A STUDY OF PHASE FADING OF IONOSPHERIC REFLECTIONS

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Summary

Pulsed $2 \cdot 28$ Mc/s radio waves were transmitted and measurements were made on the first-hop, vertically-incident reflections from the ionosphere. A method of continuously recording the changes of phase difference between the signals at two aerials is described. The general features of the records are described and it is shown that the quasi-periodic type of fading can be explained in terms of two component rays being reflected from two reflecting areas of the ionosphere and interfering at the receiving aerials. The horizontal separation of the two regions is about 50 km in the case analysed. The direction of arrival of the radio waves, the velocity of the amplitude pattern over the ground, and the statistical distribution of the phase difference are also discussed for this type of fading.

I. INTRODUCTION

If the amplitude of one of the magneto-ionic components of a radio wave reflected from a region of the ionosphere is observed at the ground it is found to " fade ", i.e. the amplitude and phase appear to vary in a random manner. This phenomenon can be interpreted as due to the movement across the ground of a pattern of phase and amplitude, and this movement has been related to the movement of the ionosphere (Pawsey 1935 ; Mitra 1949). Much work has been done in attempting to account for the various features of the pattern by considering a diffraction mechanism involving small-scale irregularities of electron densities in the ionosphere. This aspect of the work has been reviewed by Ratcliffe (1956).

Investigations along these lines have been confined almost entirely to considerations of the amplitude fluctuations. However, Bramley (1951, 1955) and Bramley and Ross (1951) have made some measurements of the phase difference between the signals at two aerials in order to study direction-of-arrival phenomena and the angular spread of the components of the echo.

The present paper describes a method for obtaining a continuous record of the phase differences between the signals at two pairs of aerials, discusses some features of the records obtained, and suggests an explanation of some of these features, with special reference to the quasi-periodic type of fading.

II. EQUIPMENT

(*a*) *General Principle*

The equipment used was installed at Brisbane (geomagnetic latitude $35 \cdot 7°$ S.). The transmitter provided a mains-locked pulse of $2 \cdot 28$ Mc/s radio waves of about 100 μs duration and a pulse repetition frequency of 50 c/s. The receiving

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system was located at the same site so that only vertically- or almost vertically-reflected waves from the ionosphere were received. Three crossed-loop, circularly-polarized aerials were used for reception of the echoes and these were situated at three corners of a square, of sides 100 m, oriented in geographic N.-S. and E.-W. directions. The three aerials will be referred to as the O-, E-, and N-aerials.

In the measurement of phase difference, the phase of the signal received at the O-aerial was used as a reference and this was compared with the phase of the signals at the E- and N-aerials respectively. The general layout of the equipment used for this measurement is presented in simplified form, in Figure 1,

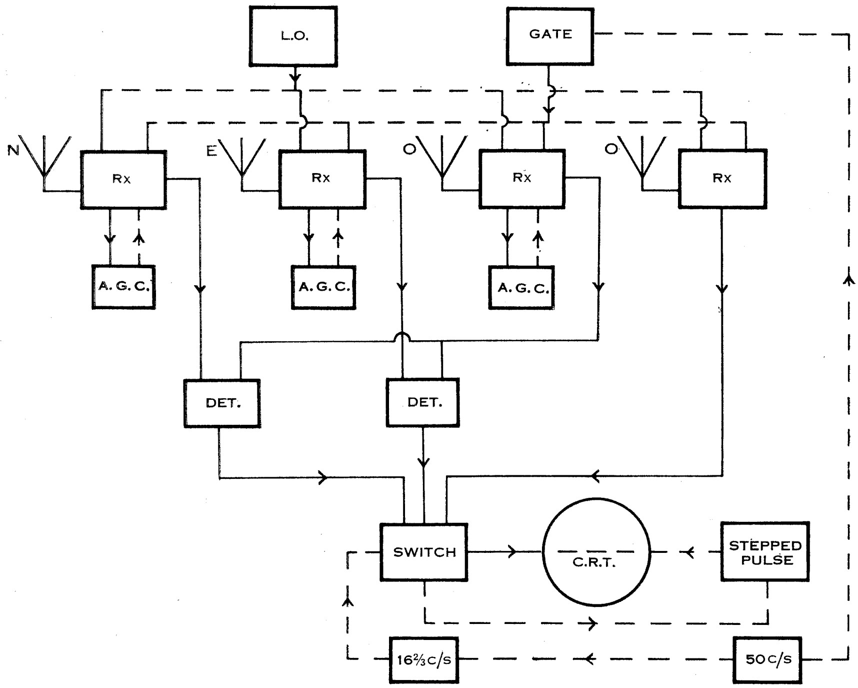


Fig. 1.—Block diagram of the equipment used in the measurement of phase differences.

where the full lines are the paths of the signals under test and the dashed lines are the paths of internally-generated synchronizing signals etc. The negative-going edge of a mains-locked 50 c/s control square wave was used to synchronize the various units.

The equipment was manually operated and all observations were made on the ordinary magneto-ionic component of the first-hop, vertically-reflected signals from the F region of the ionosphere.

(*b*) *Receivers*

Three receivers were used in the measurement of phase difference. A common local oscillator fed all three mixing stages, so that the relative phases of the signals were preserved through the receivers. A variable-delay, variablewidth " gate " was applied to the intermediate-frequency (i.f.) stages, so that only the desired echo appeared at the outputs of the receivers. Automatic gain control (A.G.C.) was applied to the i.f. stages. This had a time constant of 0·5 s; thus the i.f. outputs of the receivers were maintained at a steady and equal level, except in the case of very rapid fading.

(c) *Phase Detectors*

A phase detector consisted essentially of a simple adding circuit, giving an (i.f.) output, the amplitude of which depended only on the phase difference between the two signals at the input. The situation is represented in vector form in Figure 2. It can be seen that the same amplitude will be recorded for phase differences of $\pm\varphi$ and that an output is obtained which does not have a linear relationship with the phase difference, the scale being compressed about $\varphi=0$. The equipment was adjusted so that when the signals at the aerials were

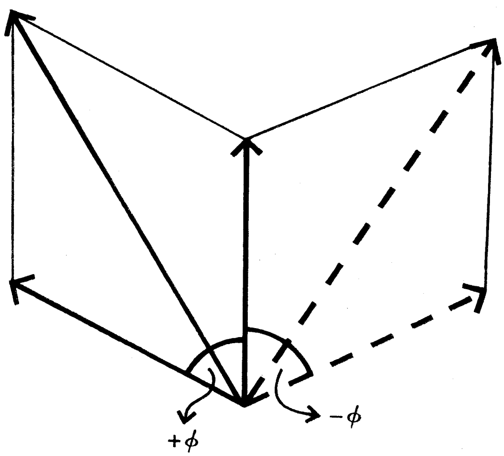


Fig. 2.—The addition of two vectors of equal magnitude.

in phase there existed a phase difference of about 90° at the inputs to the phase detector. This had the effect of reducing the ambiguities to a minimum and almost maximizing the sensitivity of the equipment to small changes in phase difference.

The output of the phase detector was rectified and amplified to give a negative video pulse.

No attempt was made to obtain absolute phase differences, as these were not required for the purpose of this investigation.

(d) *Display and Recording*

Provision was made to record the rectified signal amplitude at the O-aerial. This and the two phase difference outputs were displayed simultaneously by the deflection of three spots on one C.R.T. face. The zero positions of the spots were adjusted by applying a 16·67 c/s stepped-voltage to one of the horizontal deflecting plates; the video pulses, which were switched on synchronously using an electronic switch, were applied to the other horizontal deflecting plate. A camera recorded the resulting trace on moving film, the effective velocity across the C.R.T. face being 3·7 cm/min.

(e) *Calibration*

The equipment was calibrated by setting up a small portable transmitter at a number of points, calculated to provide phase differences at 20 deg intervals, between each pair of loops (single loops used). The calibration curve thus obtained was found to depart only very slightly from the theoretical. The appropriate corrections were applied throughout the investigation.

(f) *Limitations of Equipment*

As has already been pointed out, the phase equipment was not suitable for recording with a signal which was fading rapidly (say, with a quasi-period less than about 2 s). Also, it was only useful when the signal was in the form of a discrete pulse. If the echo was subject to spreading or if two echoes differed in virtual range by less than the pulse length then it was impossible to record satisfactorily as the resultant trace was too confused to interpret. Further, the signal-to-noise ratio had to be reasonably high. For low values of this ratio the A.G.C. responded to the noise and hence constant signal amplitude was not maintained. Because of these limitations, records could normally be taken only during the later afternoon and night-time hours.

(g) *Accuracy*

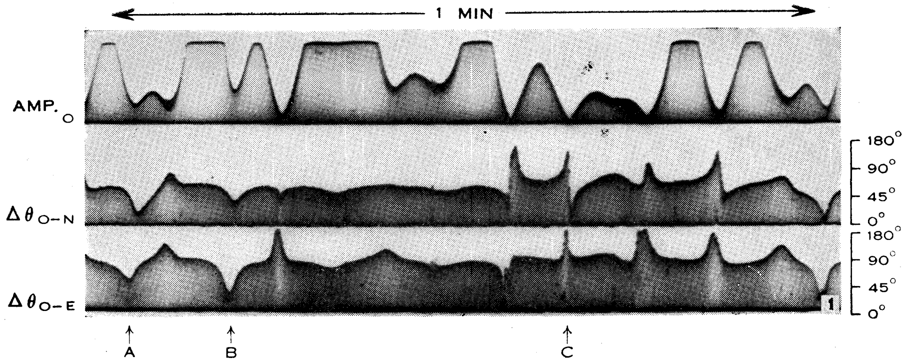
For the measurements made in this investigation site errors of the type considered by Ross, Bramley, and Ashwell (1951) were negligible as only vertically- or almost vertically-incident radiation was received. The most important sources of error were those due to the electronic limitations of the equipment; e.g. as the A.G.C. changes the gain of a stage, the input impedance also changes (Miller effect), and this in turn produces a slight variation in the change in phase through this stage. From tests made, under all fading conditions, while two receivers were connected to a common aerial, it was concluded that any effect due to the design of the equipment did not seriously reduce the accuracy of the measurements.

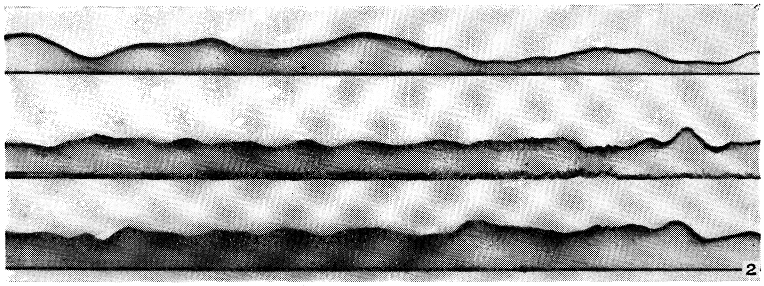
Taking the film reading resolution into account, it was considered that changes in phase difference could, on most occasions, be measured with a maximum error of $\pm 5°$.

(h) *Amplitude Comparisons*

Equipment was also available (Burke 1957) which would record the amplitudes of the signals at the O-, E-, and N-aerials thus enabling the relative time shifts of the amplitude patterns to be obtained. These records were taken simultaneously with all phase records. These records will be referred to as the amplitude-fading records in contrast to the phase-fading records discussed under (*d*) above.

PHASE-FADING OF IONOSPHERIC REFLECTIONS





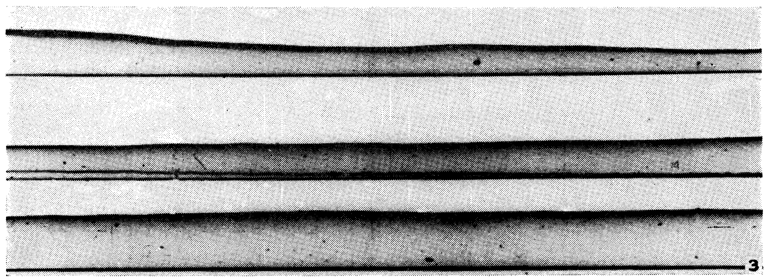


Fig. 1.—A phase-fading record taken during a period of quasi-periodic amplitude fading on November 10, 1960. The scales do not represent absolute values of phase difference.

Fig. 2.—A phase-fading record taken during a period of irregular amplitude fading.

Fig. 3.—A phase-fading record taken during a period of slow amplitude fading.

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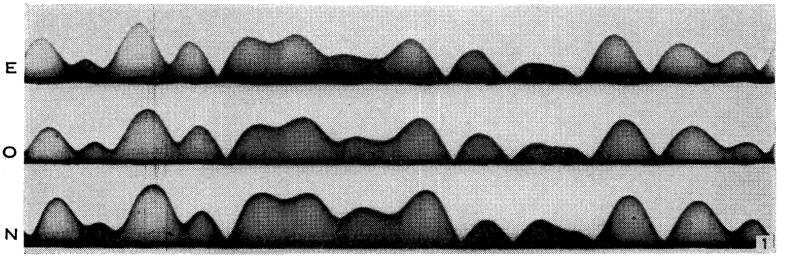

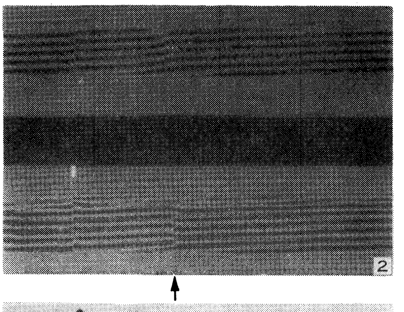

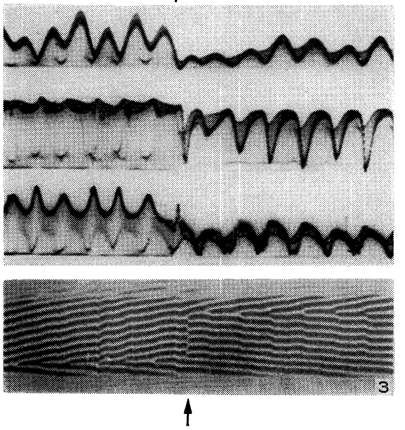

Fig. 1.—The amplitude record taken at the same time as the phase-fading record of Plate 1, Figure 1.

Fig. 2.—A phase-path record taken simultaneously at two aerials during a period of quasi-periodic amplitude fading.

Fig. 3.—A phase-path record and a phase-fading record taken simultaneously.

(i) *Phase-path Records*

On some occasions, it was necessary to record the changes in phase path (McNicol and Thomas 1960) of the received echo. Equipment, constructed by those workers and described in McNicol and Thomas' paper, was available for these measurements. The time-base of the C.R.O. used for phase-path recording was triggered just prior to the reception of the echo so that greater resolution could be obtained in reading changes of group height.

III. Results

(a) *General Appearance of Records*

Typical phase-fading records are shown in Plate 1, Figures 1, 2, and 3. Plate 2, Figure 1, shows the amplitude-fading record taken simultaneously with the phase-fading record of Plate 1, Figure 1.

The following is a list of the main features that were observed:

(i) Large rapid changes in phase difference as indicated, for example, at points A and B in Plate 1, Figure 1. These only occurred when the incoming signal amplitude was passing through a minimum; the deeper the minimum the greater the phase changes.

(ii) The feature indicated at point C in the $\Delta\theta_{O-N}$ trace of Plate 1, Figure 1. This only occurred for a very deep minimum of amplitude. The phase-detector output rose to the maximum value, dropped quickly to zero, and then recovered to the steady reading value. At the minimum preceding that marked C the same type of behaviour occurred but in the reverse sense.

(iii) Slow phase changes: If there was little or no amplitude fading then the phase difference was found to change over a period of minutes, or tens of minutes, by values up to 10°. When the amplitude fading was more rapid these slow changes still existed but they were much larger with values up to about 40°.

(iv) The type of phase fading that was recorded depended on the type of amplitude fading that was occurring at the time. The rapid phase changes which were associated with amplitude minima occurred at times when the amplitude fading was the quasi-periodic type (as in Plate 1, Fig. 1) with a quasi-period of about 2 to 20 s. On the other hand, when the amplitude fading was irregular, as in Plate 1, Figure 2, there appeared to be little, or no correspondence between the phase fading and the amplitude fading. Also, in this case, there appeared to be little correspondence between the two phase-fading patterns. Also, many other types of fading intermediate between these two could be identified on the records.

These general features are consistent with those obtained by Bramley and Ross (1951).

(b) *Phase Path*

Plate 2, Figure 2, shows phase-path records obtained simultaneously at two aerials while a phase-fading record was also being taken. When large rapid changes in phase difference (of the type described in (a) (i) above) were observed, then the phase paths recorded at the two aerials showed sudden changes in the same direction. However, when the feature described in (*a*) (ii) occurred then the sudden changes in phase path were in opposite directions. Plate 2, Figure 2, shows an example of this latter occurrence at the time indicated.

Plate 2, Figure 3, shows the phase-path record taken at one aerial when the corresponding amplitude fading was particularly rapid.

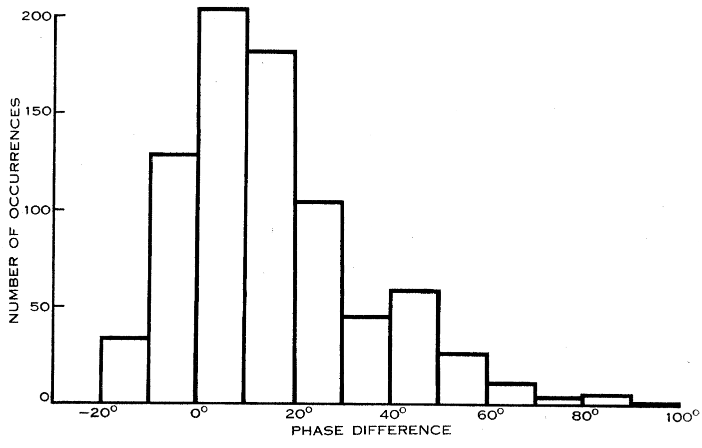

Fig. 3.—Distribution of phase differences during the period 1800–1920 on July 27, 1960.

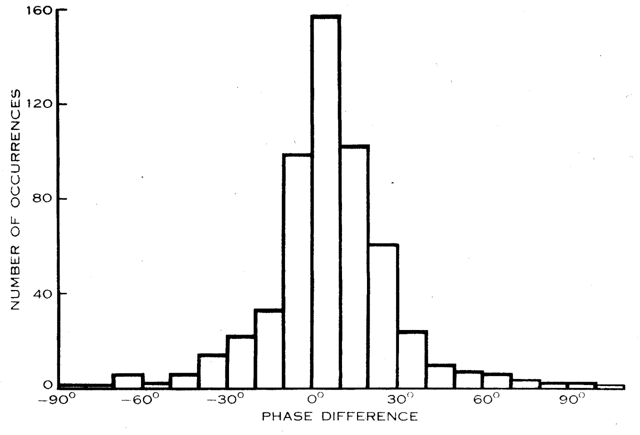

Fig. 4.—Distribution of phase differences during the period 2125–2250 on November 10, 1960.

(*c*) *Distribution of Phase Difference*

Figures 3 and 4 show histograms of the distribution of phase difference of the *F*-region signals at two aerials at times when they were fading in a quasi-periodic fashion. In these two histograms the phase-difference scales are arbitrary and the values marked do not give absolute values of phase difference. It is seen that the distribution in Figure 3 is asymmetric while in Figure 4 the histogram is symmetric about the mean value.

(*d*) *Direction of Arrival*

If a single downcoming ray comes from a direction in space defined by the azimuth angle, δ, and zenith angle, θ, then by rearranging the relationships given by Thomas and McNicol (1955) we get

$$\tan \delta = \frac{\Delta\theta_{O-E}}{\Delta\theta_{O-N}},$$

$$\sin^2 \theta = \left(\frac{\lambda}{2\pi d}\right)^2 \{\Delta\theta^2_{O-E} + \Delta\theta^2_{O-N}\},$$

where $\Delta\theta_{O-E}$ and $\Delta\theta_{O-N}$ are the phase differences introduced between the signals at the aerials indicated.

If it is assumed that the slow phase changes described in (*a*) (iii) are associated with the direction of arrival of the radio waves then it is possible to obtain information about the azimuth and zenith angles involved. It was first necessary to find the level of the phase-fading pattern that corresponded to zero

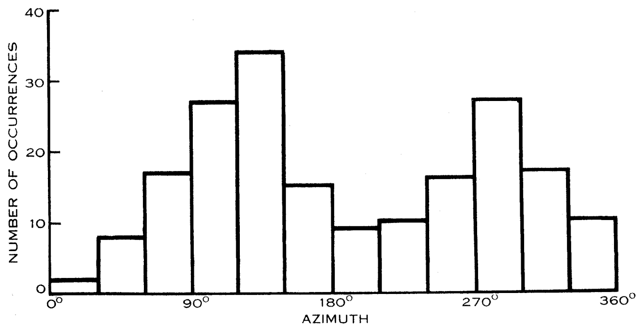

Fig. 5.—Distribution of the azimuth angles of arrival from the *F* region during the period 2125–2250 on November 10, 1960.

phase difference between the signals at the two aerials. This was done by taking a large number of readings from the records of the appropriate night and the mean value of these readings was taken as indicating zero phase difference. This assumed that, on the average, the rays were reflected from vertically overhead.

Directions of arrival have been calculated on this basis for the night of November 10, 1960, during times when the fading was quasi-periodic. The records were read in the manner to be described in Section IV (*c*). A histogram showing the distribution of the azimuth angles of the *F*-region echo is given in Figure 5, and that for the zenith angles in the same period in Figure 6. Although there were ambiguities in measuring the directions of arrival, the method of recording was such that either all the azimuth angles are shown in their correct position in Figure 5 or they are all in error by 180°.

(*e*) *Direction of Drift of the Amplitude Pattern*

The direction of drift of the *F*-region amplitude-fading pattern was also calculated from the amplitude records for the same period as the direction of arrival results. The distribution of the direction of drift is shown in Figure 7. Note that the histograms for azimuth angles and directions of drift both show peaks at 120°.

(*f*) *Changes in Phase and Group Height*

It is well known that if the phase height and the group height are observed to change in the same direction then this represents a change in the true path length of the radio wave, whereas if the changes are opposite in sign then this represents an appearance or disappearance of ionization below the reflecting region. In this way it was usually possible to recognize the passing overhead of a large-scale irregularity in the reflecting surface.

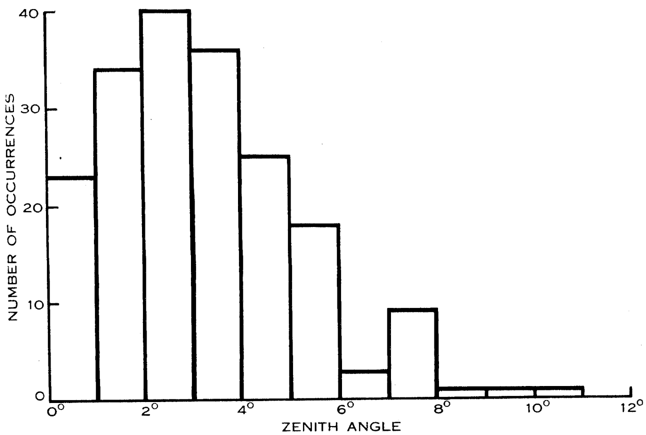

Fig. 6.—Distribution of the zenithal angles of arrival for the same period as in Figure 5.

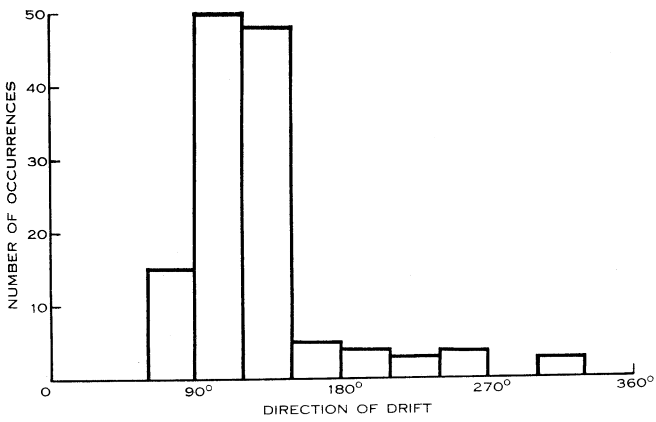

Fig. 7.—Distribution of the directions of drift of the amplitude pattern for the same period as in Figure 5.

Figures 8 and 9 show tracings of the changes in phase height and group height on May 15 and July 1, 1961. Also indicated on these two diagrams are the times when quasi-periodic fading occurred. It can be seen from the figures, and this is generally characteristic, that quasi-periodic fading tended to occur at times when the passage of a large-scale irregularity also occurred. However, it can also be seen that there are times (e.g. 2020 May 15, 1961) when such an irregularity appeared to pass overhead and quasi-periodic fading did not occur, and also there were a few occasions (none shown here) when this type of fading occurred, apparently without the presence of an irregularity.

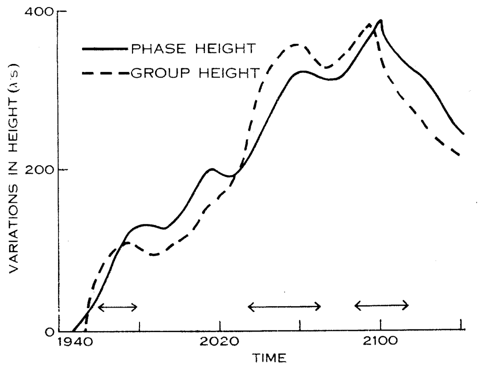

Fig. 8.—Changes in phase and group height on May 15, 1961.

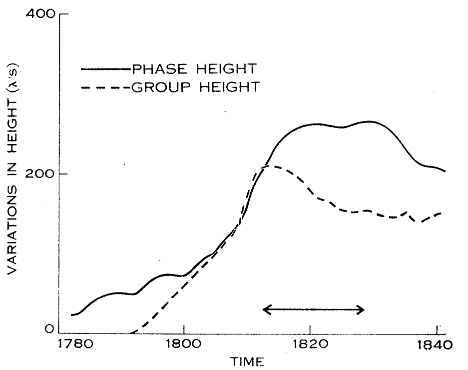

Fig. 9.—Changes in phase and group height on July 1, 1961.

IV. Interpretation

(a) *Rapid Phase Changes*

It is suggested that the quasi-periodic amplitude fading, and the associated phase changes, are due to the interference, at the aerials, between two rays reflected from horizontally displaced parts of the ionosphere.

An expression giving the magnitudes of the rapid changes in phase difference will first be derived. If two signals of the same frequency but different amplitudes, A and B, and phases α and β, are received simultaneously at an aerial, the resultant has amplitude C and phase γ, where

$$C \cos (\omega t+\gamma)=A \cos (\omega t+\alpha)+B \cos (\omega t+\beta).$$

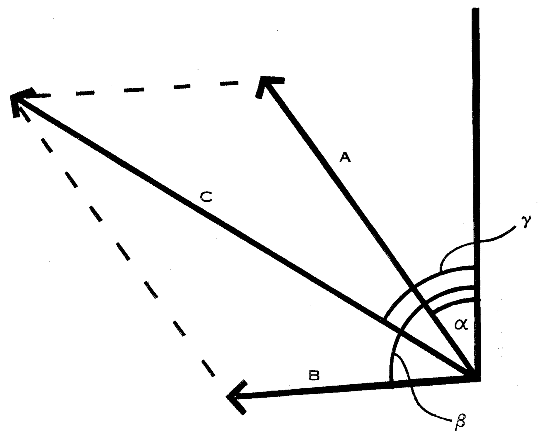

Fig. 10.—The addition of two independently rotating vectors.

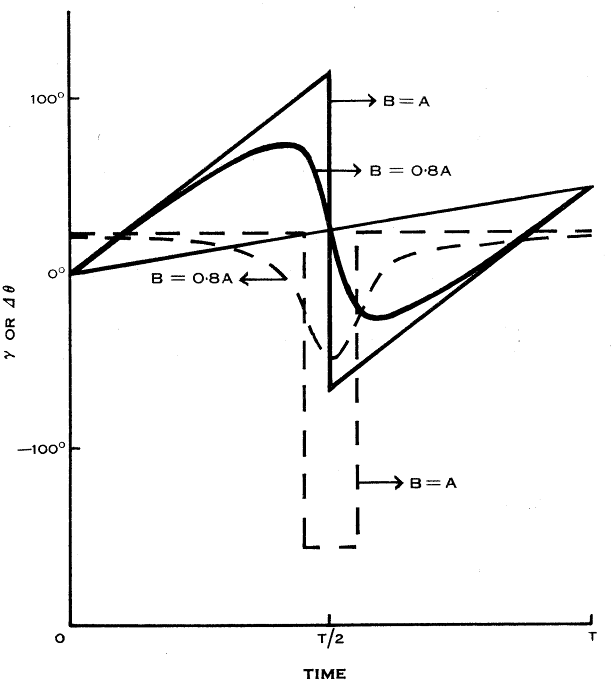

Fig. 11.—Phase v. time characteristics of equation (1) for various values of r.

The phases α, β, and γ are defined with respect to some arbitrary reference as shown in Figure 10. If α and β vary linearly at different rates k_1 and k_2 respectively, then, if $t=0$ when the phases are equal, it is easily shown that

$$\gamma = k_1 t \pm \cos^{-1}\left\{\left(1+r\cos\frac{2\pi t}{T}\right)\Big/\left(1+r^2+2r\cos\frac{2\pi t}{T}\right)^{\frac{1}{2}}\right\}, \tag{1}$$

where $r=B/A$ and $T=2\pi/(k_2-k_1)$.

In Figure 11, γ is plotted against t for values of r of $0\cdot8$ and $1\cdot0$. Since the two components cannot be identified separately we are at liberty to choose A, and hence k_1, to represent always the larger component. Thus values of r greater than unity need be considered only in special cases.

A mechanism which will produce two signals varying in phase in the required manner is reflection from two plane ionospheric facets, at approximately the same distance from the receiving station, but at different azimuths, both moving with the same horizontal velocity. The radial components of velocity, which determine k_1 and k_2, are (in general) different in the two cases. If we thus picture an ionosphere moving bodily, but retaining its configuration, it is clear that the phase of the resultant signal at the N-aerial must vary in the same manner as that at the O-aerial, save for a time displacement, τ, which is related to the space displacement, d, of the aerials by

$$\tau = d/v_N,$$

where v_N is the N.-S. component of the velocity, v, of the amplitude pattern, i.e. twice the velocity of the ionosphere (Pawsey 1935).

The phase difference which should be observed between the N- and O-aerials may thus be calculated from

$$\Delta\theta = \gamma(t+\tfrac{1}{2}\tau) - \gamma(t-\tfrac{1}{2}\tau).$$

The dotted lines in Figure 11 show $\Delta\theta$ as a function of t for $\tau=T/10$. It will be seen that $\Delta\theta$ will be maximal or minimal for $t=0$ and $t=\frac{1}{2}T$. We shall compute $\Delta\theta$ for these values only, obtaining respectively

$$\Delta\theta' = k_1\tau + 2\cos^{-1}\left\{\frac{1+r\cos\pi a}{(1+r^2+2r\cos\pi a)^{\frac{1}{2}}}\right\}, \tag{2}$$

and

$$\Delta\theta'' = k_1\tau - 2\cos^{-1}\left\{\frac{1-r\cos\pi a}{(1+r^2-2r\cos\pi a)^{\frac{1}{2}}}\right\}, \tag{3}$$

where $a=\tau/T$.

Thus we should expect the extreme excursions shown on the phase records to amount to

$$\Delta\theta' - \Delta\theta'' = 2\cos^{-1}\left\{\frac{1+r\cos\pi a}{(1+r^2+2r\cos\pi a)^{\frac{1}{2}}}\right\} + 2\cos^{-1}\left\{\frac{1-r\cos\pi a}{(1+r^2-2r\cos\pi a)^{\frac{1}{2}}}\right\}. \tag{4}$$

A check on this hypothesis may be made by deducing values of r and a from the amplitude-fading records, and hence calculating $\Delta\theta' - \Delta\theta''$ for comparison with values actually found. T, the quasi-period of the fading, was taken as the time between the two maxima on either side of the minimum in question. τ was the time shift between the two appropriate amplitude patterns. To find the ratio, r, the amplitude of the minimum, s, was found and the mean of the amplitudes of the two maxima on either side of the minimum, t. Then $r=(t-s)/(t+s)$.

The results of the check are summarized in graphical form in Figure 12. Of the 320 calculated values, 282 were within 20° of the observed values. This was considered to be a satisfactory agreement as the accuracy in determining r and a was not very high. For example, the time shift, τ, could normally only be found with an accuracy of 0·1 or 0·2 s. It was often found that the calculated value differed greatly from the observed value when τ was small, or when it was difficult to determine accurately.

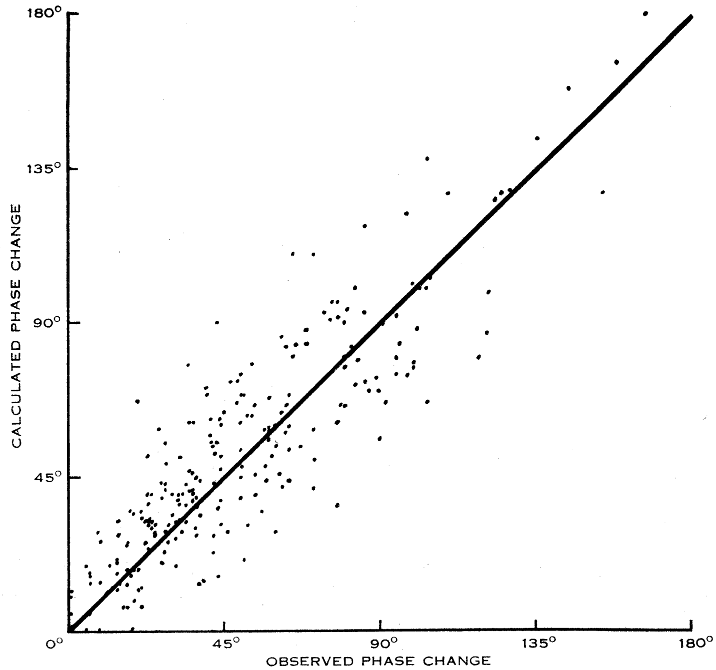

Fig. 12.—Comparison of observed and calculated values of changes in phase difference.

The theory given so far explains most of the rapid phase-difference fluctuations indicated in Plate 1, Figure 1, but not the type of fluctuation exemplified by the $\Delta\theta_{O-N}$ trace at C. For this, it is suggested that the relative amplitudes of the two components are not the same for the two aerials, the ratio, r, being slightly less than unity at O and slightly greater than unity at N. In Figure 13, curve A, i.e. $\gamma_1(t)$, refers to $r=0\cdot 9$ and curve B, i.e. $\gamma_2(t)$, to $r=1\cdot 1$. The function $\gamma_1(t+\frac{1}{10}T)-\gamma_2(t-\frac{1}{10}T)$ is represented by curve C. However, equipment limitations would be expected to deform this curve. If the difference in phase lags in the receivers is φ, the correct phase difference will be recorded if $\gamma_1-\gamma_2+\varphi$ lies between 0° and 180°. If it lies between 180° and 360° (i.e. between 0° and −180°) the record indicates, instead, $2\pi-(\gamma_1-\gamma_2+\varphi)\equiv-(\gamma_1-\gamma_2+\varphi)$. Allowing for this, curve C is converted to the form D, for the case $\varphi=40°$. Further deformation occurs on the records due to the non-linearity of the scale.

This also explains the phase-path record shown in Plate 2, Figure 2, where the sudden phase-path changes were in opposite directions at the time of one of these occurrences.

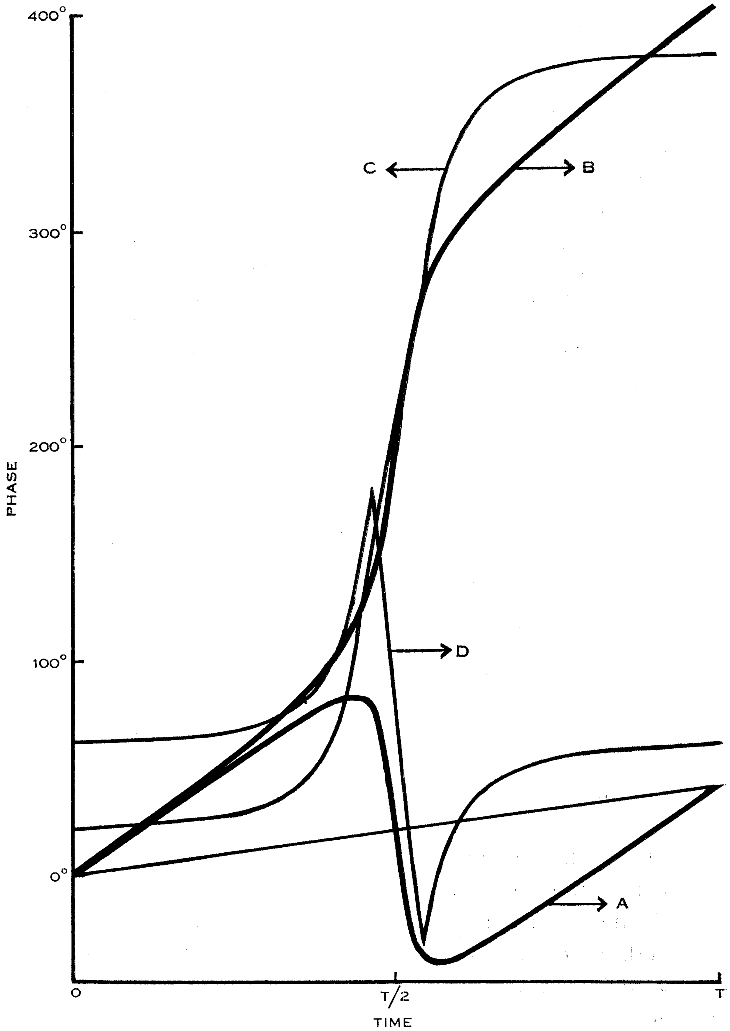

Fig. 13.—Phase *v.* time characteristics when the phase difference changes through 360°.

(*b*) *Distribution of Phase Difference*

The histogram of Figure 3 shows that, for this period on the night of July 27, 1960, most of the rapid changes in phase difference were in one direction. On the other hand, on the night of November 10, 1960 (Fig. 3), as many of the rapid changes were in one direction as were in the other, as is suggested by the portion of the record shown in Plate 1, Figure 1.

Note that if the direction of drift of the amplitude-fading pattern remains the same (or at least towards the same quadrant), then the rapid changes in phase difference will reverse in direction if the amplitude of the B-ray changes from being less than the amplitude of A to greater than A. Thus if the distribution is asymmetric then the implication is that the amplitude of one component is consistently larger than the other, whereas when it is symmetric one component is the larger as often as the other is.

(c) *Direction of Arrival*

It is of interest to determine the directions in space that are indicated at various times by the recorded phase differences. First a time will be chosen when the amplitude pattern has a maximum value, i.e. when A and B are in phase at the receiving point, and this corresponds to the time, $t=0$, in the previous work. As shown in Figure 14, let A and B be reflected from the ionosphere such that on returning to the receiving point, the ray directions make angles θ_1

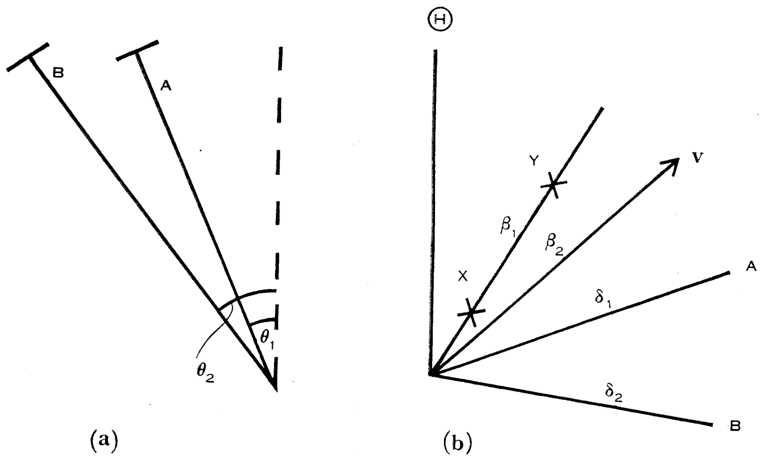

Fig. 14.—Diagrams illustrating the various angles defined in the text.

and θ_2 respectively with the zenith, and angles δ_1 and δ_2 respectively with some arbitrary azimuthal direction, Θ. Also suppose that the line joining a pair of aerials, X and Y, makes an angle β_1 with the direction Θ, and that the distance between the aerials is d. If the direction in space indicated by the phase differences, $\Delta'\theta$ say, at $t=0$ be defined by the zenith and azimuthal angles, θ_3 and δ_3 respectively then

$$\begin{aligned}\Delta'\theta &= \frac{2\pi d}{\lambda}\theta_3 \cos(\delta_3-\beta_1)\\ &= \frac{2\pi d}{\lambda}\theta_1 \cos(\delta_1-\beta_1)+2\Gamma\left[\frac{d}{2\lambda}\left(\theta_2\cos(\delta_2-\beta_1)-\theta_1\cos(\delta_1-\beta_1)\right)\right], \qquad (5)\end{aligned}$$

where the last term is defined by

$$\Gamma[\tfrac{1}{2}a] \equiv \cos^{-1}\left\{\frac{1+r\cos\pi a}{(1+r^2+2r\cos\pi a)^{\frac{1}{2}}}\right\}, \qquad (6)$$

and the approximation $\theta_n \doteqdot \sin\theta_n$ is made, which is not in error by more than 5% in practical cases.

Thus equation (5) shows how the direction in space, defined by the two angles θ_3 and δ_3, or by the phase differences when the two rays A and B are in phase at the receiving point, is related to the direction of arrival of the rays A and B. It can be shown that the phase difference given by equation (5) indicates a direction in space in the plane defined by the rays A and B, but directed between these two rays. Its position with respect to A and B is determined largely by the ratio r.

It has been shown in Section III (d) that the distribution of azimuth angles (Fig. 5) showed peaks at two positions separated by approximately 180°. Further, it is seen from Figure 7 that the distribution of directions of drift of the diffraction pattern also peaks at one of these positions, viz. 120°. Therefore, if this is related to the direction of drift, β_2, of the ionosphere, it seems reasonable to assume that the angles δ_1 and δ_2, and therefore δ_3, and β_2 are, on the average, related by the expression

$$\delta_1=\delta_2+n\pi=\delta_3+n\pi=\beta_2+n\pi,$$

where $n=0$ or 1 in each case.

With this assumption, equation (5) reduces to

$$\pm\frac{2\pi d}{\lambda}\theta_3 \cos(\beta_2-\beta_1)=\pm\frac{2\pi d}{\lambda}\theta_1 \cos(\beta_2-\beta_1)+2\Gamma\left[\frac{d\varphi}{2\lambda}\cos(\beta_2-\beta_1)\right], \qquad (7)$$

where φ is the angle between the two rays.

The mean phase difference over a complete fading cycle will now be considered in order to determine the direction in space given by it. To do this, reference is made to equation (1). The phase difference at any time is given by

$$\begin{aligned}\Delta\theta&=\gamma(t+\tfrac{1}{2}\tau)-\gamma(t-\tfrac{1}{2}\tau)\\&=k_1\tau+\Gamma\left[\frac{t+\frac{1}{2}\tau}{T}\right]-\Gamma\left[\frac{t-\frac{1}{2}\tau}{T}\right],\end{aligned}$$

where τ is the appropriate displacement. The mean phase difference, $\overline{\Delta\theta}$, over a complete cycle is then given by

$$\begin{aligned}\overline{\Delta\theta}&=\frac{1}{T}\int_0^T \Delta\theta \mathrm{d}t\\&=k_1\tau.\end{aligned}$$

By comparing equations (2) and (5), which are both derived for the same instant in time, it can be seen, then, that

$$\overline{\Delta\theta}=\frac{2\pi d}{\lambda}\theta_1(\delta_1-\beta_2).$$

This represents the phase difference introduced at the two aerials by the ray whose direction is defined by the angles θ_1 and δ_1, which, in turn, refer to the larger component. Thus, by averaging the phase difference over a complete cycle, the direction of arrival of the larger component may be computed.

In obtaining the angles of arrival for Figures 5 and 6, then, the mean phase difference over each cycle was taken, thus giving values for the component which had the larger amplitude.

(*d*) *Separation of the Reflecting Regions*

If the ionosphere has a large-scale drift velocity, v, then the rate of change of path length (R_1) of A is given by

$$R_1 = 2v \sin \theta_1 \cos (\delta_1 - \beta_2),$$

and of B

$$R_2 = 2v \sin \theta_2 \cos (\delta_2 - \beta_2).$$

If these two rays interfere at the receiving point then the period of fading, T, is given by

$$T = \frac{\lambda}{R_2 - R_1},$$

where λ is the wavelength.

If the assumptions made in the last section are applied, then

$$T = \lambda / 2v\varphi. \tag{8}$$

An equation similar to equation (8) has been derived by Briggs (1951).

Equations (7) and (8) provide two different methods of determining the angle (φ) between the two rays. Using the results from the night of November 10, 1960 for the F region the mean value of the quasi-period, T (6·55 s), and the mean value of the velocity, v (54 m/s), were taken from the amplitude records. With $\lambda = 131$ m, then the value of φ from equation (8) was 10·6°.

Using equation (7), the mean value of the phase difference was assumed to be zero, i.e. the term on the left-hand side of the equation was zero. The mean value of the zenith angle of the larger component, θ_1, was found to be 3·5° and the mean value of r was 0·506. With $(\beta_1 - \beta_2)$ as 120° (see Fig. 7), φ was calculated to be 10·4°.

The mean value (10·5°) for the angular separation of the two rays corresponds to a lateral separation of about 50 km when the layer height is 300 km, as it was at the time of recording.

(*e*) *Origin of Components*

In an endeavour to find the origin of the two components in the ionosphere, phase-path records have been taken concurrently with phase-fading records. Contours such as those shown in Figures 8 and 9 resulted, which indicated a tendency for the quasi-periodic type of fading to occur during the passage overhead of a large-scale irregularity. However, it is only possible to compute the true contour of the reflecting surface if accurate measurements of direction of arrival can be made and if the drift velocity of the ionosphere is known. Thus, although it is always possible to construct a surface that will provide just two reflecting regions, no attempt is made here to give a more accurate description of the reflecting surfaces.

(*f*) *General Discussion*

The record shown in Plate 2, Figure 3, is not completely typical of the type of record that has been analysed but it does illustrate some of the features of this work. The rapid fading is obviously due to the interaction of two components, as can be seen from the phase-path records. However, the components are not completely superimposed, resulting in a phase-fading record which is not well defined. At the point arrowed, the relative amplitudes of the two components changed, so that after this point the component which previously had the larger amplitude then had the smaller one. The result of this was that the rapid changes in phase difference (in the phase-fading record) changed in direction, and also the phase path changed abruptly to follow the larger component. If the directions of arrival of the two components are measured (by taking mean values of phase difference before and after the point arrowed) then it will be found that their angular separation, φ, is very large. As the fading is rapid, this is to be expected from equation (8).

Even though two components are proposed to explain quasi-periodic fading it is not suggested that each component by itself does not fade. In fact, it is simple to show that they do fade but at a rate which is much smaller than the combination of the two. It has therefore been necessary to speak of each component as being reflected from a finite area of the ionosphere, not simply from a point, and to conclude that each area acts, in some ways, like a diffracting screen. However, the results of diffraction theory should not be applied to the quasi-periodic type of fading to derive information about the size of the small-scale ionospheric irregularities. It is conceivable that such information could be obtained from fading such as that shown in Plate 1, Figure 2, where there appears to be little or no correspondence between the amplitude fading and the phase fading. However, no work has yet been done to attempt to classify this type of fading nor the large number of other types of fading that appears on the records.

V. Conclusions

This work has shown that a continuous recording of phase difference between the signals at two aerials provides an important method for studying the features of the fading pattern of ionospheric echoes.

It has been shown that quasi-periodic fading may be explained in terms of the interference of two downcoming rays from the ionosphere and that these two rays are reflected from reflecting areas in the ionosphere which have a lateral separation which is large in comparison with the dimensions of the areas themselves. It has also been pointed out that the ionospheric features which are probably mainly responsible for providing two separate reflecting areas are shallow large-scale irregularities which have a velocity of the order of 50 m/s.

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