PHASE MEASUREMENTS OF VLF TRANSMISSIONS OVER A 11000 KM TRANSEQUATORIAL PATH

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PHASE MEASUREMENTS OF VLF TRANSMISSIONS OVER A 11000 KM TRANSEQUATORIAL PATH

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Abstract

Phase measurements of 18.6 kHz Jim Creek's transmissions were recorded during 1964 and 1965 at São José dos Campos (SP), Brazil. The diurnal signal phase variation presents an average time shift delay of 80 μs, which is rather regular throughout the year. Observations of solar flare effects during the period were utilized to determine the product $\alpha_{eff} \cdot N_2$ of the effective recombination coefficient and electron density at the reflection height. The value of $5.0 \times 10^{-4} s^{-1}$ obtained for the product is approximately constant for all observed flares. The behavior of the phase rate of change during sunrise and sunset is discussed in terms of the interference pattern of propagation modes and in terms of the angle between the sunrise (and sunset) line and the transmitter-receiver great circle path. Experimental evidence permits one to conclude that the phase-path reflection height is a strong controlling factor of the second order mode propagation. Observations also show that the angle mentioned above is an important parameter in VLF phase studies.

1. Introduction

This paper presents experimental results based on measurements made in the Southern Hemisphere, at São José dos Campos, Brazil, utilizing the 18.6 kHz signals of the NPG/NLK Station. The distance between transmitter (48.2°N, 121.9°W) and receiver (23.3°S, 45.8° W) is 10950 km in an approximately northwest-southeast transequatorial path, as is shown in Figure 1.

The diurnal variations of phase display an average day-to-night phase delay of about 80 μs (1.49 cycles). This value corresponds to an increase in the height of reflection of 19 km, if one assumes the day reflection height of 70 km and only one transmission mode, namely n=1 (Wait, 1962).

The latitudinal variations of ionization due to cosmic rays have little influence in the present case, since the geomagnetic field along the path presents a symmetry which is caused by the existence of the Brazilian magnetic anomaly. Then, drifts in phase caused by the latitudinal variation of ionization should play a minor role in the predicted diurnal phase variation. The horizontal magnetic field along the path is shown in Figure 2.

Although observations took place in the period of the quiet sun, six flares were recorded and, due to the quality of the data obtained, it was possible to use all of the observed flare effects to measure the product $\alpha_{eff}.N_2 = 5.0 \times 10^{-4} s^{-1}$, a value approximately constant for all observed flares.

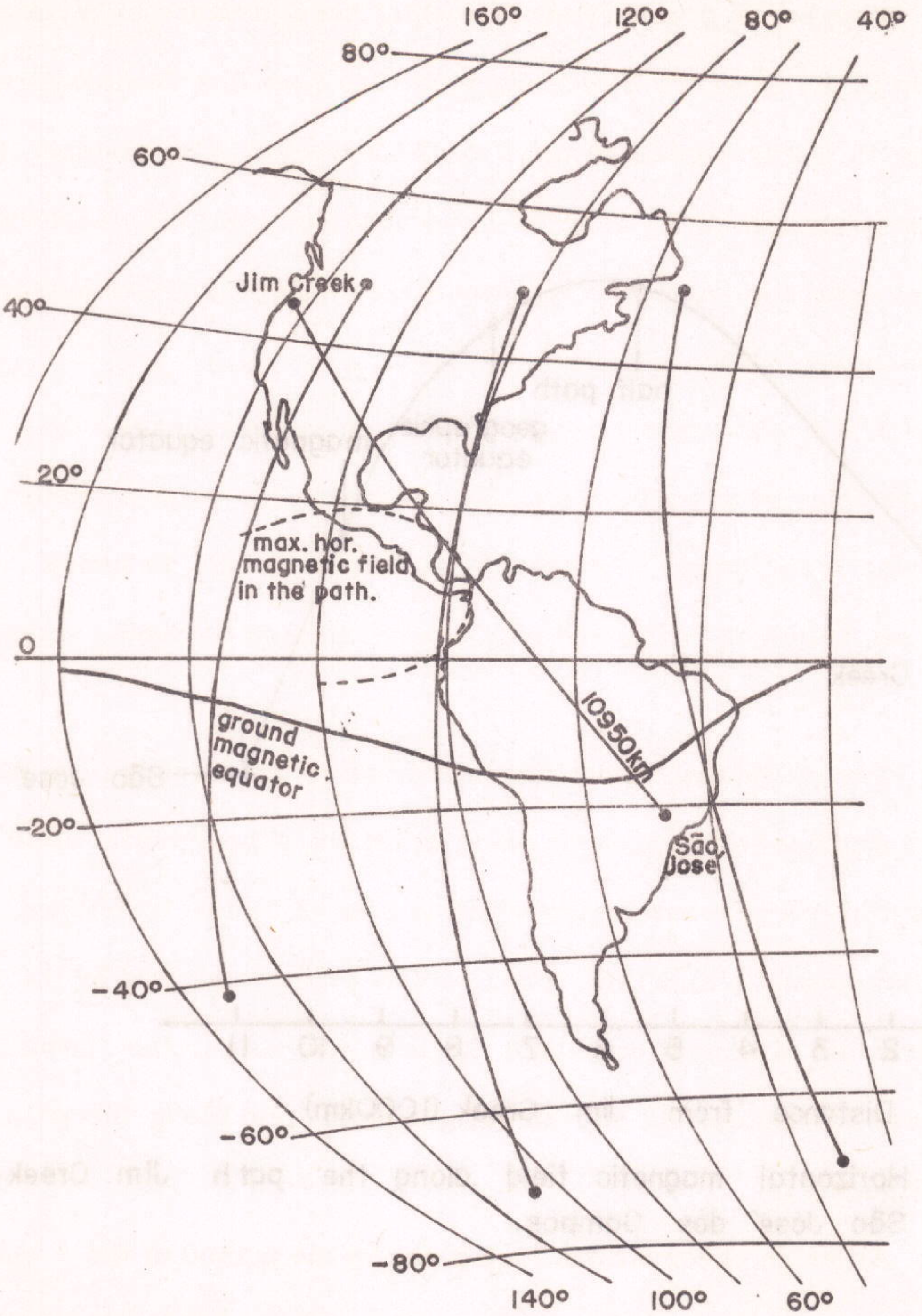

Fig. 1 — VLF transmission path NPG — Jim Creek to São José — Brazil. Also shown are 3 approximate geomagnetic meridians.

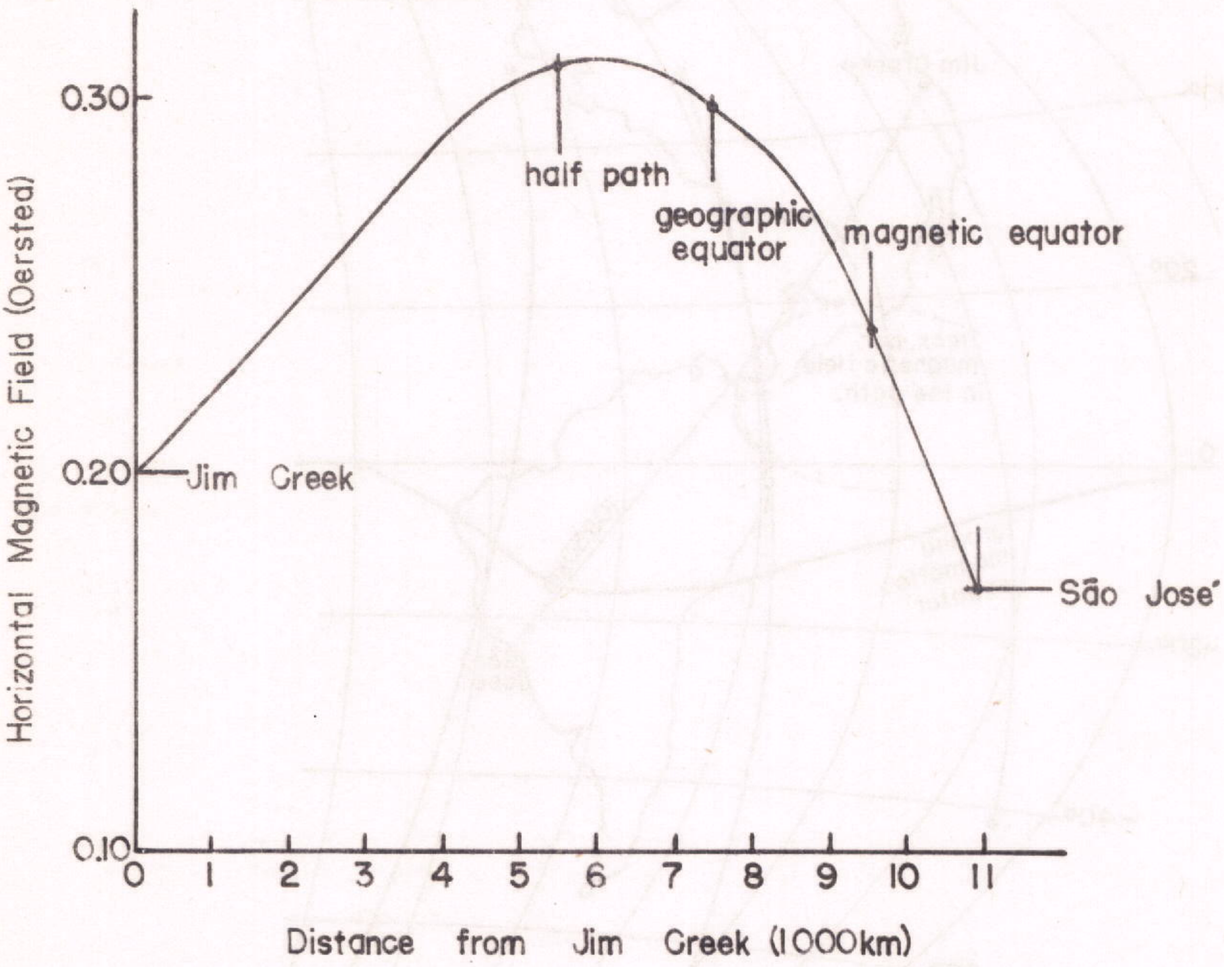

Fig. 2 - Horizontal magnetic field along the path Jim Creek-São Jose' dos Campos.

The behavior of the phase rate of change is such that during sunrise one may observe up to five points of maximum. These points occur with a certain regularity during the summer months in the southern hemisphere (negative declination of the sun), but literally disappear during May, June and July. During sunset these points of maximum rate of change of phase are observable only in the neighborhood of June and with less intensity.

There are two seasonal regions where the mentioned maxima are not observables. An explanation of this phenomenon is given based in the behavior of the path reflection height during the year and in terms of the angle between the sunrise (and sunset) line and the transmitter-receiver great circle path.

Crombie (1964) has shown that the points of maximum rate of phase variation correspond to points of fadings in signal amplitude . Thus, for simplicity sometimes we refer to fadings in this paper although we are dealing with phase measurements only.

2. Equipment

Phase-locked reception of VLF signals allows determination of frequency to an accuracy that is generally several orders of magnitude better than that obtainable by reception of HF stations such as WWV or WWVH over an equivalent observational period. Frequency measurements to an accuracy of 1 part in 10^9 can be achieved in intervals as short as 30 minutes; observation over 24 hour intervals gives a measurement accuracy of several parts in 10^{11} (Pierce, 1957).

A crystal oscillator was used to produce the local reference frequency which was adjusted to stay within 1 part in 10^9 to the frequency of NPG/NLK. The system used is comprised of a transistorized Textran Model 599 CS VLF Tracking Receiver which incorporates a VLF receiver, phase comparator and servo phase shifter for automatic phase - locked operation. A front panel digital dial continuously displays the shaft position of the phase shifter. This display may be interpreted as the difference in the time that would be indicated by two clocks, one synchronized to the incoming VLF signal and the other to the local standard. Outputs for a chart recorder are provided so that a permanent record of time difference can be made. This phase shift was recorded in microseconds with a precision better than 0.5 microsecond.

3. Brief Remarks on D Region and VLF Propagation

Radiations of solar origin penetrating below 85 km in the terrestrial atmosphere are: (1) X-rays of $\lambda < 10$ Å; (2) Lyman-α (1215.7Å) and (3) wavelenghts greater than 1800 Å. These radiations can ionize (1) molecular nitrogen and oxygen; (2) nitric oxide and (3) atoms of sodium and calcium. Molecular oxygen and nitrogen are also ionized by cosmic rays. It is possible to explain normal conditions of ionization by cosmic rays and Lyman-α (Nicolet and Aikin, 1960). Conditions and effects due to solar flares must be explained in terms of X-rays fluxes. At 70 km , the height where the reflection of VLF electromagnetic waves possibly takes place, the ionization is mainly due to cosmic rays and Lyman-α.

Production of ions-pairs by cosmic rays,at a given time,varies with magnetic latitude, thus the reflection height is not constant along a path that crosses different magnetic latitudes.

With the occurrence of a SID (Sudden Ionospheric Disturbance) the production function varies abruptly changing the reflection height of VLF waves. As soon as the event is over the ionosphere returns slowly to the equilibrium state.

One of the effects observed on the earth as a result of solar flares is a sudden decrease in the phase-path height of long-wave ionospheric reflections. Such effects, called SPA (Sudden Phase Anomalies) are explained by extra ionization due to X-rays, that penetrate below 70 km. Observations show that this decrease in phase is very fast, after which the phase returns slowly to its normal variation. A relationship exists among the change in phase height during the decay time, the time of decay and the local value of the recombination coefficient. Mitra and Jones (1954) showed that for large flares

$$\alpha_{eff} = \frac{1 - \left(\phi_2/\phi_1\right)^2}{N_2 \, . \, (t_2 - t_1)} \qquad (1)$$

where α_{eff} is the effective recombination coefficient at the height of reflections; ϕ_1 and ϕ_2 are the values of the phase just after the maximum effect (t_1) and at a suitable chosen time t_2 during the decay period respectively, as indicated in Figure 3. N_2 is the electron density required for reflection of the incident wave.

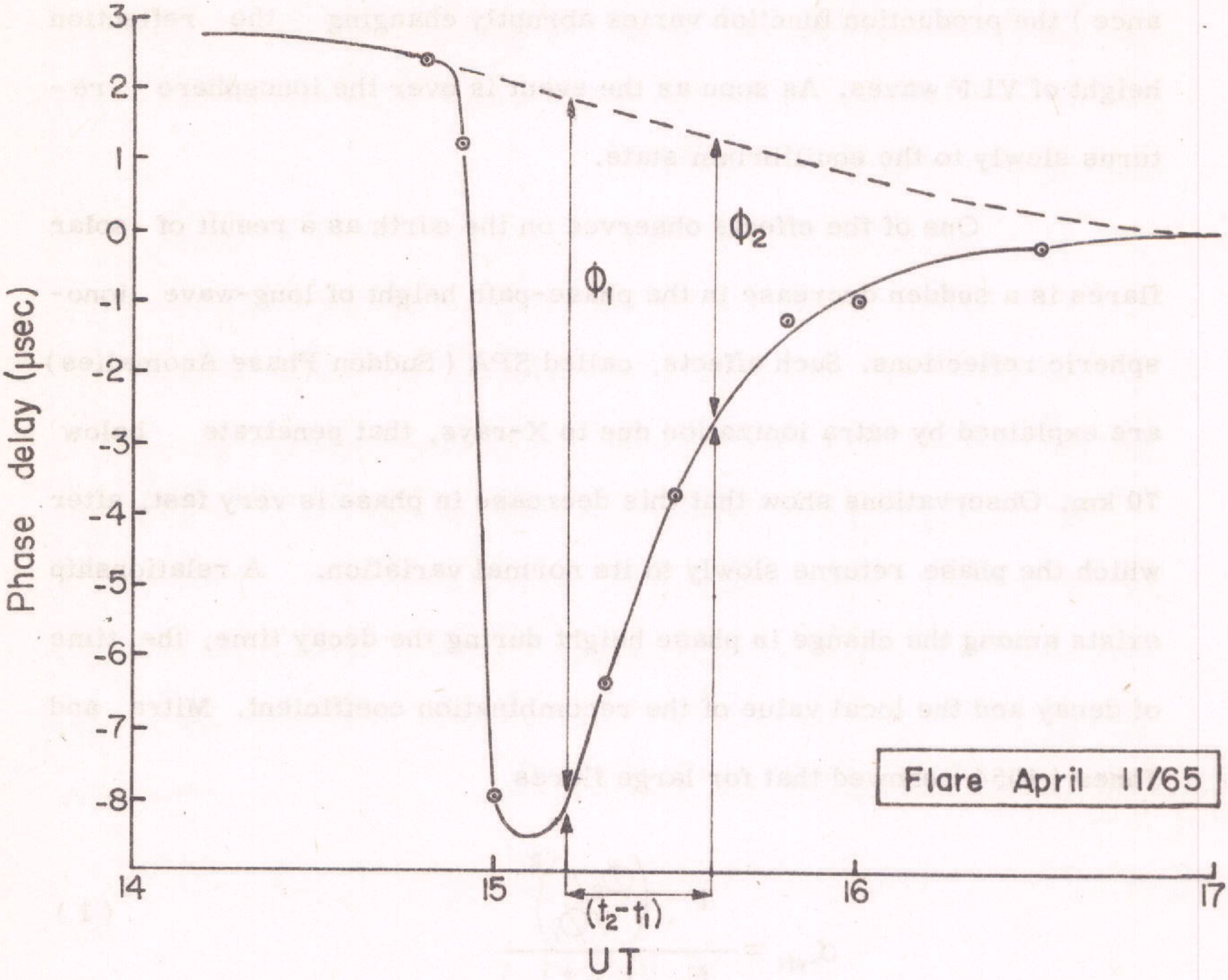

Fig. 3 - Typical flare effect and involved parameters.

Equation 1 is an approximation obtained by assuming that the increment in electron density (ΔN) due to the solar flare is much greater than the normal electron density (N), and assuming also α_{eff} as being constant at the height interval $h_0 \geqslant h \geqslant (h_0 - \Delta h)$, where h_0 is the reflection height at normal conditions and Δh the abrupt variation in reflection height due to the flare. The value of α_{eff} at 70 km is of the order of 10^{-6} cm.^{3} s^{-1}.

The phase of VLF signals received over short and long distances varies diurnally in a trapezoidal manner. This diurnal variation has been interpreted as being due to a change in reflection height between day and night. Calculations indicate the reflection heights to be 85 to 90 km at night and 70 to 75 km during the day (Bracewell et al., 1951; Pierce, 1955, 1956; Wait, 1962).

Long distances VLF propagation is best described theoretically by guided-wave theory (Budden, 1951; Wait, 1962) in which the earth and the ionosphere are considered to be the sharp boundaries of a lossy wave-guide. The " sharpness " of the ionosphere is justified by the fact that the variation of electron density with height is very fast compared with wave-lenght in the vicinity of the reflection point.

We will consider only transverse magnetic propagation modes of order n (TM_n). Wait (1962 and 1963a) showed that a good approximation to the phase velocity in the earth-ionosphere wave-guide is given by the expression:

$$V_{pn} = c\left(1 - \frac{h}{2a}\right)\left\{1 - \frac{\lambda^2 (n-1/2)^2}{4h^2}\right\}^{-1/2} \qquad (2)$$

where

V_{pn} is the phase velocity of the n^{th} transverse magnetic mode,

h height of upper boundary,

c velocity of light,

λ wavelength in free space and

a earth's radius.

For the n^{th} mode the phase-path length ϕ_n in cycles is given by:

$$\phi_n = \frac{d.c}{\lambda . V_{pn}} \qquad (3)$$

where d is the path length.

By combining equations 2 and 3 and setting n=1, we find that the phase change $\Delta\phi$ for a reflection height change from h_1 to h_2 is

$$\Delta\phi = \frac{d}{\lambda}\left[\frac{1}{2a} + \frac{\lambda^2 (h_1 + h_2)}{32\, h_1^2 . h_2^2}\right] \cdot (h_2 - h_1) \qquad (4)$$

Generally this equation is used assuming an average height of reflection of 70-75 km along the path during the day (h_1) and an average height of 85-90 km at night. Naturally this height varies with the zenith angle of the sun and with magnetic latitude.

Lately, concerning the field of VLF research, some emphasis has been put in the study of fadings in the sunrise and sunset patterns. The discussions of the sunrise and sunset fadings made by Crombie (1964) and measurements made by Bates and Albee (1965), show that the propagation of the second order mode may affect strongly the diurnal variation of phase and amplitude of VLF signals. The above results show that the discrepancies observed treating propagation with only one mode can be justified with a model utilizing interference between independently propagating waves. Sunrise and sunset interferences seem to be caused by mode conversion that may produce a strong disturbing wave (Wait,1963b). This mode conversion takes place at the sunrise or sunset transition region along the propagation path in the D region.

By this model, for the west-to-east propagation, it is assumed that, at sunrise, the two modes excited by the transmitter in the night time waveguide are converted at or near the sunrise boundary into two first order modes and two second order modes. These second order modes thus generated are attenuated at the illuminated path and one first order mode will interfer with the other first order mode giving the observed sunrise fading pattern. At sunset the first order mode is converted back into a first and a second order mode at the sunset boundary.

If this is true, at least the second order mode is relevant at night and the phase measured at night is the composition of modes 1 and 2. It seems that this phenomenon is the principal source of small deviations of the predicted values obtainable by the Wait formulation.

4. Experimental Results

We shall discuss now the phase measurements made at São José dos Campos utilizing the signals transmitted from the station NPG/NLK at 18.6 kHz (Jim Creek).

For the purpose of discussion we shall treat the present topic in three parts, namely, observed phase averages, observed solar flares

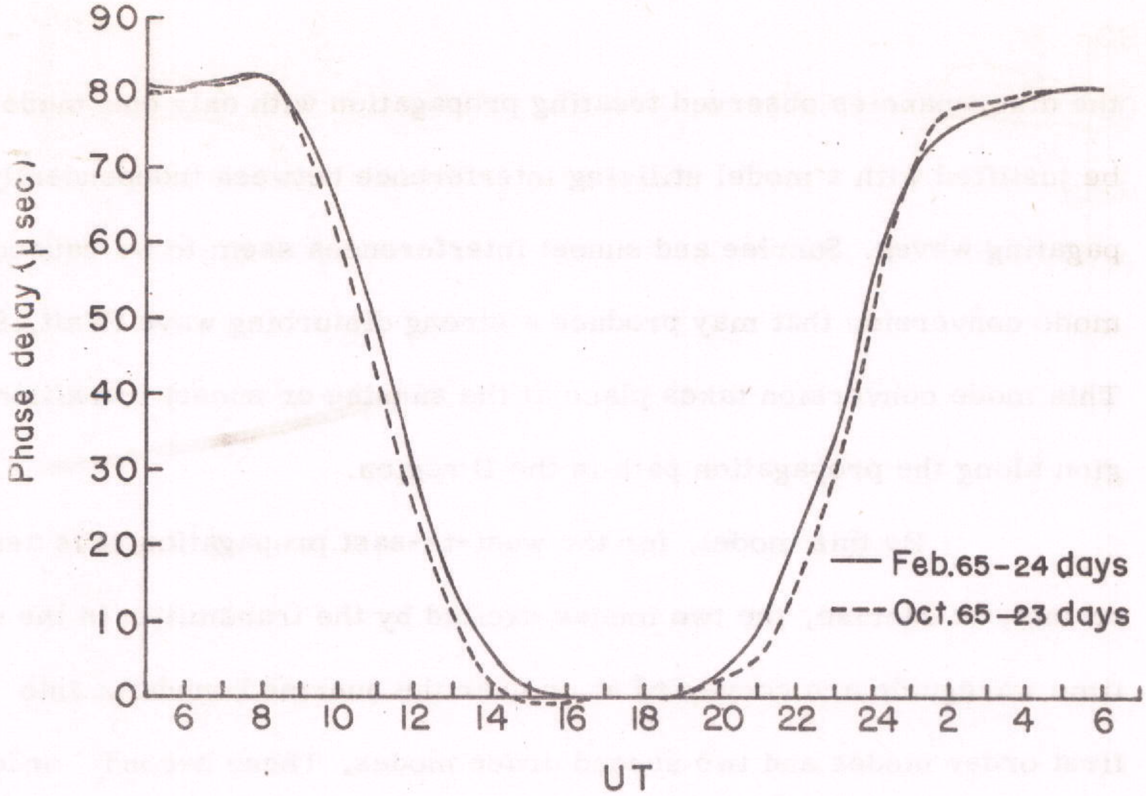

Fig. 4b — The diurnal variation in the phase of the NPG/NLK signal observed at São José dos Campos.

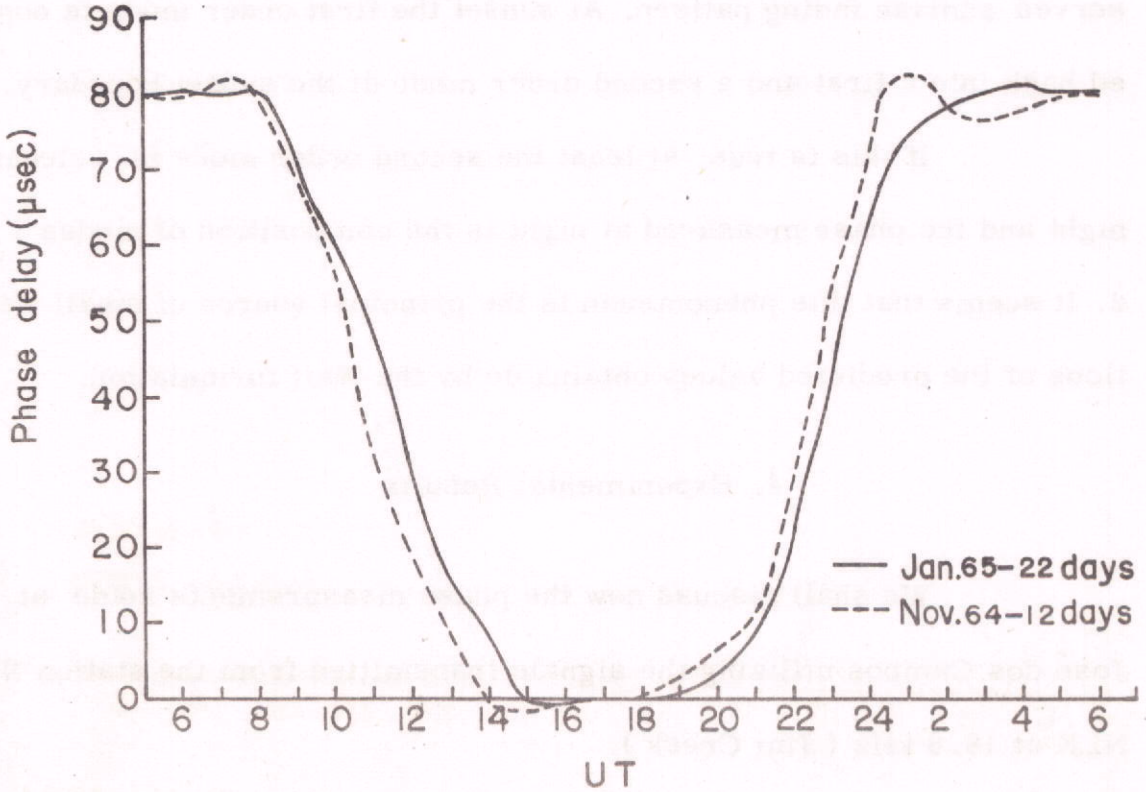

Fig.4a—The diurnal variation in the phase of the NPG/NLK signal observed at São José dos Campos.

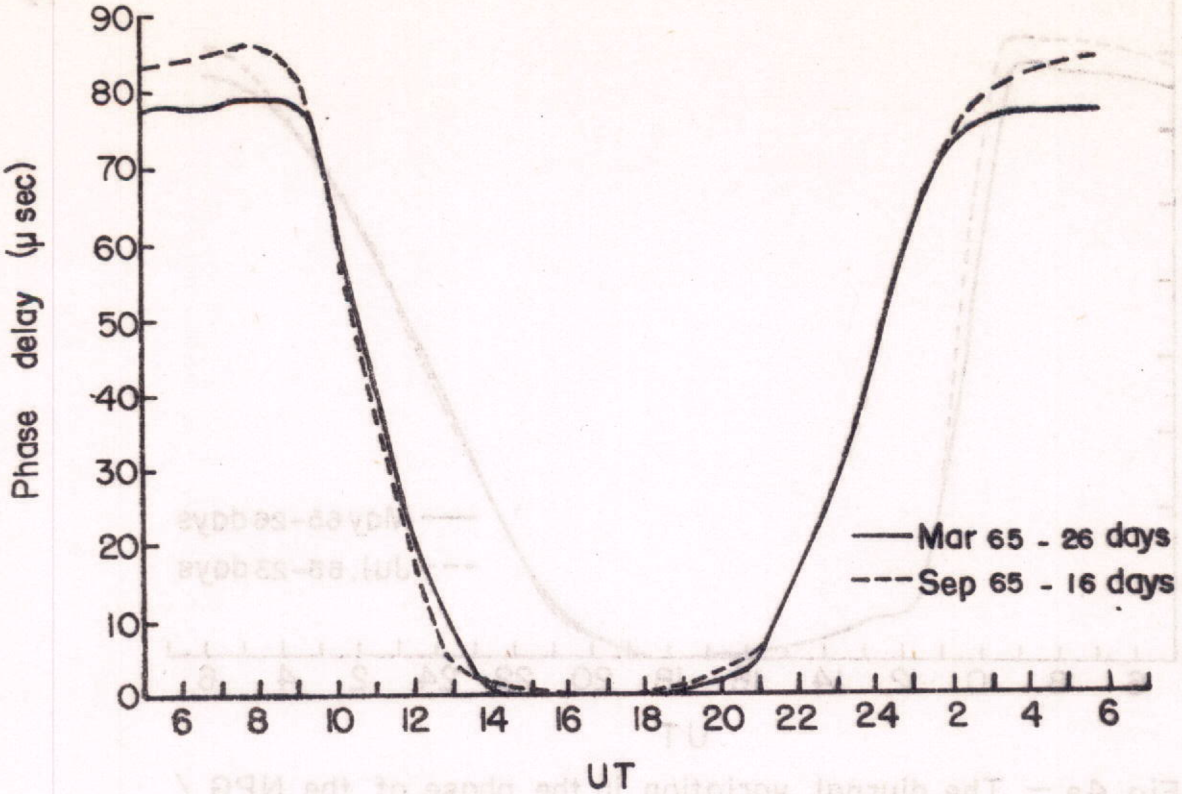

Fig. 4c — The diurnal variation in the phase of the NPG/NLK signal observed at São José dos Campos.

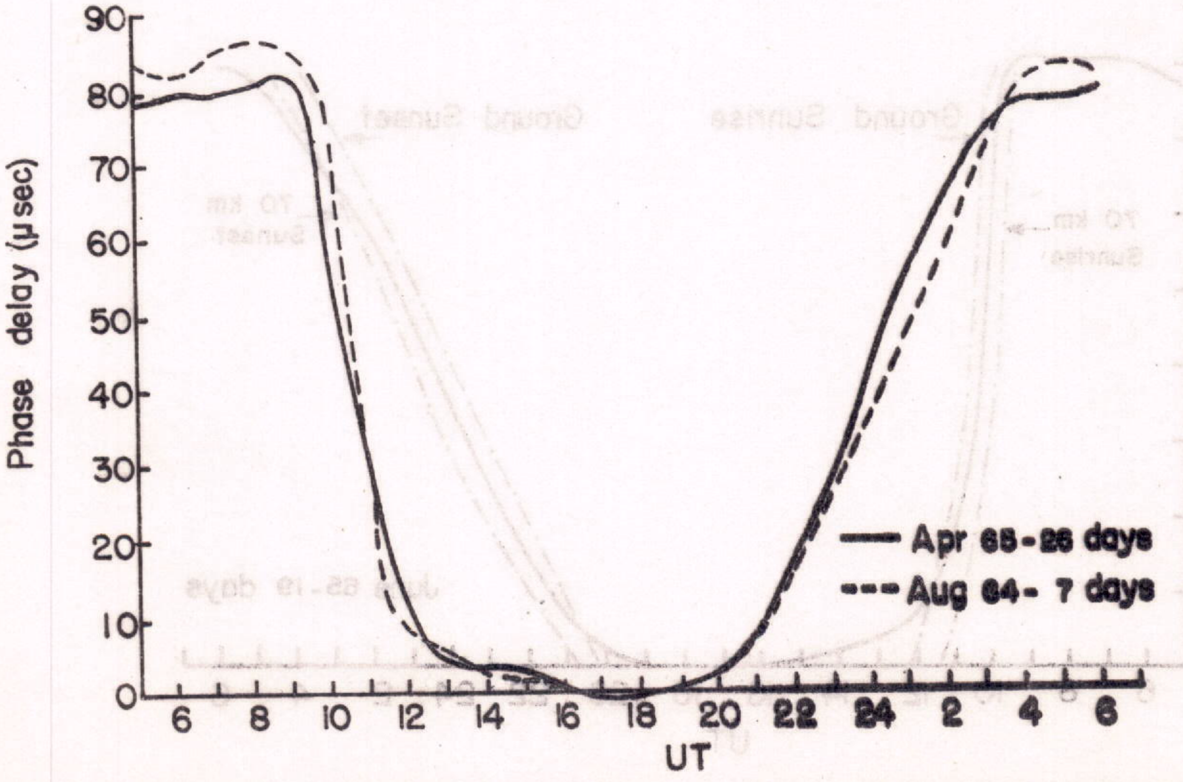

Fig. 4d — The diurnal variation in the phase of the NPG/NLK signal observed at São José dos Campos.

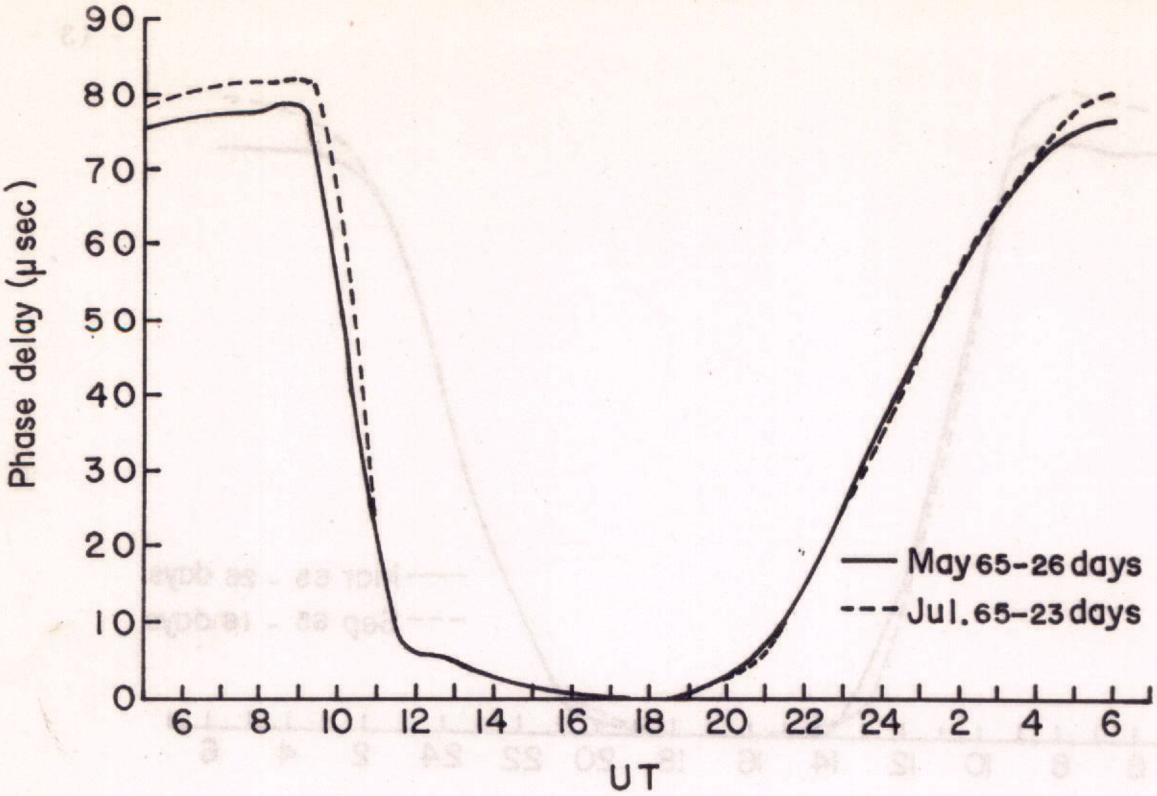

Fig. 4e — The diurnal variation in the phase of the NPG / NLK signal observed at São José dos Campos.

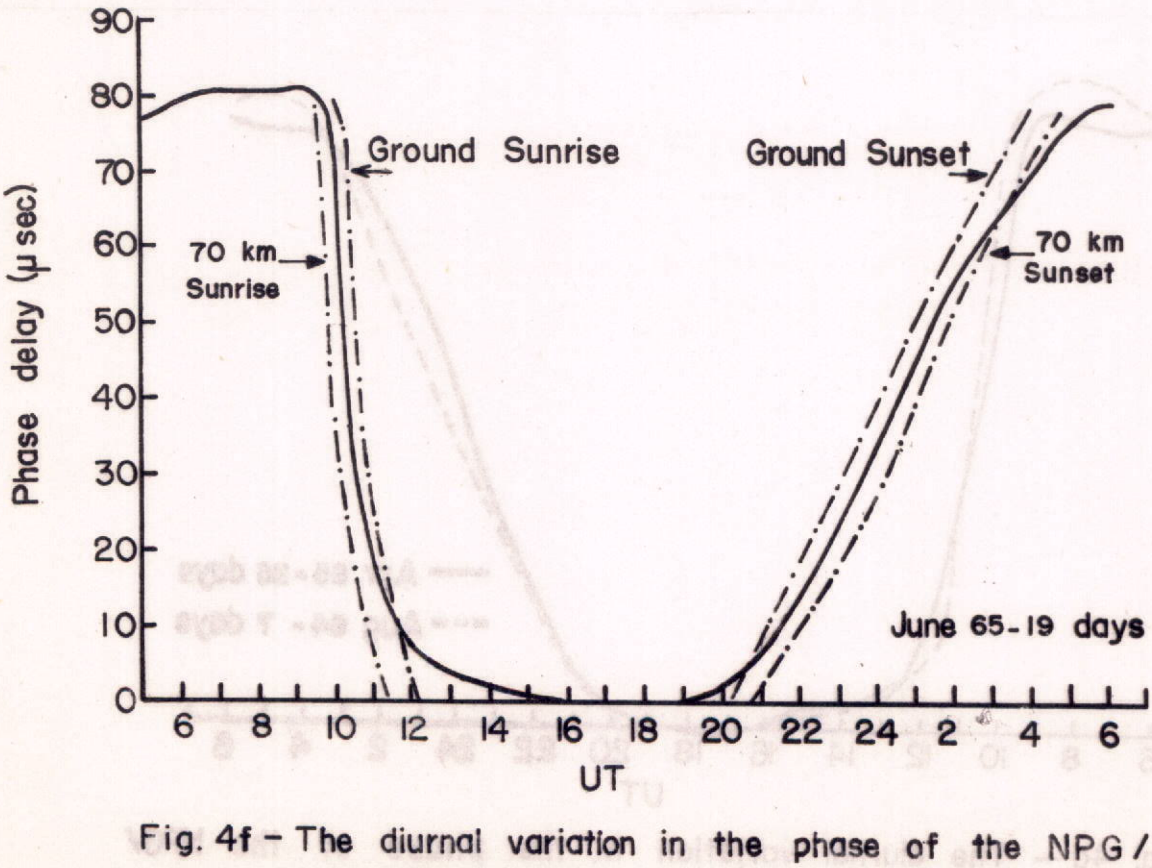

Fig. 4f - The diurnal variation in the phase of the NPG / NLK signal observed at São José dos Campos.

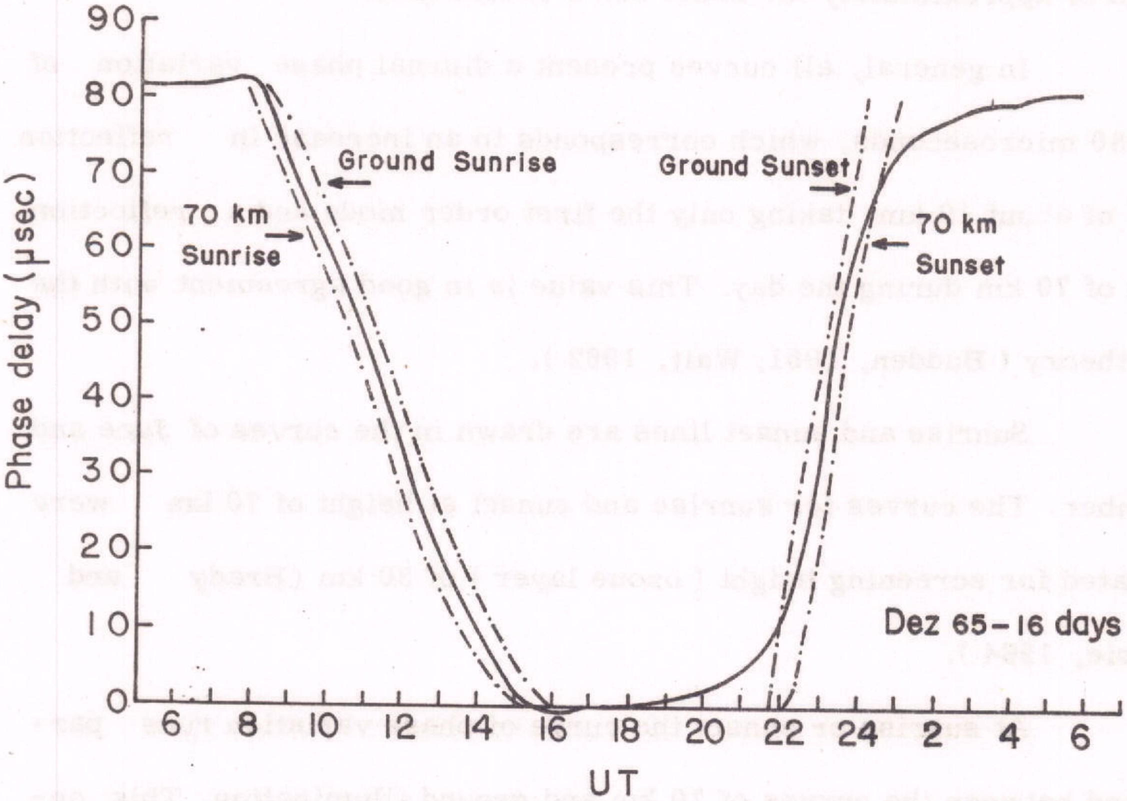

Fig. 4g — The diurnal variation in the phase of the NPG / NLK signal observed at São José dos Campos.

and phase rate of change patterns.

4.1 - Observed Phase Averages: Figures 4a to 4g show the monthly averages of phase measurements of the 18.6 kHz NPG/NLK signals. The two curves shown in each figure represent measurements made during months of approximately the same sun's declination.

In general, all curves present a diurnal phase variation of about 80 microseconds, which corresponds to an increase in reflection height of about 19 km, taking only the first order mode and a reflection height of 70 km during the day. This value is in good agreement with the mode theory (Budden, 1951; Wait, 1962).

Sunrise and sunset lines are drawn in the curves of June and December. The curves for sunrise and sunset at height of 70 km were calculated for screening height (ozone layer) of 30 km (Brady and Crombie, 1964).

At sunrise or sunset the curve of phase variation runs parallel and between the curves of 70 km and ground illumination. This occurs in a similar fashion for all the other months (not drawn).

4.2 - Solar Flares : Figures 3 and 5a to 5e show the reduced data of the observed flares during 1965. It is quite easy to reduce the data (phase variation during SPA) with some accuracy because the signal/noise ratio of NPG/NLK signal is high at São José dos Campos, Figure 6 illustrate the recording of a solar flare observed on 5 June 1965.

With the curve of reduced flares and applying equation (1) from the theoretical studies of Mitra and Jones, we obtain the values in

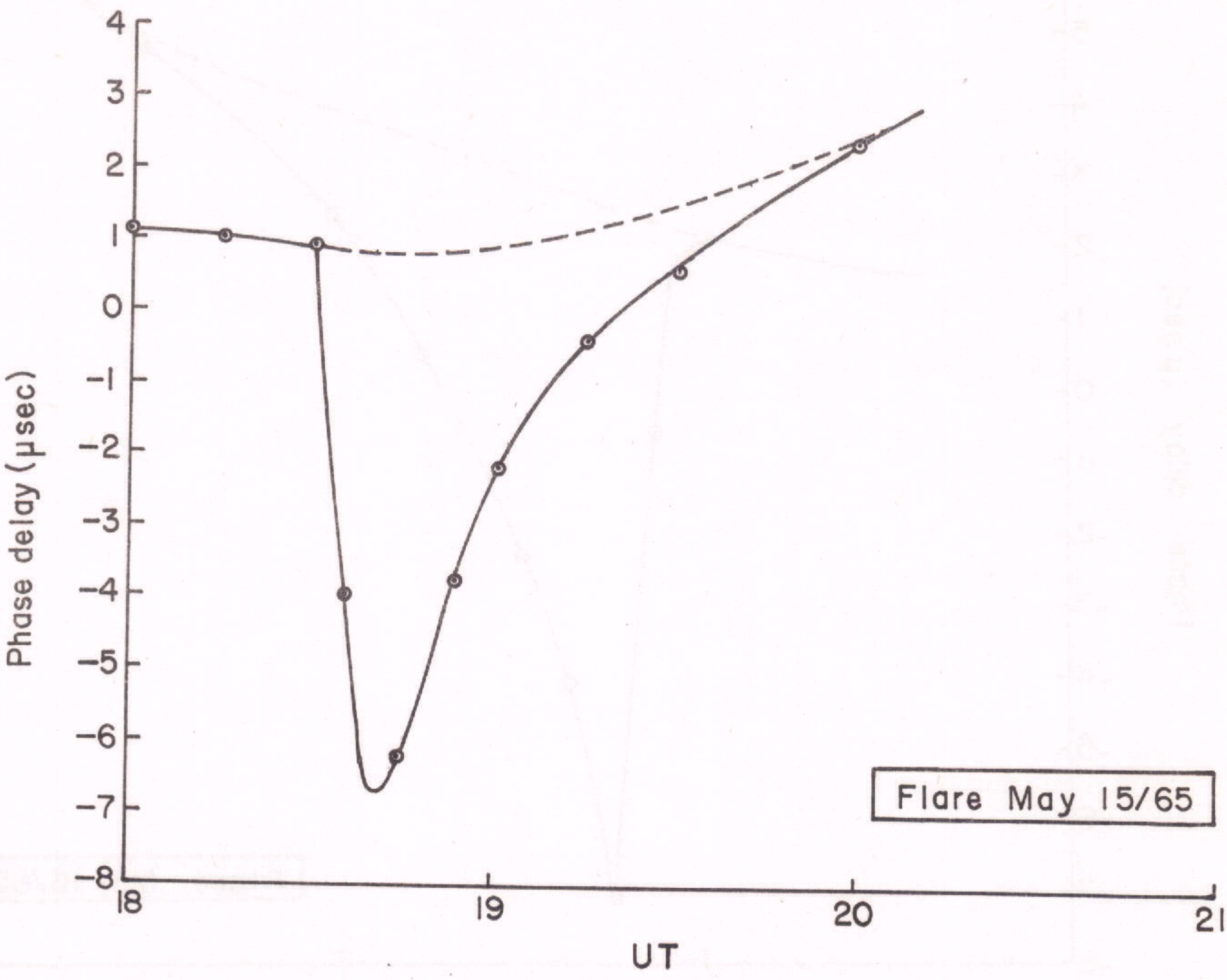

Fig. 5a — Reduced data from SPA observation of solar flare occurred on May 15, 1965.

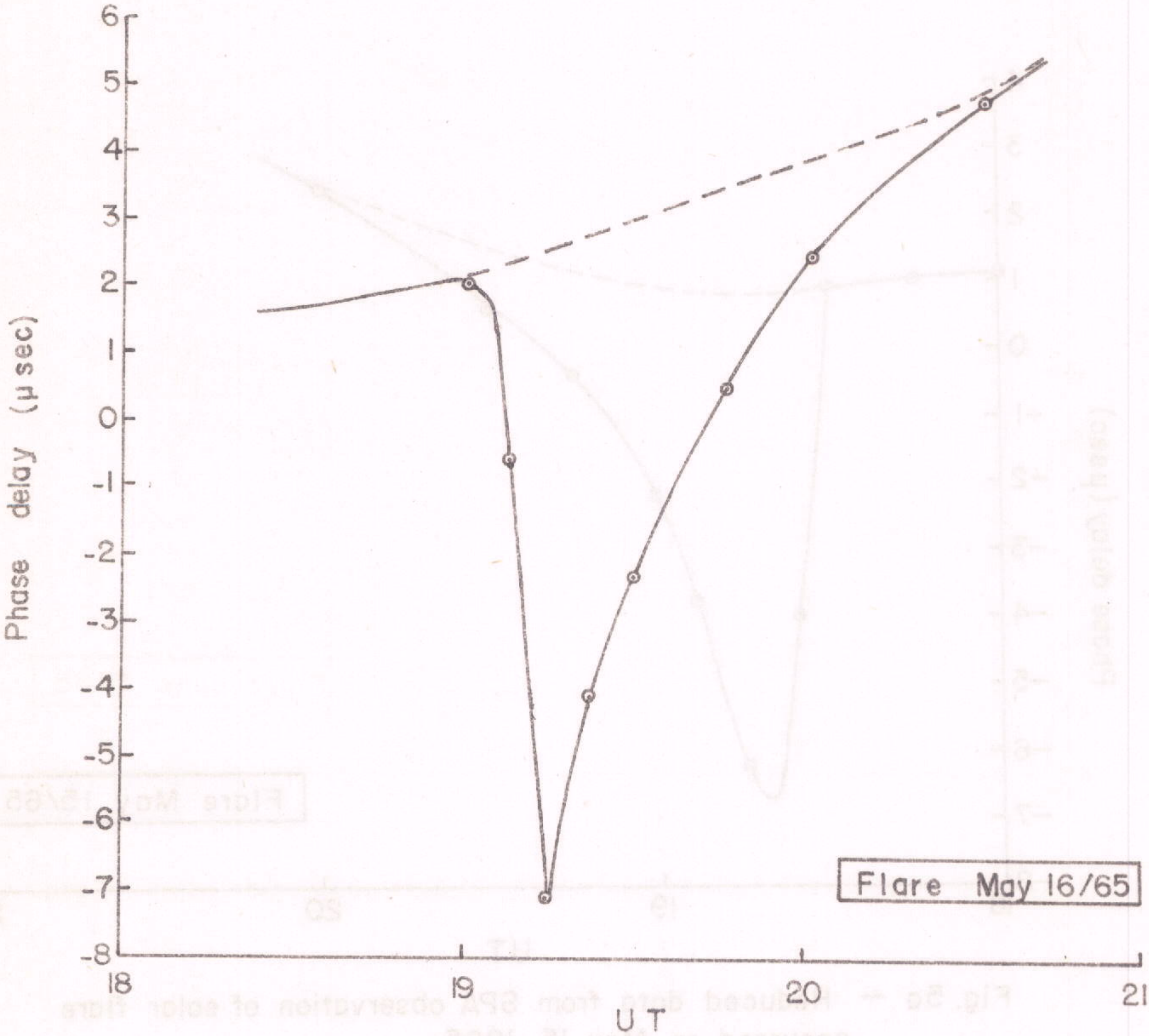

Fig. 5b — Reduced data from SPA observation of solar flare occurred on May 16, 1965.

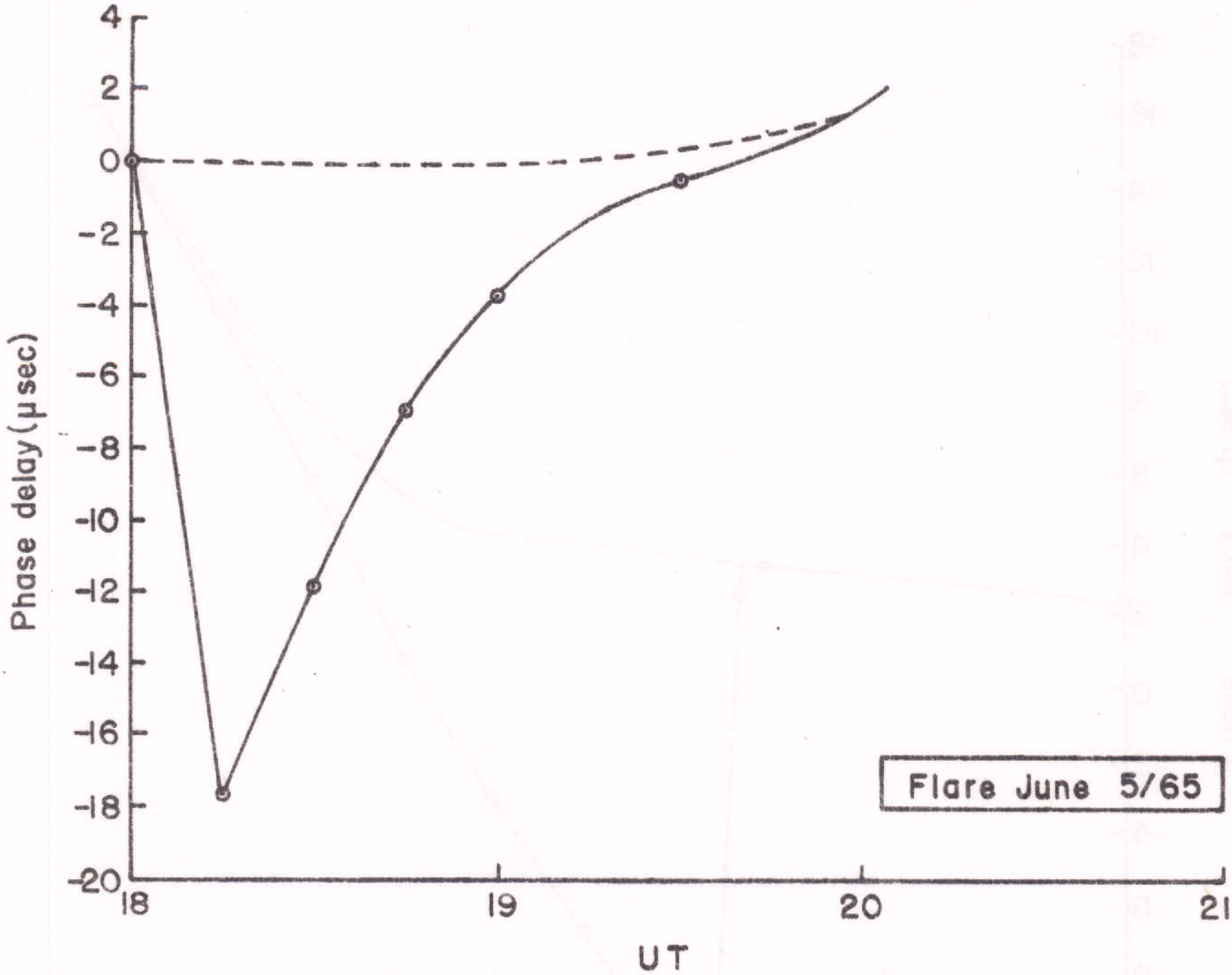

Fig. 5c — Reduced data from SPA observation of solar flare occurred on June 5, 1965.

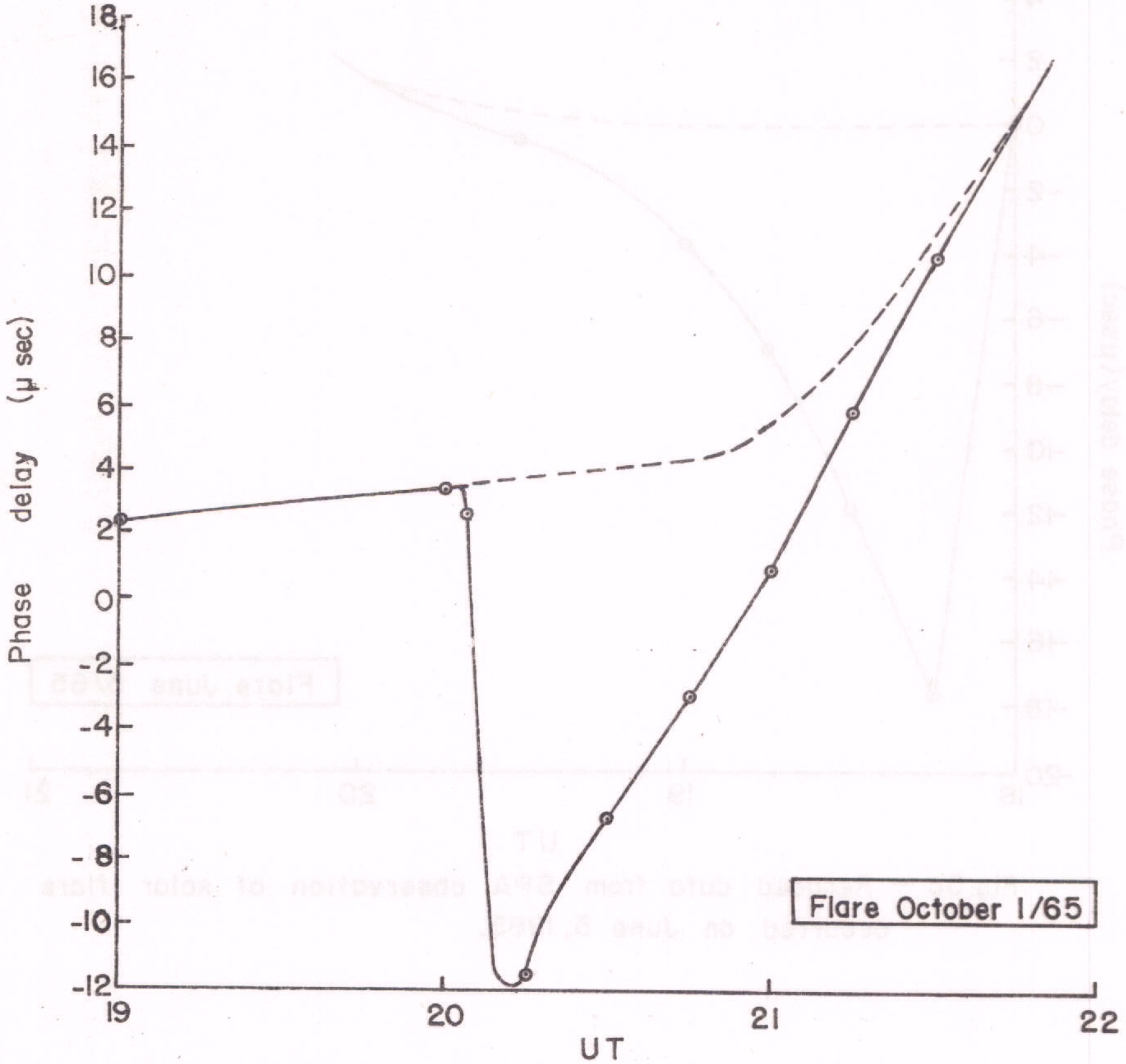

Fig. 5d — Reduced data from SPA observation of solar flare occurred on October 1, 1965.

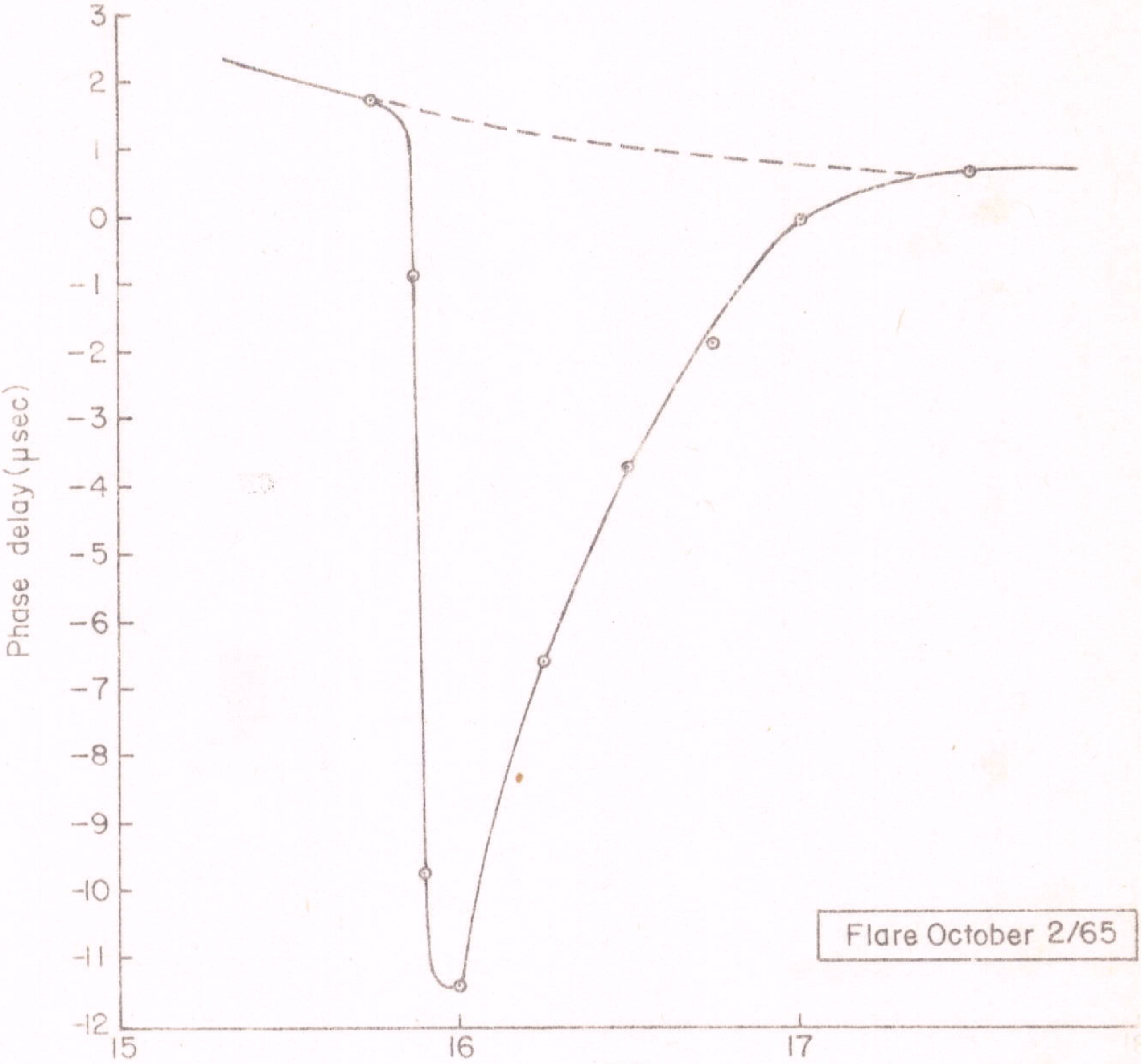

Fig. 5e — Reduced data from SPA observation of solar flare occurred on October 2, 1965.

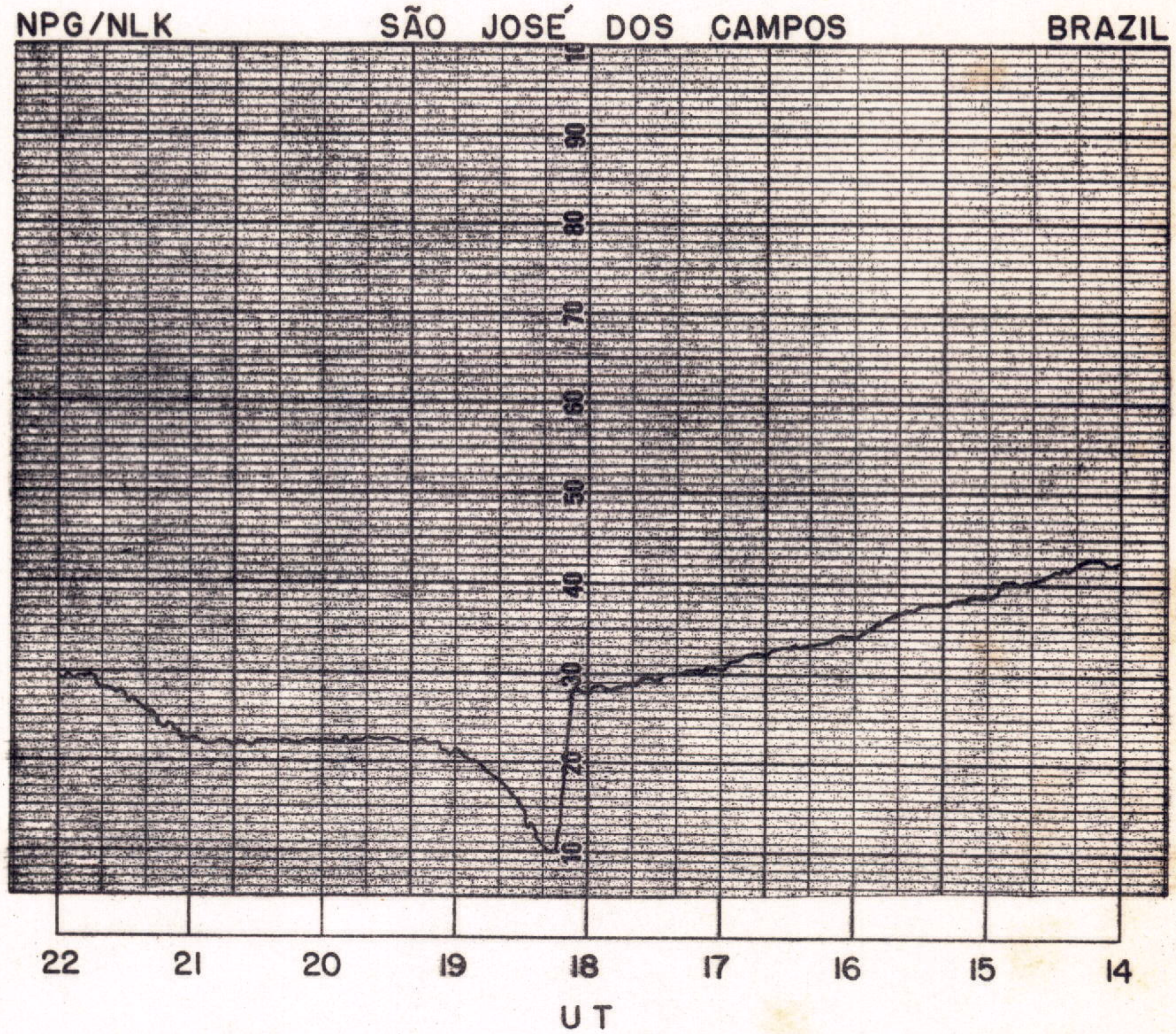

Fig. 6 — SPA record of solar flare occurred on 5 June 1965

Table I, where the reflection height variation was calculated by means of the formula:

$$\Delta h = \frac{-c.\Delta t}{d\left[\frac{X^2}{16h_0^3}+\frac{1}{2a}\right]} \qquad (5)$$

which is a first order approximation (Westfall, 1961).

TABLE I

Calculated values of the product $\alpha_{eff}N_2$ for six flares, using a suitable time interval $(t_2 - t_1)$ of 1800 seconds.

Solar Flares (1965)		Δh (km)	$\frac{\phi_2}{\phi_1}$	$\alpha_{eff}N_2$ 10^{-4} s^{-1}
11 April	14.9 UT	2.4	3.2/10.0	5.0
15 May	18.5 UT	1.6	1.6/7.0	5.2
16 May	19.0 UT	2.0	3.0/9.7	5.0
5 June	18.0 UT	3.9	7.0/17.7	4.7
1 October	20.0 UT	3.3	7.1/15.4	4.4
2 October	15.8 UT	2.9	4.7/12.9	4.8

The height h_0 before the flare was taken as 70 km for all flares. The calculated value of $\alpha_{eff}N_2$ is an approximated average along the path, at the vicinity of the height of 70 km. It is interesting to note that although the observed flares belong to distinguishable classes (Δh varying from 1.6 to 3.9 km) the value of $\alpha_{eff}N_2$ is approximately constant and equal to 5.0×10^{-4} s^{-1}. For example, if we take the electron density at reflection height as 300 cm^{-3} we obtain the effective recombination coefficient equal to 1.7×10^{-6} $cm^3.s^{-1}$, an acceptable value at 70 km.

The discrepancy in the value of the product $\alpha_{eff}N_2$ obtained from the flare of 1 October 1965, namely a value that is less than those obtained for the other days, can be justified on grounds that it was difficult to get correctly the normal behavior at the time of occurrence of the flare (beginning of sunset) and also it probably corresponds to a height above 70 km.

4. 3 - Patterns of the Phase Rate of Change: During sunrise and sunset the phase rate of change of the VLF signals display patterns with several points of maximum which have been observed in the reception of 18.6 kHz NPG/NLK signals at São José dos Campos. It is possible to identify up to 5 points of maximum rate of change of phase during the sunrise and 3 points during the sunset.

The most interesting feature of these observed points of maximum phase change is that, when the sun's declination varies from -23^o (São José dos Campos) to approximately 11^o (half of the path) it is possible to observe them only during sunrise. For these declinations of the sun the phase variation at sunset presents a smooth pattern. Figure 7 shows a typical diurnal variation for this situation.

On the other hand, when the sun's declination is close to 23^o (nearer the transmitter) the situation is reversed, i. e., it is then possible to observe sunset and not sunrise points of maximum phase rate of change. Figure 8 shows a typical diurnal variation of phase for these cases.

There are two seasonal epochs (April-May and July-August) when the mentioned points are not detectable, i. e., the phase varies di-

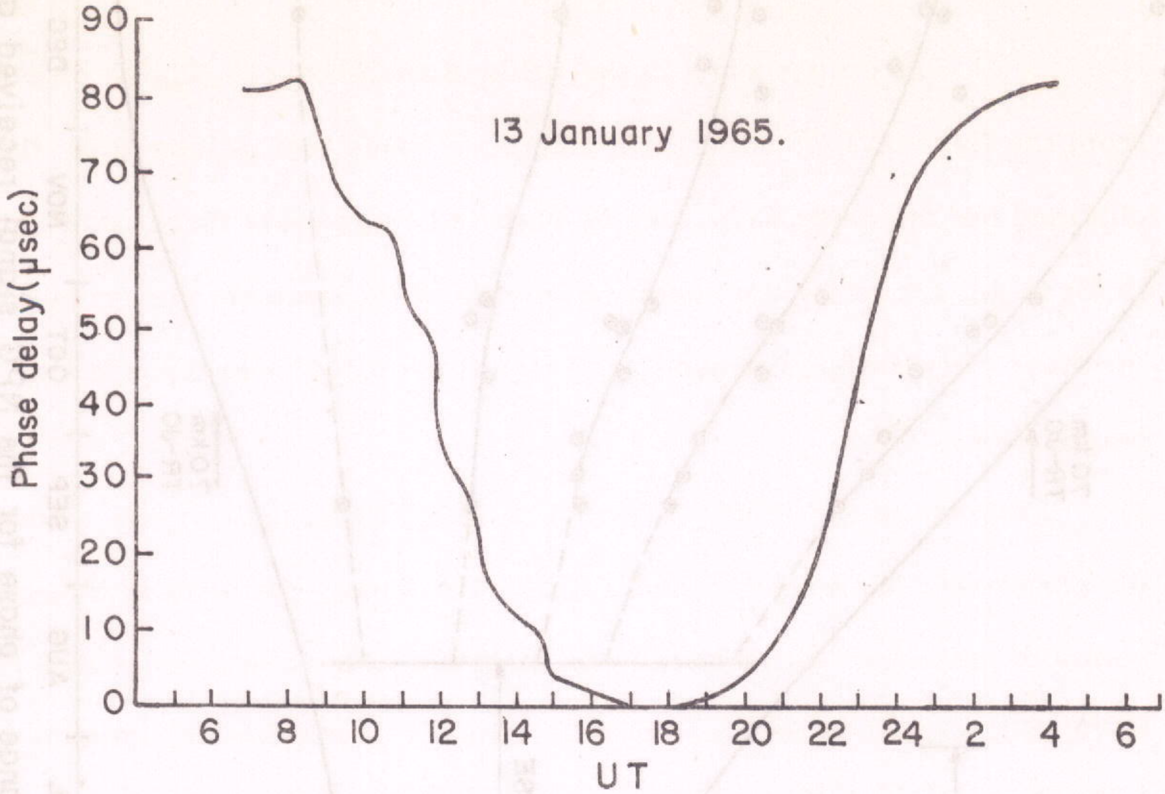

Fig. 7 — Typical diurnal phase variation of the signal received from NPG at São José dos Campos in January.

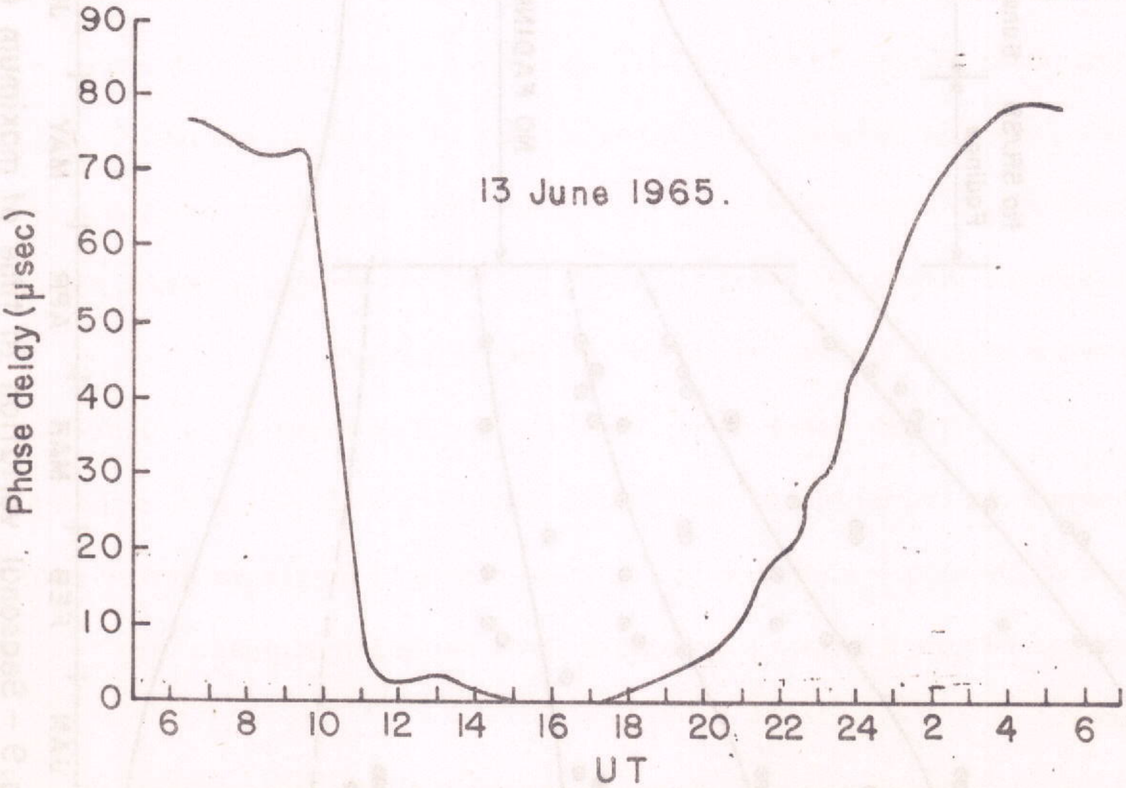

Fig. 8 — Typical diurnal phase variation of the signal received from NPG at São José dos Campos in June.

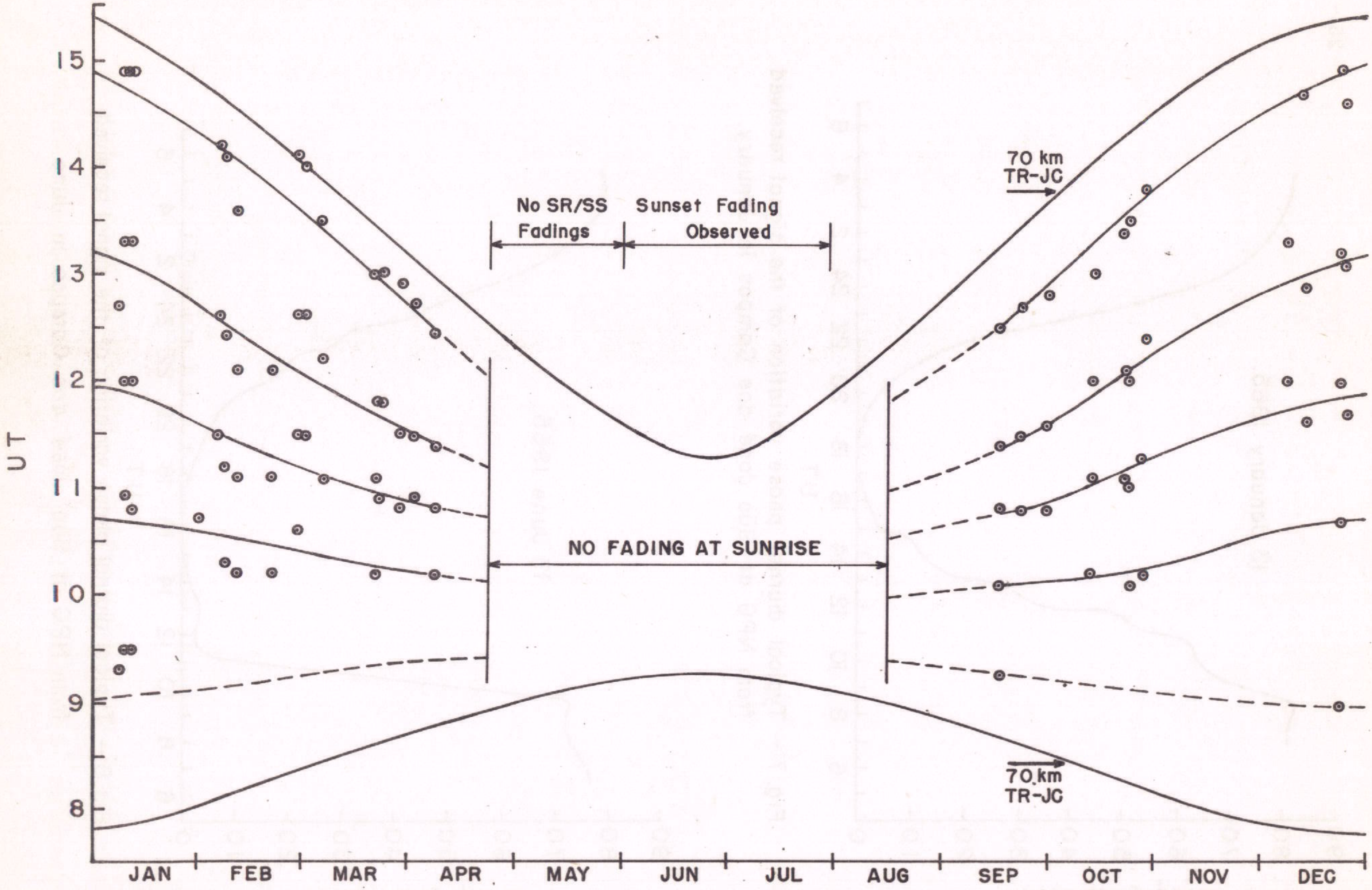

Fig. 9 – Seasonal variation in time of maximum rate of change of phase for the NPG signal received at São José dos Campos.

urnally in a regular trapezoidal fashion.

Some regularity in the times of occurrence of maximum phase variation, following seasonally the sunrise curves is observable, as illustrated in Figure 9. It is difficult to obtain points of maximum rate of change at sunset with a certain accuracy and the mentioned seasonal variation is not presented for these cases.

In what follows we will try to give an explanation of these observed effects in the phase variation. One of the first measurements of this type of phenomenon (Crombie, 1964) were made dealing with paths close to the west-east direction in middle latitude reception. In our case however we are dealing with a path that can strongly control the behavior of the second order mode. Note that the sun's declination is within the latitude range between transmitter (48.2^{o}) and receiver (-23.3^{o}).

Let us consider now the influence of variation of the sun's declination on the geometry of the problem.

SOUTHERN SOLSTICE: Figure 10 is a sketch of the path reflection height during the southern hemisphere summer.

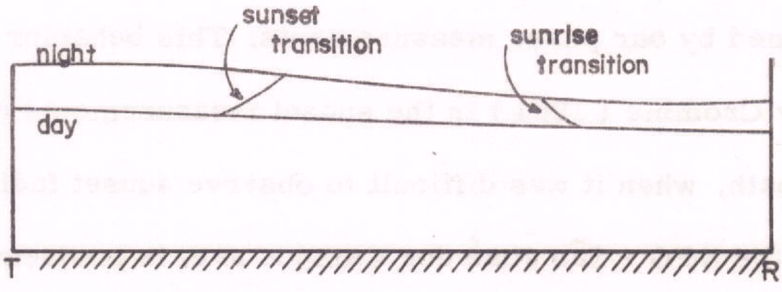

Fig. 10— Sketch of the path reflection height during the southern hemisphere summer.

At this time the reflection height is larger at night near the transmitter, i.e., bottom of E region in northern hemisphere winter

(Parkinson, 1956). Then, the second order mode may propagate with low attenuation for long distances (for example, 2.2 db/1000 km for h = 100 km) and have comparable amplitude to the first order mode (~ 1.6 db/1000 km). Thus, at the sunrise transition line the second order mode may have an intensity sufficiently high to excite a first order mode (and a second order mode that will be attenuated at the illuminated path) of amplitude high enough to produce interference, at the receiver, with the first order mode excited by the first order mode of the dark path. This model also shows that the fadings will be enhanced when the sunrise transition is nearer the transmitter, a fact that was ascertained by Crombie (1964) and now by the present measurements.

At sunset, the second order mode excited by the first order mode of the illuminated path is greatly attenuated on the part of the path near the receiver, where the bottom level of the E region is low at summer nights (for example, 4 db/1000 km at h = 80 km).

In view of this, it may not be possible to observe sunset fadings at the receiver, close to the southern solstice, a conclusion which is confirmed by our phase measurements. This behavior was also observed by Crombie (1964) in the sunset measurements of the NPM - Boulder path, when it was difficult to observe sunset fadings in summer. However the NPG - São José dos Campos path is transequatorial; then the interfering second order mode must cross a region where the reflection height is low, i.e., high attenuation. Alternatively there are indications that the angle at which the sunrise (sunset) line crosses the path appears to influence the amount of mode conversion at the transition in the

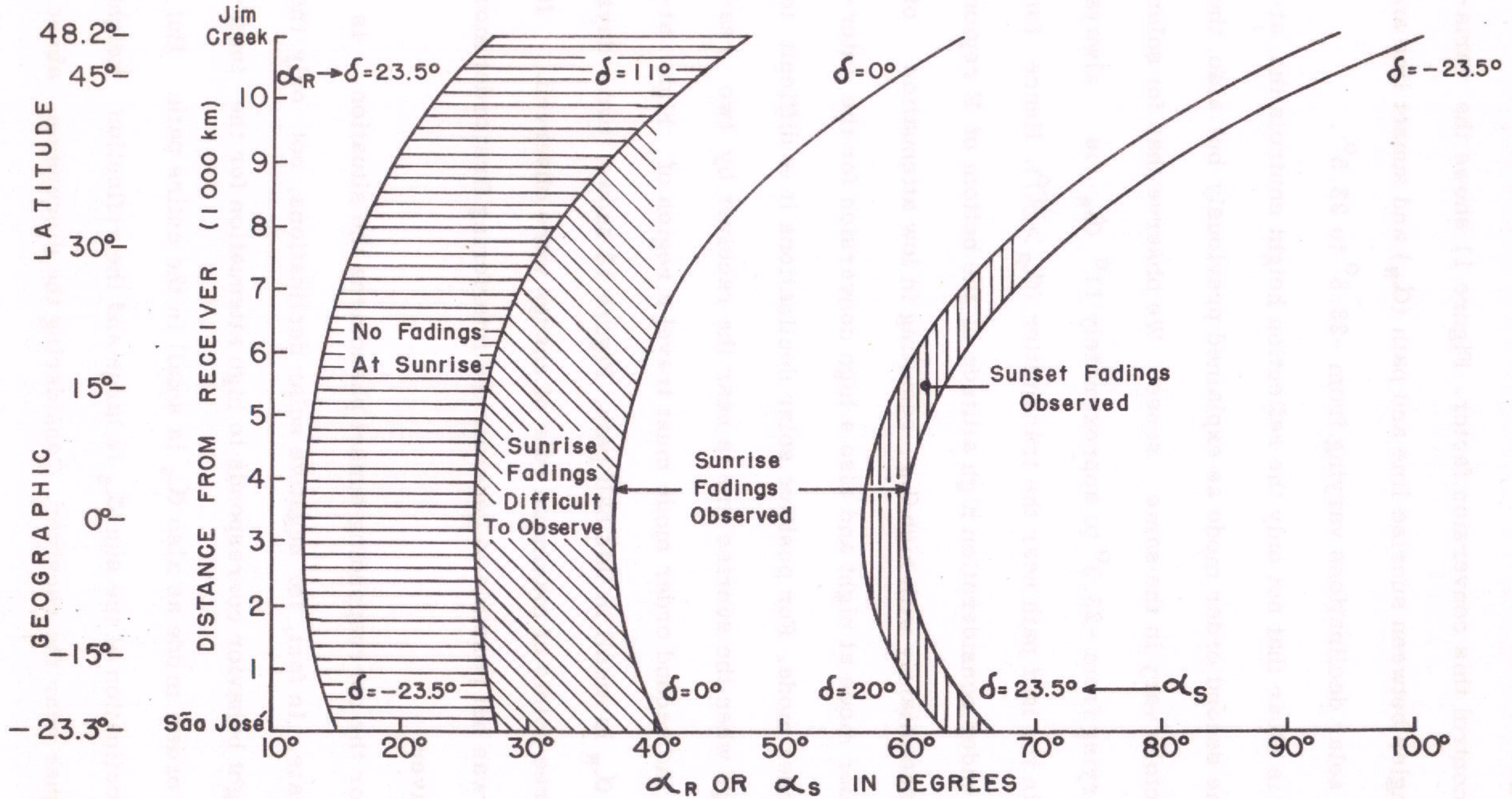

Fig. 11 — Variation of angle between path and sunrise line (α_R) and between path and sunset line (α_S) with solar declination as parameter for a zenith angle of 90°.

waveguide height (Crombie, 1964). Here, there are also evidences that the path may control this conversion factor. Figure 11 shows the variations of the angles between sunrise line and path (α_R) and sunset line and path (α_S) for solar declinations varying from -23.5^o to 23.5^o .

It is clear that not only the reflection height controls the attenuation of the second order mode as explained previously but also the conversion factors vary in the same sense . We observe that for solar declination varying from -23.5^o to approximately 11^o α_R is always large mainly in the half path near the transmitter ($\alpha_R > 30^o$). Hence for the geometry under consideration high altitude of the bottom of E region is attained concomitantly with high α_R , resulting in low attenuation of the second order mode at night and also a high conversion for the interfering first order mode. For positive solar declinations it is difficult to observe fadings when the sunrise line is near the receiver by two reasons, namely the second order mode must travel a region of high attenuation and α_R is small in this half path. Figure 12 shows two days where only three points of maximum rate of change were observed. It seems that it was not possible to generate the interfering first order mode near the receiver.

For the corresponding sunset phenomena the situation is more complicate. In fact, for negative solar declinations, not only the reflection height behavior corresponds to high attenuation for the interfering second order mode as also α_S is small in the entire path. But, for positive declination of the sun α_S is large and the reflection height at night is higher near the receiver. Considering the discussion above

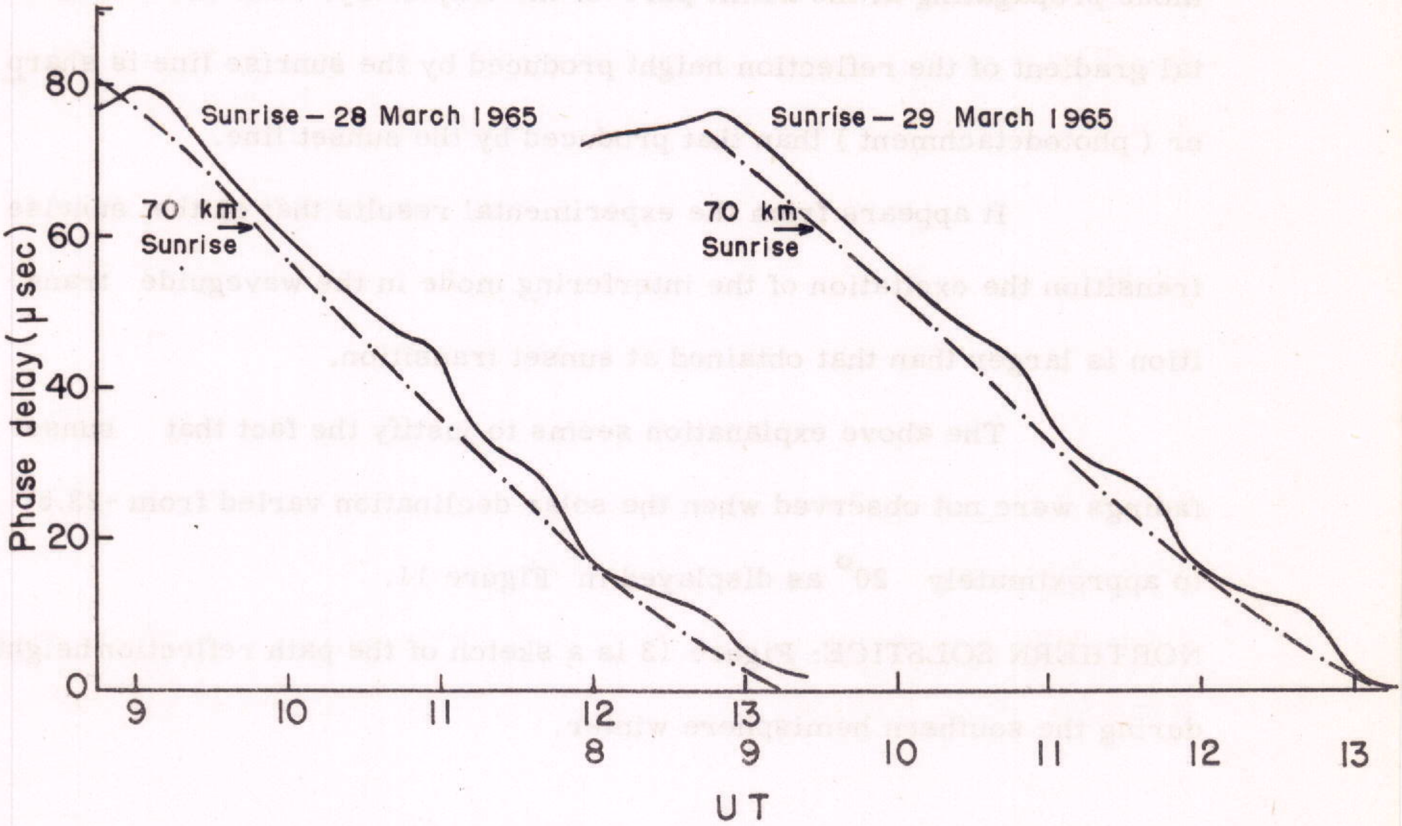

Fig. 12 — Illustration of sunrise phase patern for 4° solar declination.

one may conclude that after March it should be possible to observe sunset fadings. However the mode generation phenomena of the two types of fadings are different because sunrise fadings are generated by the second order mode excited directly by the transmitter and the sunset fadings are generated at the sunset point transition by the wave of the first order mode propagating at the sunlit part of the trajectory. Also the horizontal gradient of the reflection height produced by the sunrise line is sharper (photodetachment) than that produced by the sunset line.

It appears from the experimental results that on the sunrise transition the excitation of the interfering mode in the waveguide transition is larger than that obtained at sunset transition.

The above explanation seems to justify the fact that sunset fadings were not observed when the solar declination varied from -23.5^{o} to approximately 20^{o} as displayed in Figure 11.

NORTHERN SOLSTICE: Figure 13 is a sketch of the path reflection height during the southern hemisphere winter.

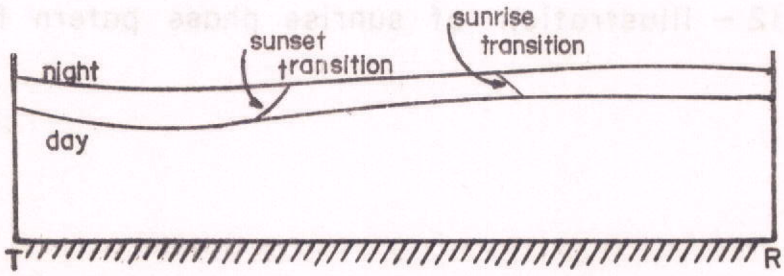

Fig. 13 – Sketch of the path reflection height during the southern hemisphere winter.

Still considering sunrise effects it is known that the reflection height at night near the transmitter is lower (bottom of E region in northern hemisphere summer) than the previous case, and second order mode will travel along a region of low reflection height near the transmitter, suffering high attenuation. This is concomitant with low values of α_R which is associated with low conversion factors. These conditions imply in low excitations level of the interfering first order mode in the illuminated path and may account for the absence of fadings in the observations at sunrise, as we have verified. At sunset the second order mode excited by the first order mode of the illuminated path may propagate with low attenuation only near the receiver (high bottom level of E region in the winter of the southern hemisphere). Also α_S is large in the entire path ($\alpha_S > 56°$). This will imply in fadings occuring only when the sunset transition is near the receiver if the attenuation were the main controlling factor of the process. This is in agreement with the experimental observations.

The previous discussion shows that it is possible to exist a time period where the interfering modes are so negligible that fadings are not recorded. This occurs in the NPG-São José dos Campos path. The seasonal asymmetry in the epochs where fadings are observable or non-observable appear to be the result of a compromise between attenuation (reflection height and geomagnetic field along the path) and α_R or α_S along the path.

These points require further investigations.

5. Conclusions

From two years (IQSY) of phase measurements on VLF transmissions in a northwest-southeast transequatorial path (Jim Creek - São José dos Campos), the following features are noted:

1. The diurnal signal phase variation presents an average time shift delay of about 80 μs.

2. Observations of six solar flares of distinguishable importances lead to the value of $5.0 \times 10^{-4} s^{-1}$ for $\alpha_{eff} N_2$. This number agrees very well with the corresponding value of the effective recombination coefficient at a height of 70 km encountered in the literature.

3. The behavior of the phase rate of change during sunrise and sunset have the following characteristics :

a. It presents up to five points of maximum during sunrise ;

b. It is difficult to observe sunrise maxima in phase rate caused by mode interference generated near the receiver for positive solar declinations;

c. The points of maximum referred above literaly disappear in the winter of the southern hemisphere;

d. Sunset points of maximum phase rate of change are observed only in the winter of the southern hemisphere ($\delta > +20^o$) and with less intensity;

e. Only sunset phase rate maxima generated near the receiver are observed;

f. There are two seasonal regions when sunrise and sunset phase rate maxima are not observables.

4. An explanation of these experimental results concerning the patterns for phase rate of change is given as follow . It is suggested that the night reflection height of the path is a strong controlling factor of the second order mode propagation. There is evidence that the conversion factor at the sunrise (or sunset) line is also controlled by the angle between the sunrise (or sunset) line and the transmitter-receiver great circle path. The possibility of observing the presence or absence of the mentioned patterns during sunrise (or sunset) appear to be a compromise between attenuation (reflection height and geomagnetic field along the path) and the angles referred above. The seasonal variations in the reflection height at night appear to be larger than the values encountered in the literature at present.

Undoubtelly, further investigations is needed for the explanation of the details of the modes conversion at the shadow line.

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6. References

Bates, H. F., and P. R. Albee (1965), General VLF phase variations observed at College, Alaska, J. Geophys. Res., 70 (9), 2187-2208.

Bracewell, R. N., K. G. Budden, J. A. Ratcliffe, T. W. Straker, and K. Weekes (1951), The ionospheric propagation of low and very low frequency radio waves over distances less than 1000 km. Proc. IEE London, 98, part 3, 221-236 .

Brady, A. H., and D. D. Crombie (1964), Calculation of sunrise and sunset times at ionospheric heights along a great circle path. NBS Technical Note nº 209 .

Budden, K. G. (1951), The reflection of very low frequency radio waves at the surface of a sharply bounded ionosphere with superimposed magnetic field. Phil. Mag. 42, 833-850 .

Crombie, D. D. (1964), Periodic Fadings of VLF signals received over long paths during sunrise and sunset. Radio Sci. 68 D (1), 27-34 .

Mitra, A. P., and R. E. Jones (1954) Recombination in the lower ionosphere - J. Geophys. Res., 59, 391- 406 .

Nicolet, M., and A. C. Aikin (1960) The formation of the D region of the ionosphere - J. Geophys. Res. 65, 1469-1483 .

Parkinson, R. W. (1956), The nighttime lower ionosphere as deduced from theoretical and experimental study of coupling phenomena, J. Atmosph. Terrestr. Phys. 1, 203-234 .

Pierce, J. A. (1955), The diurnal carrier-phase variation of a 16 Kc/s transatlantic signal. Proc. IRE, 43, 584-588.

Pierce, J.A. (1956), VLF phase shifts associated with the disturbances of February 23, 1956. J. Geophys. Res. 61, 475-483.

Pierce, J.A. (1957), Intercontinental frequency comparison by very low frequency radio transmission - Proc. IRE, 45 (6), 794-803.

Wait, J.R. (1962), Electromagnetic waves in stratified media - Chapters 6, 7 and 9. The Macmillan Co. - N.Y.

Wait, J.R. (1963a) A note on diurnal phase changes of very-low - frequency waves for long paths. J. Geophys. Res. 68 (1), 338-340.

Wait, J.R. (1963b) VLF propagation in the earth-ionosphere waveguide of non-uniform width. The ionosphere, Institute of Physics and the Physical Society, London, pp. 446.

Westfall, W.D. (1961), Prediction of VLF diurnal phase changes and solar flare effect, J. Geophys. Res. 66 (9), 2733-2736.

7. Additional References

Barber, N.F., and D.D. Crombie (1959), VLF reflections from the ionosphere in the presence of a transverse magnetic field. J. Atmosph. Terrestr. Phys. 16, 37.

Budden, K.G. (1961), The wave guide mode theory of wave propagation. Logos. Press, London, and Prentice Hall, Englewood Cliffs, N.J.

Chilton, C.J., D.D. Crombie, and A. G. Jean. (1964), Phase variations in VLF propagation. AGAR Dograph 74, edited by W. T. Blackband , pp. 275-296, Pergamon Press, London.

Chilton, C.J., F.K. Steele, and R.B. Norton (1963), VLF phase observations of solar flares ionization in the D region of the ionosphere. J. Geophys. Res., 68 (19), 5421-5435.

Chilton, C. J., A. H. Diede and, S. M. Radicella (1964), Transequatorial reception of a very-low-frequency transmission. J. Geophys. Res. 69 (7), 1319-1329.

Crombie, D. D., and H. L. Rath (1964), Reserval of the diurnal phase variations of GBR (16 Kc/s) observed over a path of 720 km. J. Geophys. Res., 69 (23), 5023-5027.

Crombie, D. D., A. H. Allan, and M. Newman (1958) Phase variations of 16 Kc/s transmission from Rugby as received in New Zealand Proc. IEE B. 301-304.

Crombie, D. D. (1958) Differences between the east-west and west-east propagation of VLF signals over long distances. J. Atmosph. Terrestr. Phys., 12, 110-117.

Johler, J. R. (1961), Magneto-ionic propagation phenomena in low and very low radio frequency waves reflected by ionosphere. J. Res., NBS 65 D, nº 1, 53-66.

Sechrist, C. F. (1962), VLF phase perturbations observed during geomagnetic storms. J. Geophys. Res., 67 (4), 1685-1686.

Straker, T. W. (1955), The ionospheric propagation of radio waves of frequency 16 Kc/s over short distances. Proc. IEE 102 C, 122-133.

Wait, J. R. (1964), On phase changes in very-low frequency propagation induced by an ionospheric depression of finite extent. J. Geophys. Res., 69 (3), 441-445.

Wait, J. R. (1962), Excitation of modes at VLF in the earth-ionosphere wave guide. J. Geophys. Res., 67 (10), 3823-3828.

Whitten, R. C., and J. G. Poppoff (1961), A model of solar flare induced ionization in the D region. J. Geophys. Res., 66 (10) 2779 - 2786 .