Fig. 1.

The experimental results were subjected to a spectrum analysis to determine the gravity wave periods present. The spaced ionosonde measurements yielded information on the phase velocity and direction of the TIDs from the real iso-height contours deduced from the ionograms, as well as the critical frequency of the ionosphere.

Fig. 2 is a comparison of results for three heights from one of the ionosonde stations. There is an obvious movement of power to the longer periods as the height increases.

Fig. 3 is a comparison of the results from the different experiments. Peaks below the largest peak are scaled according to 0-3, 3-6 and 6-9 db.

The only two parameters to be used in the TID simulation model which were not measured directly were the scale height H and the velocity amplitude of the neutral atmosphere gravity wave.

3. Results

(a) Oblique Incidence Group and Phase Path Simulation

Ray tracing using the three dimensional program as developed by Jones consumes a large amount of computer time. An excellent summary of the possible options of the ray tracing program and their relative accuracies and computer time has been given by Hammer (1971).

Initially it was intended to simulate vertical incidence ionograms using the TID model with the ray tracing program. This would require a large amount of computer time to generate the ionograms as the TID moved through the ionosphere. The ray tracing would be required to be performed on a continuous range of closely spaced frequencies up to the critical frequency as well as on a range of azimuthal and elevation angles around the vertical to determine which rays returned to the receiver. This process would have to be repeated on various phases of the TID as it moved through the ionosphere. Some preliminary work was performed generating the ionograms. It was found that the cusps appeared and moved through the frequency range of the ionogram as the TID passed overhead. As well the critical frequency varied with the period of the TID inserted in the model ionosphere. These results are well known and it was decided to devote more time to oblique incidence propagation of high frequency radio waves through TID models.

As mentioned in the last section, one of the unknown parameters to be inserted into the TID model was the amplitude of the neutral atmosphere gravity wave velocity. Initially a value of around 10 metres per second was used. It was found that larger values of this parameter were required to produce ionospheric perturbations consistent with those experimentally observed. Values of the order of 50 metres per second were used. These are of the same order as the daytime neutral wind velocity as determined from experimental observations by Roble et. al. (1974).

For the oblique incidence ray tracing, the TID perturbed model was generated to cover the ionosphere between the latitude and longitude of the transmitter and the receiver up to the peak of the F region. The initial ionosphere was generated for zero phase of the TID model at around the mid-point of the ray path. Subsequent ionospheres were generated at one, two or four minute intervals as the TID moved through the ionosphere with the velocity and direction as determined by the three spaced ionosonde network.

Fig. 4 shows the results of the ray tracing for the group and phase paths through the TID perturbed ionospheres. Also shown is the reflection height. The receiver location was specified to .01 degrees of latitude and longitude in order to locate the receiver to an accuracy of less than 1 kilometer in ground range.

The variation in the azimuthal and elevation angle is also indicated in Fig. 5. The doppler frequency shift calculated from the phase path P by $\Delta F = -\frac{f}{c}\frac{dP}{dt}$ is shown in Fig. 6.

The parameters used were as follows: $f_oF_2 = 9.5$ MHz, $h_mF_2 = 290$ Km, H = 50 Km, horizontal velocity = 173 ms^{-1}, azimuth (° geomagnetic) = 180, period = 26 mins.

The most interesting result is the phase relation between the group and phase paths. There is a slight positive shift in phase for the phase path from being in phase with the group path. Since the phase refractive index n is related to the square root of the electron density N, by

$$n = \left\{1 - \frac{kN}{f^2}\right\}^{\frac{1}{2}} ,$$

an increase in electron density produces a decrease in the refractive index and hence a decrease in the total integral of n along the ray path, i.e. in phase path. Similarly a decrease in N produces an increase in n and an increase in the phase path length. On the other hand, the group refractive index is given by $n_g = \frac{1}{n}$ (neglecting the geomagnetic field and collisions). Hence the group and phase paths should be out of phase. The ray tracing results can be explained in terms of a lowering of the reflection height and also of the elevation of the ray and a consequent decrease in the total integral of the group refractive index and vice versa.

The doppler shifts are consistent with the experimentally measured values which are generally less than 1 Hz for daytime measurements on 7.335 MHz over the 474 Km path.

It is emphasized that the ray tracing results reported above were carried out in one azimuthal direction only. Ray tracing carried out at different azimuthal directions at oblique incidence through the TID model ionosphere as well as for different velocities and directions of the TID would not necessarily yield the same result. Obviously the velocity of the TID will affect the doppler frequency shift but not necessarily the maximum deviations of the group and phase paths.

(b) Total Electron Content Simulation

The TID model for the total electron content simulation was generated by perturbing an undisturbed ionosphere consisting of an α Chapman layer below the peak of the electron density and a variable scale height Chapman model above the peak up to a height of 1090 kilometres. The variable scale height profile h_s was calculated from the equation

$$h_s = \frac{\log h}{2.186 \times 10^{-2}} - 203.447$$

as given by Damon and Hartranft (1970) where h is the height. The ionosphere between the receiver and the 1090 kilometre sub-ionospheric point along the ray path to the satellite was calculated.

The ray tracing program was used

to obtain the electron density in steps along the ray path on 137 MHz. From this the total electron content of the ionosphere up to a height of 1090 kilometres was calculated.

The parameters used in generating the ionosphere were as follows: f_oF_2 = 10.5 MHz, h_mF_2 = 290 Km, H = 50 Km, horizontal velocity = 280 ms^{-1}, azimuth (° geomagnetic) = 172, period = 26 mins.

Fig. 7 shows the results of the total electron content calculation. The total numbers of electrons in the equivalent vertical column as the TID moves through the ionosphere shows the same sinusoidal variation as the period inserted into the TID model. The peak electron density along the ray path for the period of 26 minutes shows a peak earlier than the peak electron content. This is probably caused by the tilt on the TID wavefront, the small wavelength of the TID and the fact that more than half of the electrons measured in the total electron content variation are above the peak. On the other hand for a longer period wave of 72 minutes, the peak electron density along the ray path leads the peak in electron content by about four minutes. The wavelength of the TID is much greater in this case and the ray path traverses the one TID oscillation for most of the path length around the peak.

The variation in the peak electron density along the ray path for the 26 minute period TID is 15%, whereas the total electron content variation is only 3%. However for the 72 minute period, the variation in the peak electron density along the ray path reaches 58% and the total electron content variation is around 7%. These values are consistent with the percentage variation in the peak electron density and the total electron content as measured experimentally for these periods.

(c) Angle of Refraction Simulation

The TID model ionospheres calculated in the previous section were used with the ray tracing program to determine the group and phase paths of the rays at 137 MHz up to a height of 1090 kilometres at the azimuthal and elevation angle used in the previous section. A similar ray tracing was performed from a point 0.1 degrees of latitude and zero degrees of longitudinal from the previous point. The same azimuthal and elevation angle were used in both cases. This procedure was adopted as the accuracy required in ray tracing to a point at the top of the ionosphere with the required azimuth and elevation for the ray to reach the geostationary satellite position would consume a huge amount of computer time. The difference in the phase paths for the two spatially separated receivers is shown in Fig. 8. The shorter period TID shows a larger variation in group and phase paths, than does the larger period TID. The difference in the group and phase paths also exhibits this behaviour. This is probably due to the larger horizontal gradients when the shorter periods are present than when longer periods are present (Elkins, 1972).

The phase path differences correspond to variations in the angle of arrival of the order of tenths of a milliradian, smaller than the experimentally observed values of the order of milliradians. This probably results from the method used to determine the phase path difference.

As well a comparison was made with the integrated total electron content of the ionosphere as calculated in the previous section. For the shorter period TID, the total electron content peak was delayed for about 9 minutes i.e. 125° of phase from the peak of the phase difference whereas for the longer period TID it was delayed by about 80° of phase. These results are not inconsistent with the simple theory which predicts a quadrature relation between the two methods of measuring TIDs (see Elkins, 1972; Webster and Lyon, 1974).

4. DISCUSSION

Ionospheric data has been simulated using a realistic TID model together with ray tracing techniques. In general the model is able to reproduce results characteristic of the data from various ionospheric experimental techniques.

The simulation of group and phase paths on one hop oblique incidence paths through TIDs would provide insight into the properties of TIDs measured experimentally. Only one direction of the ray path was considered in this paper. Further studies should be carried out using various directions of the TIDs as well as a range of ray directions through the ionosphere. Of particular interest would be the measurement of the group paths.

The total electron content and refraction simulation indicate that these techniques provide a good measure of the gravity waves present in the ionosphere at the azimuthal and elevation angles considered. Obviously the magnitude of the gravity wave perturbations measured will depend on the geometry used (see Davis, 1973).

A simple calculation of the gradient in the slant electron content along the two paths in the refraction calculation shows this to be of the order of 10^{11} electrons per m^3. This is not inconsistent with the results of Elkins (1972) and Bramley (1974). Further experimental and theoretical studies are being carried out on the relation between the total electron content and the refraction effects of the ionospheric TIDs at VHF.

ACKNOWLEDGEMENTS

This work was performed while the author was on study leave at the Ionospheric Physics Laboratory of the Air Force Cambridge Research Laboratories. The interest and assistance provided by Dr. T.J. Elkins of the Ionospheric Radio Physics Branch of the Laboratory is gratefully acknowledged.

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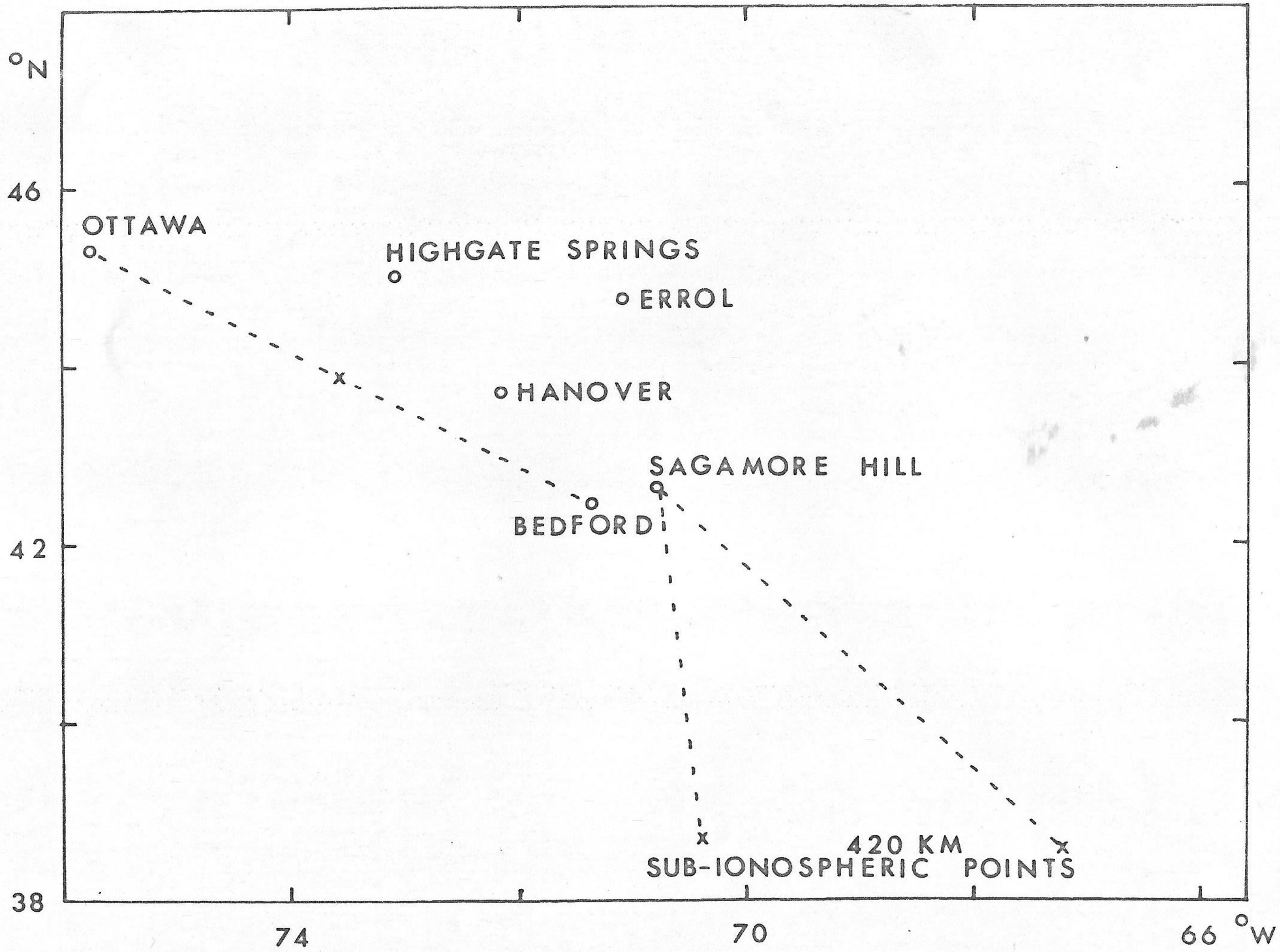

Figure 1 — Diagram showing the geographic location of the various ionospheric experiments.

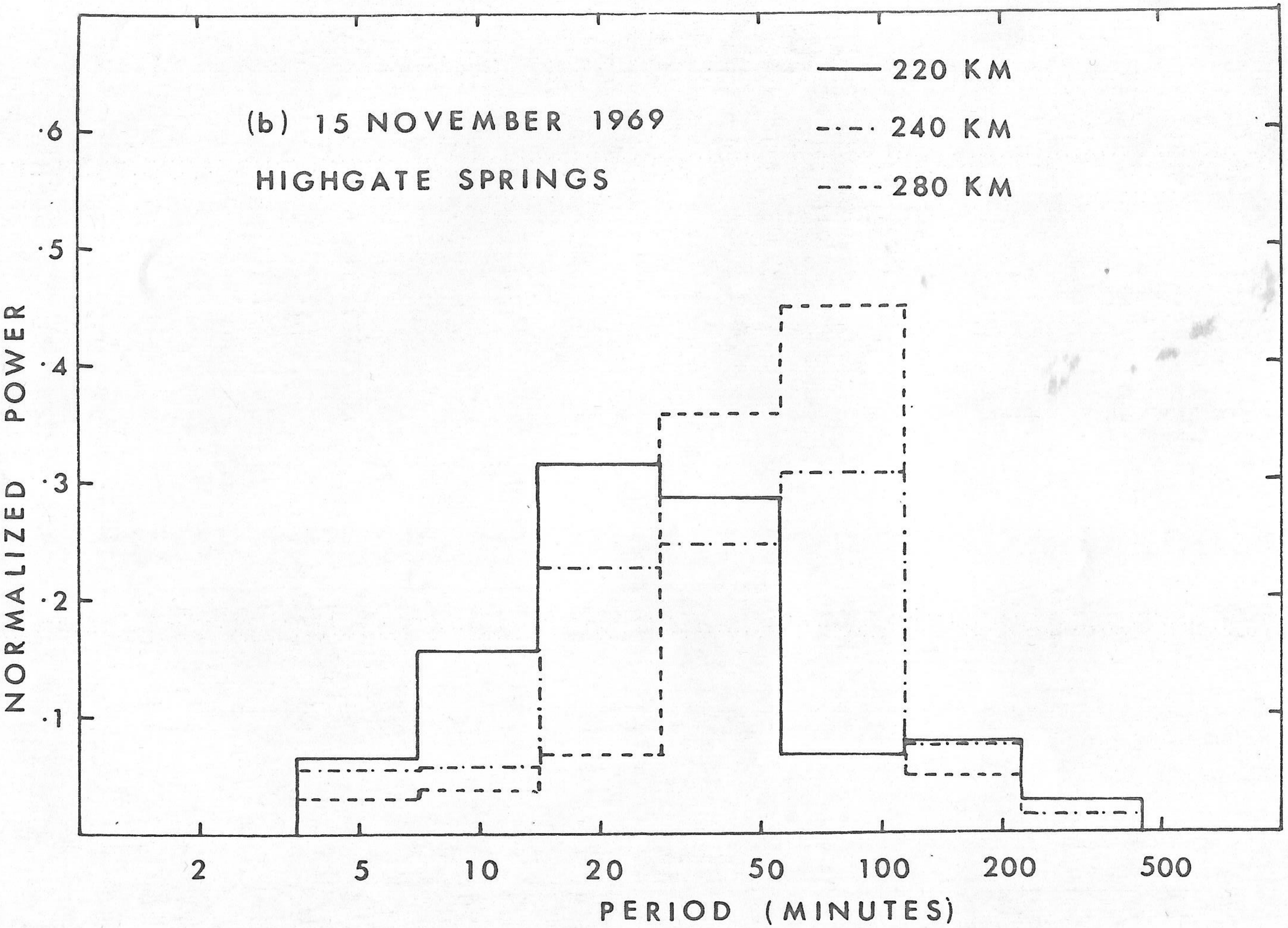

Figure 2 — Histogram of normalized power per octave of the isoheight contours from Highgate Springs ionosonde for 220, 240 and 280 kilometers for 15 November 1969, 16-20 hours UT.

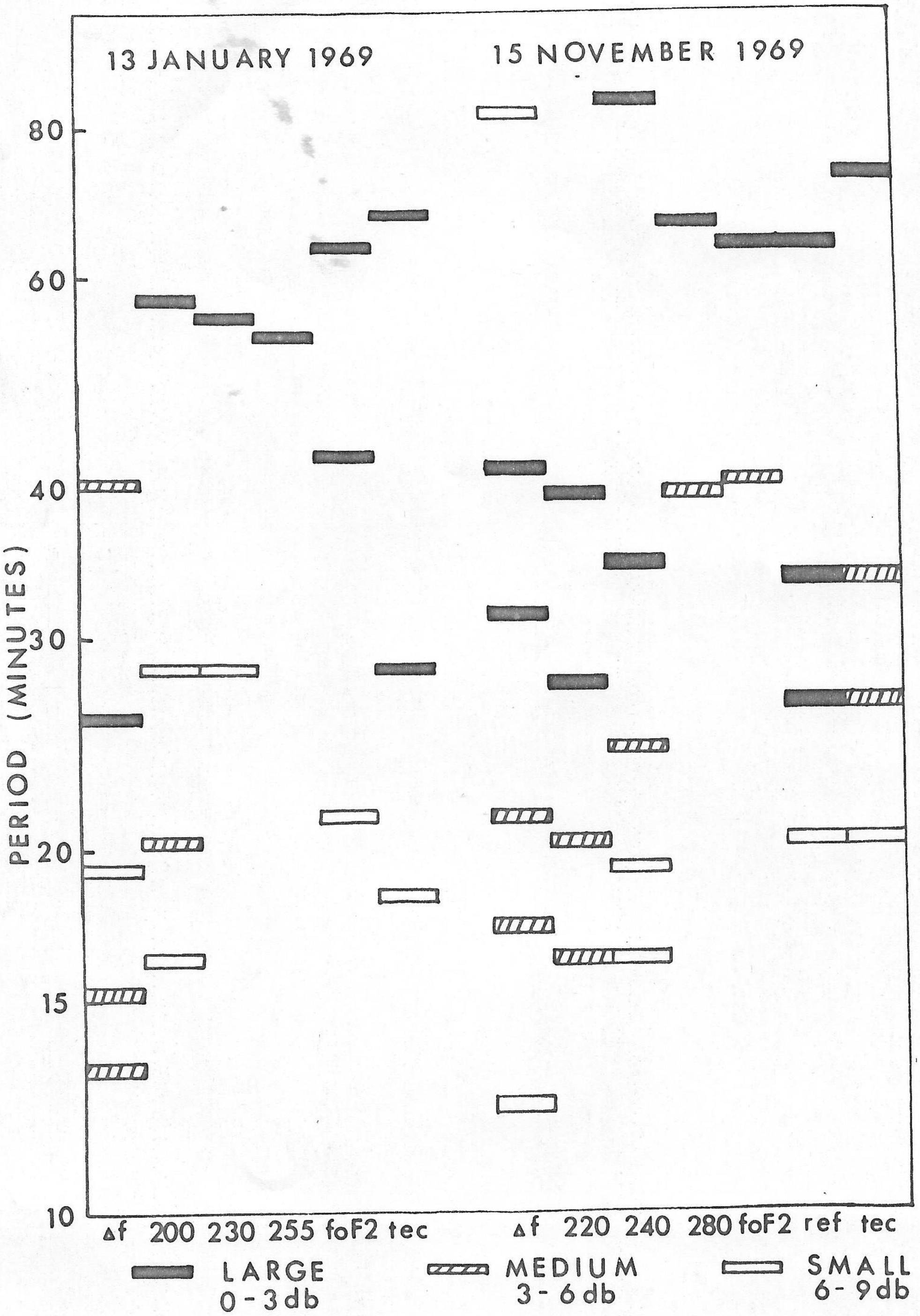

Figure 3 — Diagram showing the dominate periods present in the power spectral analysis of results from the various ionospheric experiments. The periods are graded according to 0-3db, 3-6db, 3-9db of power below the largest peak.

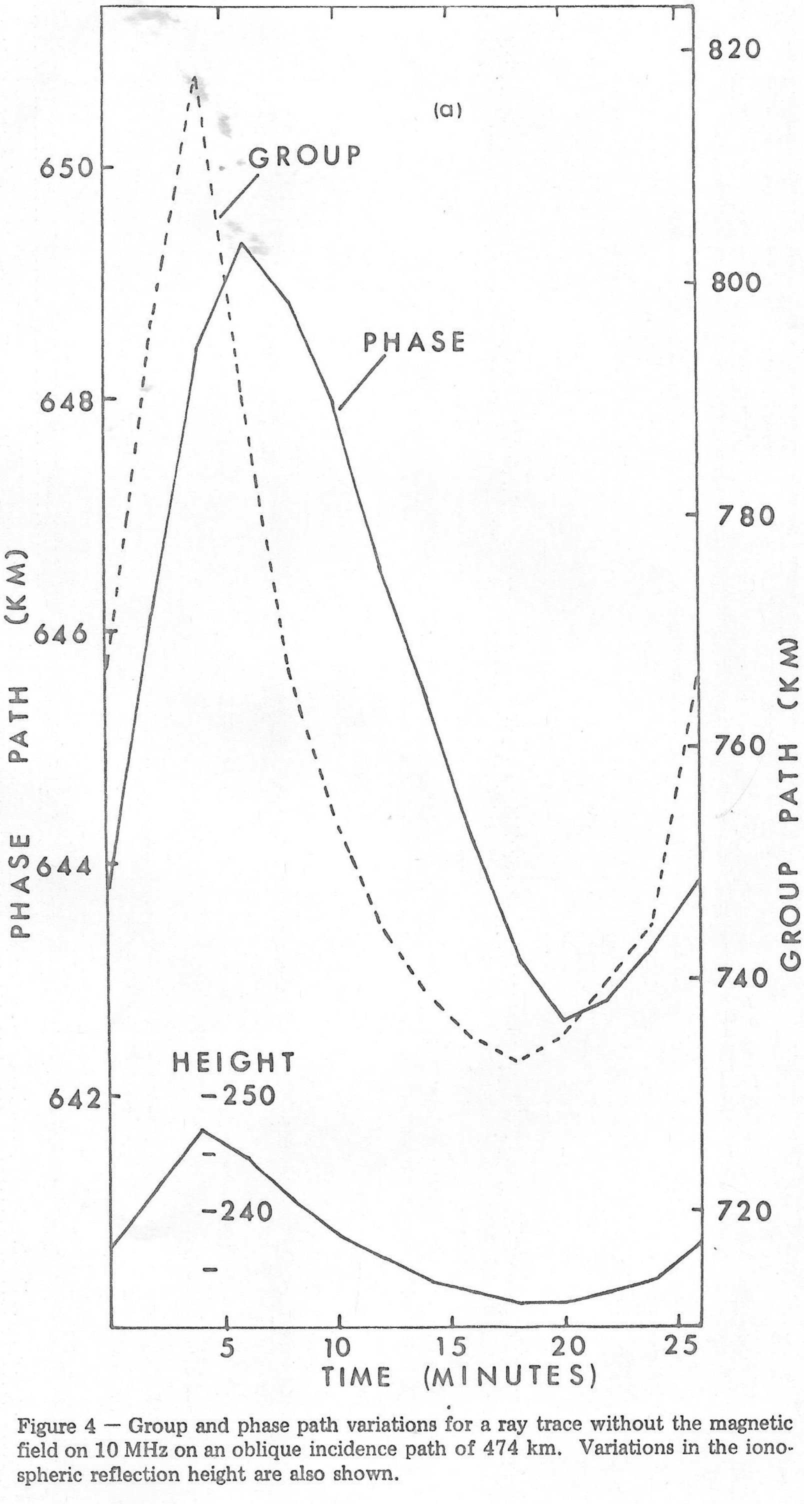

Figure 4 — Group and phase path variations for a ray trace without the magnetic field on 10 MHz on an oblique incidence path of 474 km. Variations in the ionospheric reflection height are also shown.

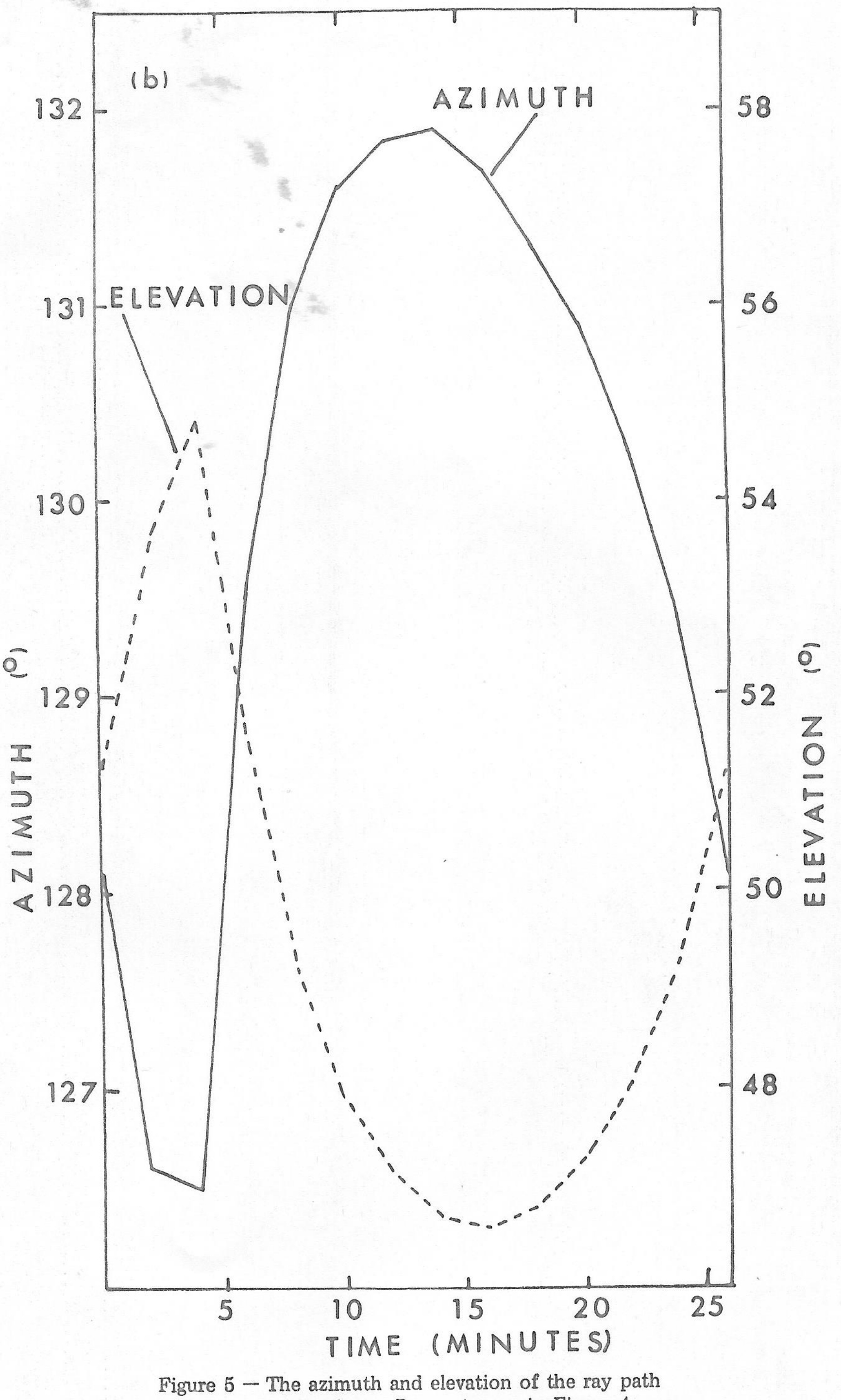

Figure 5 — The azimuth and elevation of the ray path from the transmitter. Parameters as in Figure 4.

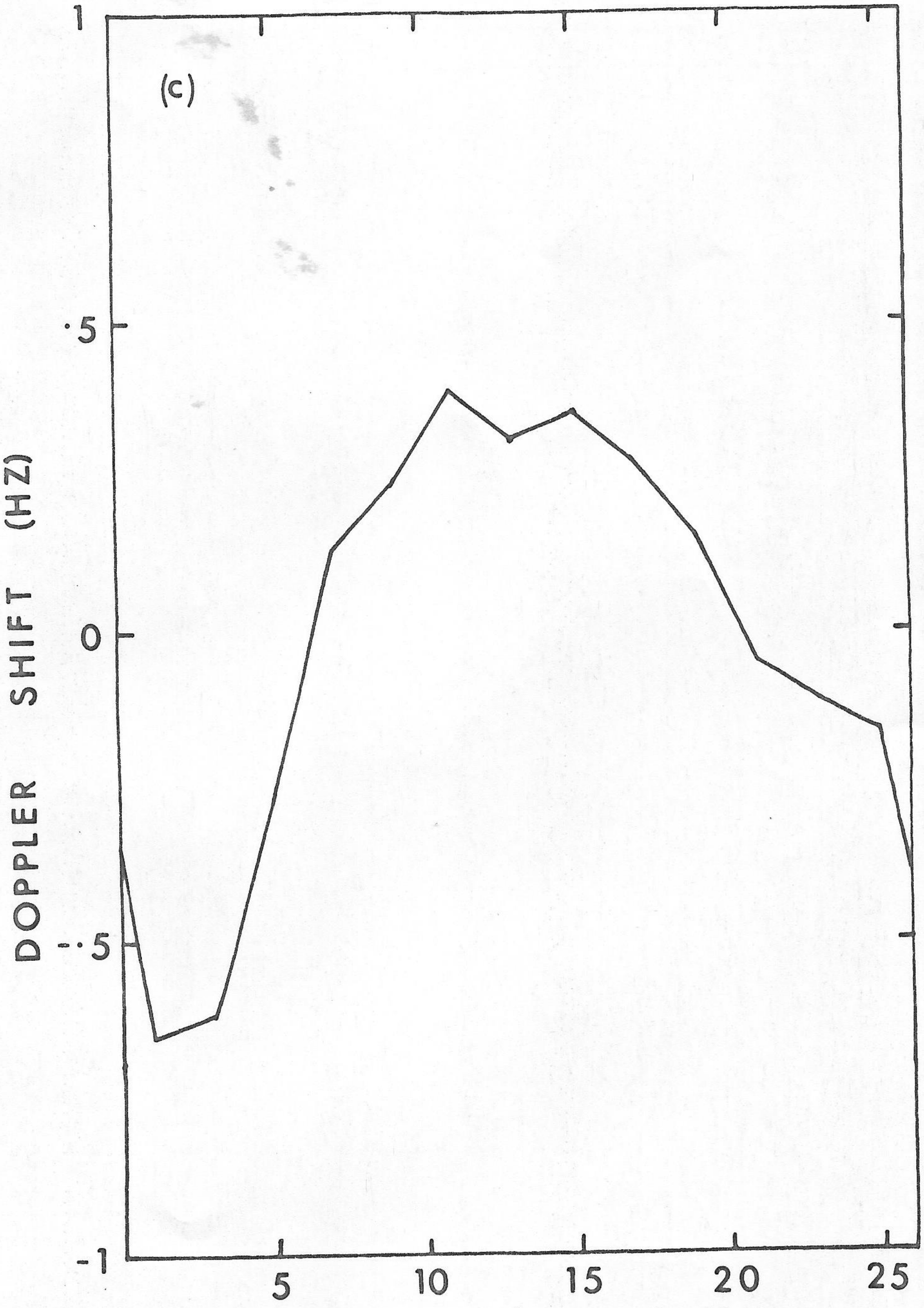

Figure 6 — The doppler frequency of the ray path from the transmitter. Parameters as in Figure 4.

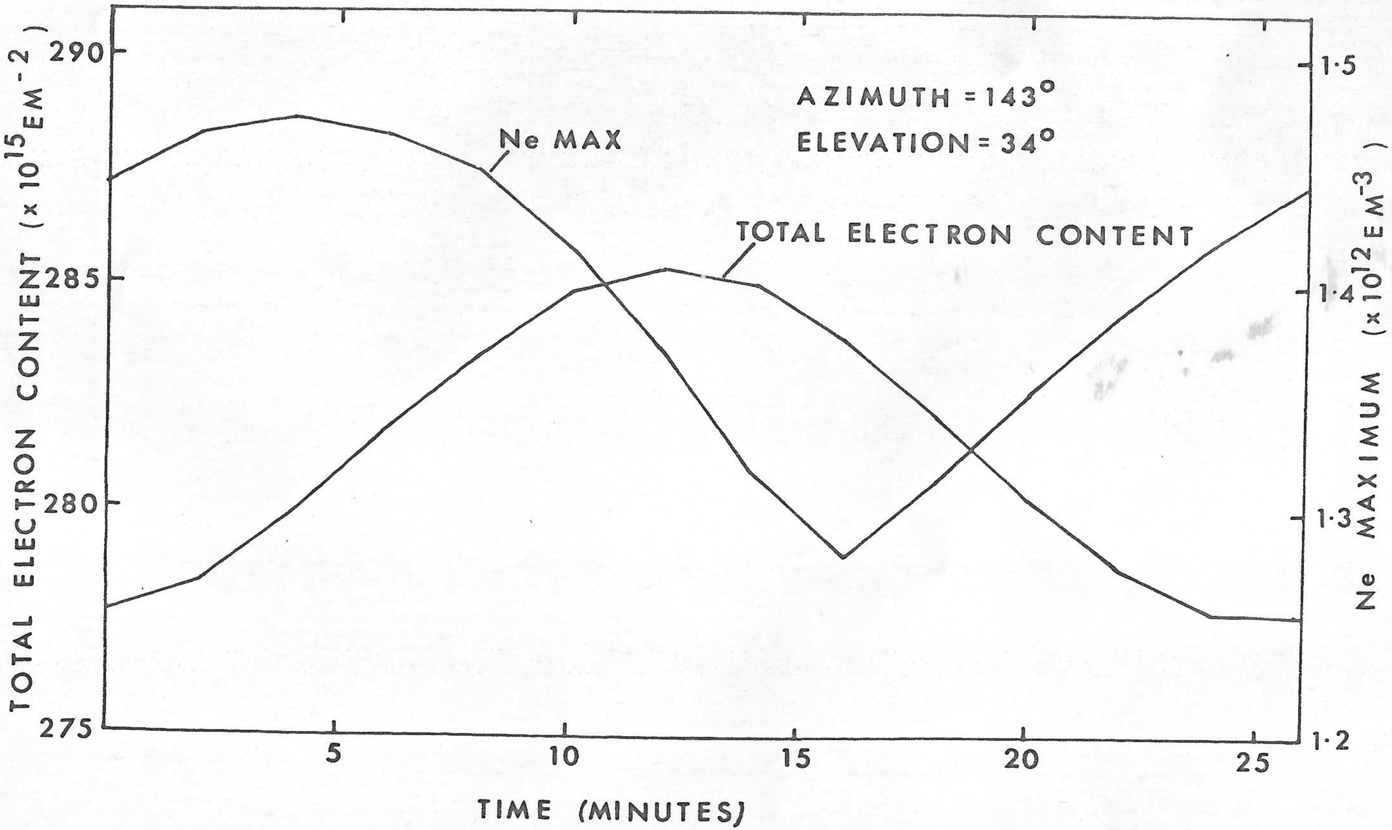

Figure 7 — Equivalent vertical total electron content variation and N_e peak variation along the ray path at 137 MHz.

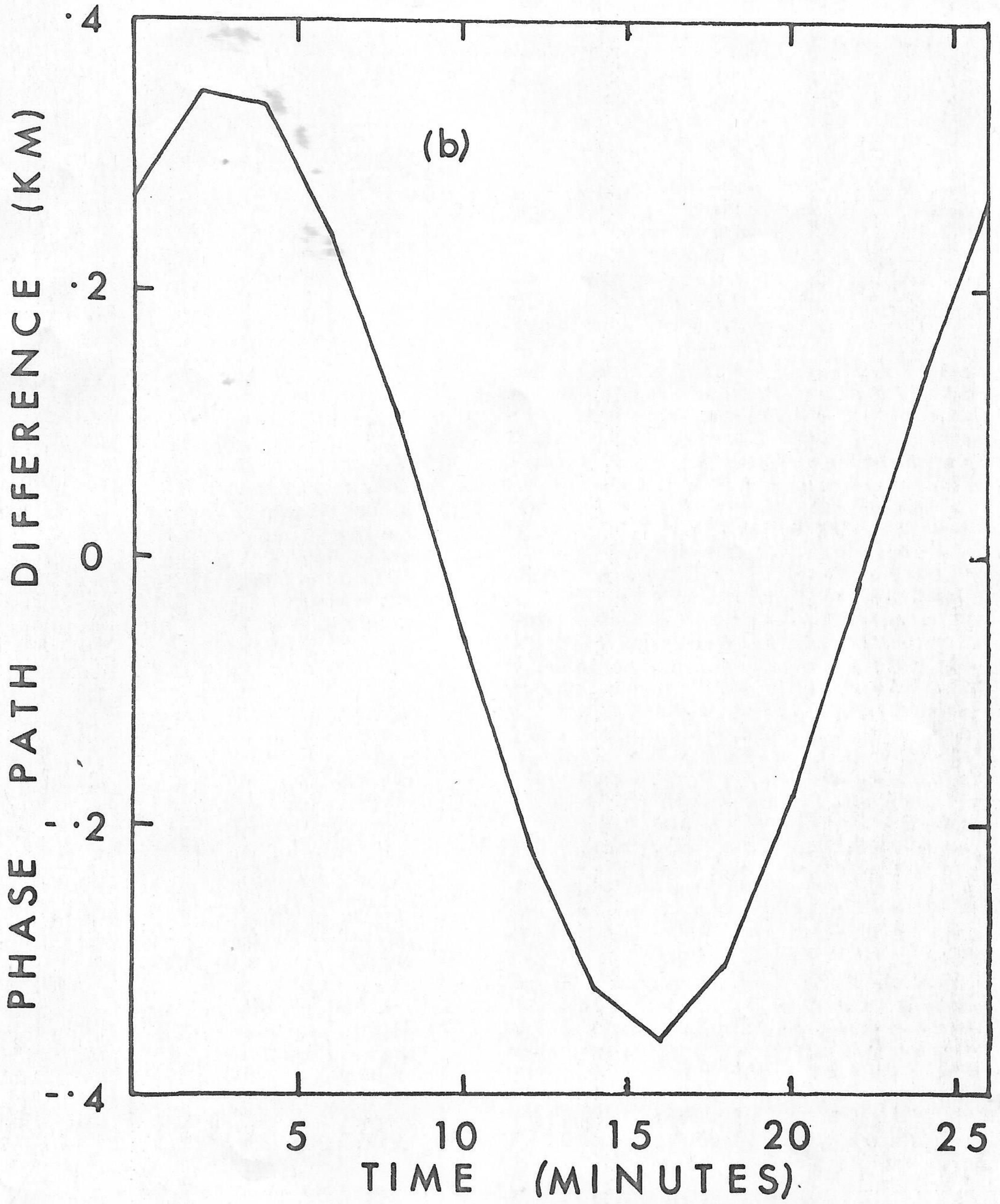

Figure 8 — Variation in the phase path difference between two points spaced 0.1 latitude apart.