MEASUREMENTS OF CHANGES IN THE PHASE PATH OF RADIO WAVES REFLECTED FROM THE IONOSPHERE AT NORMAL INCIDENCE

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Summary

Fixed-frequency measurements were made at Brisbane, using pulse transmissions, of the changes in phase of radio waves received after reflection at normal incidence from the various ionospheric layers. Because of the homodyne detector used, such phase-path records have a very good signal-to-noise ratio. Also, due to the difference in behaviour of echoes of different polarization or from different ionospheric layers, the effective resolution is high. When the echoes had a well-defined phase, the rate of change of phase path with time was measured; the slowest rates were for smooth night-time E_s layers, when values as low as 1 m sec^{-1} were sometimes found, whereas for the night-time F_2 region the rates were usually in the range 10–40 m sec^{-1}. Records were also made of reflections from drifting E_s clouds, and of the effect of underlying E_s ionization on reflections from the F_2 region.

I. Introduction

Measurements of changes in the phase of a radio wave received after reflection from the ionosphere provide much information about the characteristics of the reflecting layer and the ionization along the path of the wave below the level of reflection. The changes are due to changes in the phase path P, where P is defined by the equation

$$P=2\int_0^h \mu \mathrm{d}h,$$

μ being the refractive index corresponding to the element of height dh.

The present paper describes a simple experimental technique for recording such changes in phase path and gives a review of some of the results obtained at Brisbane (lat. 27·5 °S., geomag. lat. 35·7 °S.). Some of the applications of the phase-path technique mentioned in this review have already been described incidentally in other papers, but it was considered desirable to bring them all together in one paper, and to discuss them explicitly, along with several additional features.

II. Experimental Details

The Brisbane phase-path recording equipment employed a simplification of the techniques used by Findlay (1951) and Jones (1953). Pulse-modulated transmissions were used throughout, in order to resolve as well as possible the various echoes received.

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The complete phase-path recorder consisted of a normal fixed-frequency group-path recorder plus one extra unit, known as the " phase-path unit ", a block diagram of which is given in Figure 1. This unit consisted essentially of a " phase-reference oscillator " (see below) and a mixer, in which beats were produced between the output of the phase-reference oscillator and the echo pulses coming from the receiver. These beats were then amplified and differentiated, and pips of one polarity were selected and fed to the output terminal of the unit. An isolating stage prevented the output of the phase-reference oscillator from leaking back into the receiver, which could thus be used simultaneously for making group-path records if desired.

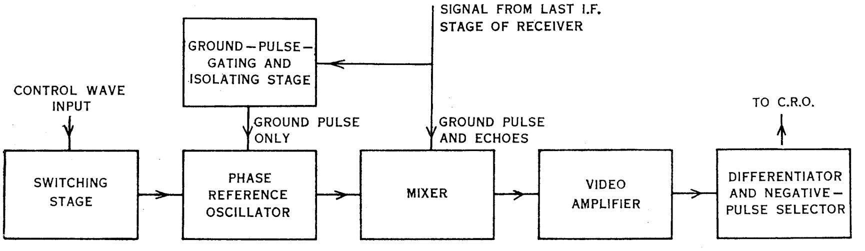

Fig. 1.—Block diagram of phase-path unit, used in conjunction with a fixed-frequency receiver, for making phase-path records.

To record changes in phase path, it is necessary to employ a suitable reference with which to compare the phase of the received signal. This reference was derived from an independent phase-reference oscillator (P.R.O.). Following Jones's technique, the P.R.O. was operated at a frequency near the intermediate frequency of the receiver, rather than near the actual signal frequency, since this allowed recording on any desired signal frequency merely by tuning the receiver to that frequency, no adjustments to the phase-path unit being necessary.

For convenience in recording, it was desirable that the P.R.O. should make several beats with the received signal within the duration of any given echo. As the duration of the transmitted pulse was about 70 μsec, the P.R.O. was operated at a frequency about 30–40 kc/s above the intermediate frequency. The positive frequency difference caused downward-sloping fringes on the phase-path record to correspond to decreasing phase path and vice versa.

It was necessary for the phase of the oscillations generated in the P.R.O. to bear some fixed relation to the phase of the oscillations in the ground pulses. This was most conveniently done by causing the initial phase of the oscillations of the P.R.O. to be exactly locked to the phase of the intermediate frequency signal at the start of each ground pulse. The P.R.O. was switched on at the instant the transmitted pulse started and a phase-locking signal, derived from the ground pulse, was injected into the oscillator tuned circuit, the feedback in the oscillator circuit being adjusted so that, after each switch-on, oscillations started gradually. The P.R.O. was switched off after all wanted echoes had been received in each pulse-repetition cycle. It will be noted that, when synchronization of the P.R.O. is achieved in this way, it does not matter whether the transmitter oscillator is itself pulse modulated or whether it runs continuously and only subsequent amplifier stages are pulsed.

A check on whether perfect synchronization has been achieved can be made by inspection of the fringes within the ground pulse. Whenever these fringes appear on the records, they should take the form of a series of straight lines parallel to the time axis of the record.

The output pips from the phase-path unit were fed to a cathode-ray display tube, where they produced brightness modulation. The pattern on the cathode-ray tube was photographed on continuously moving 35 mm film. A large enough rate of film advance was used to ensure that, even when the phase path of an echo was changing rapidly, the successive fringes on the record could be readily resolved when the film was examined in a viewer. A film speed of about 40 cm/hr was found satisfactory when the signal frequency was near 2 Mc/s, with proportionately higher speeds for higher frequencies.

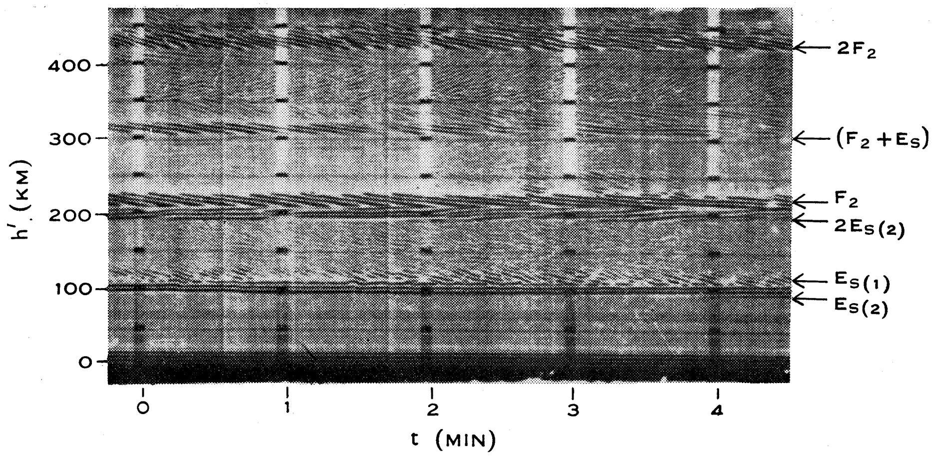

Fig. 2.—Phase-path record showing two E_s reflecting regions, at 95 and 110 km respectively, a double-hop E_s reflection at 190 km, an F_2 reflection at 210 km, an (F_2+E_s) reflection at 305 km, and a double-hop F_2 reflection at 420 km. Note the very slow rate of change of phase of the 95 km E_s reflection.

III. Outline of Results and Discussion

(a) *Phase Coherence and Phase Continuity*

(i) *Description of These Phenomena.*—A phase-coherent echo is one in which the phase remains constant throughout the duration of the echo, i.e. the phase difference between the echo signal and a purely sinusoidal reference signal at the same frequency would be constant. In the case of a phase-incoherent echo, on the other hand, rapid, virtually discontinuous jumps in phase occur during the period of reception of the echo.

A good example of a phase-coherent echo is given in Figure 2, in the case of the echo from the E_s region at 95 km, whereas Figure 3 shows highly incoherent echoes in the case of the E_s and $2E_s$ echoes at 95 and 190 km respectively.

Another important property of echoes recorded with phase-path equipment is the phase continuity. This is determined by the faithfulness with which the phase at a given portion of any particular echo is repeated from one pulse-repetition cycle to the next (after an interval of 20 msec). The records show that all echoes, whether coherent or incoherent, show at least short-term phase continuity. Thus phase-coherent echo traces consist of well-defined fringes; and even phase-incoherent echo traces show short, slightly irregular, lines, approximately parallel to the time axis, the individual lines lasting for something between a few seconds and half a minute.

(ii) *Cause of Phase Incoherence.*—Phase incoherence occurs because the echo is the resultant of a number of randomly phased components, coming from scattering centres situated at varying ranges from the recording equipment and hence being received at varying time delays after the transmitted pulse. At the start of the received echo, only those components coming from the nearest

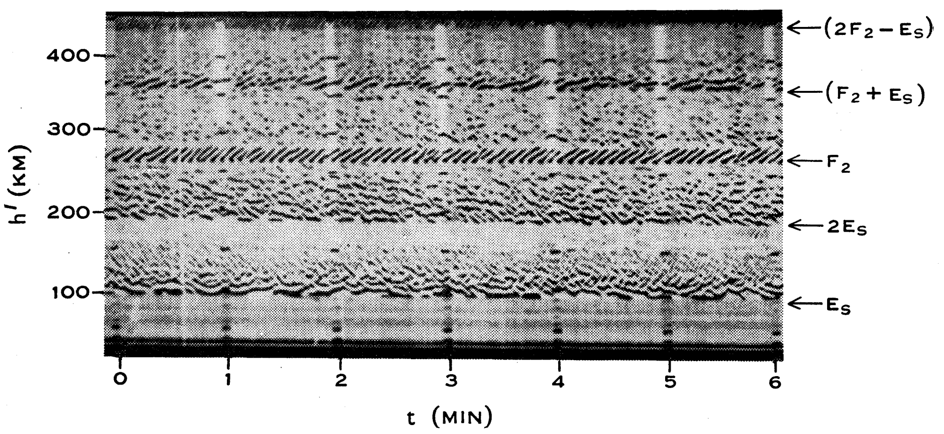

Fig. 3.—Phase-path record showing highly incoherent E_s reflections at 95 km (with a double hop at 190 km), with quite coherent F_2-region reflections at 270 km and ($2F_2$—E_s) reflections at 455 km. The incoherent trace at 365 km is an (F_2+E_s) reflection.

scatterers are received, but as time goes on during the period of reception of the echo, other components from the more remote scatterers begin to contribute to the resultant. The time required to change from the situation in which a given component is ineffective to the one in which it is effective is only the rise time of the received echo pulse from this particular scatterer, a time of only about 10 μsec. If the amplitude of any particular new component is comparable with the amplitude of the resultant immediately prior to its arrival and if the two signals are in substantially different phase, there will be a significant and rapid jump in phase as the amplitude of the new component rises from zero to near its full value. Thus the phase of the resultant of all the components, i.e. the phase of the total received echo signal, can change substantially in only a few microseconds; this explains the rapid, virtually discontinuous jumps in phase mentioned above as characteristic of phase-incoherent echoes.

(iii) *Discussion of Short-term Phase Continuity.*—It is interesting to consider the probable reason why we find traces showing short-term phase continuity, even in the case of phase-incoherent echoes. In the case of such echoes, the total signal received at any instant is the vector sum of a large number of randomly phased components, coming from discrete, irregularly situated, scattering centres. The speed with which these centres are moving along the line of sight is believed to be only of the order of a few metres per second (McNicol 1949). The phase of the individual components of the total signal cannot change substantially in a time less than it takes the centres to move distances of the order of a tenth of a wavelength of the exploring wave, and this time is at least a few seconds. The resultant signal consequently cannot change phase substantially in less than several seconds, i.e. whatever the phase of an echo is at a given instant, that phase will in general persist for at least a few seconds, except on the special occasions when the amplitude is passing through zero, at which times the phase can reverse almost discontinuously.

(b) *Time-rate-of-change of Phase Path*

In the case of phase-coherent echoes, and only in this case, it is possible to make statements about the rate of change of phase path with time, e.g. the E_s-region echo at 95 km in Figure 2 above shows a change of only one fringe in several minutes, the F_2-region echo (at 210 km) a change of about 4 fringes per minute, the (F_2+E_s) echo (at 305 km) a change of about 4 fringes per minute, and the $2F_2$ echo (at 420 km) a change of about 8 fringes per minute.*

Very slow rates of change—say less than one wavelength per minute—occur only for night-time E_s-region echoes, and then only rarely. More commonly the rates of change are of the order of several wavelengths per minute, occasionally increasing to values well in excess of this, e.g. at times of F_2-region sudden height rises (see Section III (*h*) (ii) below).

(c) *Correlation between Phase-path and "Swept-gain" Records*

The degree of coherence or incoherence of phase-path records depends on the degree of regularity or irregularity of the reflecting region. We would, therefore, expect a close correlation between phase-path records and swept-gain records, i.e. records made by reducing the receiver gain periodically at a logarithmic rate from a very high value to a very low one (McNicol, Webster, and Bowman 1956). This correlation is in fact found to occur. An example is given, in Figure 4, of swept-gain records taken simultaneously with the phase-path records of Figure 3. As mentioned above, Figure 3 shows at 95 km an echo from the E_s region with highly incoherent phase-path fringes. On the corresponding swept-gain record the E_s echo takes the form of "triangular" patches which show a considerable spread in virtual height at the start of each period, where the receiver gain is high. Both these records indicate a high degree of

* It was usually observed that multiple-hop echoes, such as the $2F_2$ mentioned above, showed phase changing at approximately twice the rate of the corresponding single-hop case, and combination echoes, such as the (F_2+E_s), showed changes corresponding to the sum of those present on the component echoes.

irregularity of the reflecting layer. On the other hand, the echo from the F_2 region, at 270 km in Figure 3, shows highly coherent phase-path fringes, and these correspond with the almost " rectangular " swept-gain patches at 270 km on Figure 4, which show almost no spread in virtual height, even at high gain. In this case the indications from both records are of reflections from a very smooth layer.

(d) *Simultaneous Phase-path and Group-path Recording*

It will be noted that the bottom edge of the recorded phase-path trace gives the value of the group path for the working frequency, albeit with slightly less precision than a normal group-path record would. Phase-path records thus offer the possibility of conveniently comparing changes in group path with

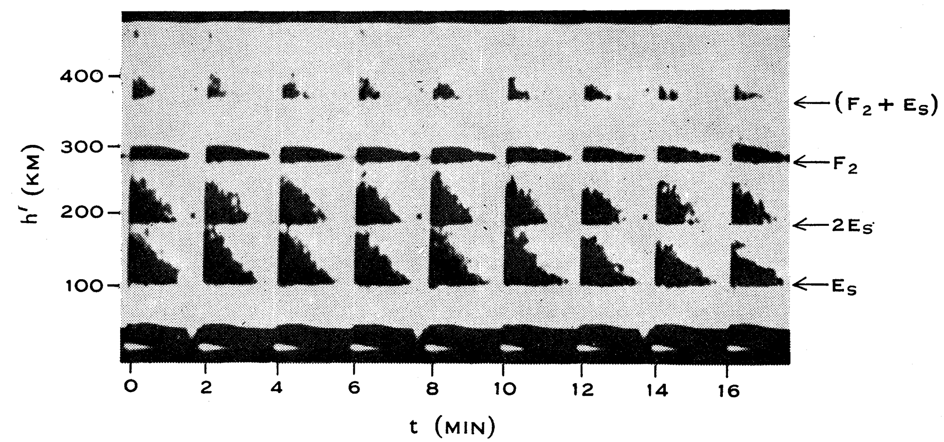

Fig. 4.—Swept-gain record corresponding to the phase-path record of Figure 3 showing reflections from irregular E_s region at 95 km (with a double hop at 190 km), reflections from a smooth F_2 region at 270 km, and weak irregular (F_2+E_s) reflections at 365 km.

changes in phase path for any particular echo. Such comparisons are particularly valuable in determining, for example, whether observed changes in group path or phase path are due to real changes in range of the reflecting region, or to changes in the ionization density along the path, below the point of reflection.

(e) *Improvement of Signal-to-noise Ratio*

It was often observed that the phase-path records were more successful in recording very weak echoes than were group-path records made simultaneously, even when both recorders used the same transmitting and receiving systems. This was due to the fact that, for the phase-path records, the mixer stage in the phase-path unit was supplied with a relatively large signal from the phase-reference oscillator as well as with the output from the final intermediate frequency amplifier in the receiver. The output from a phase-reference oscillator is phase coherent with all of the components in the frequency spectrum of the wanted echo, but not with the noise pulses, which are in random phase. We thus have virtually a homodyne detector. Goldman (1948) points out that an improvement in signal-to-noise ratio is characteristic of systems in which the coherence standard of the detector is maintained beyond its normal operating range. For the group-path records a linear amplitude-modulation detector is used and there is no corresponding improvement.

(*f*) *Improvement in Resolution of Overlapping Traces*

It frequently happens that traces which would be unresolved when using normal group-path techniques with a given pulse width may be effectively resolved on phase-path records, as, for example, the cases shown in Figures 2 and 9, because of the recognizable differences in the behaviour of the phase path of the various components of the composite echo.

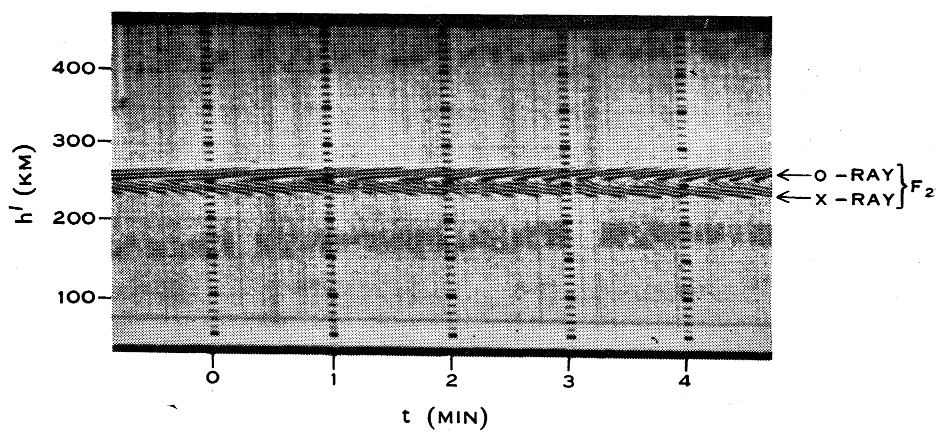

Fig. 5.—Phase-path record showing different behaviour of *o*- and *x*-reflections from F_2 region.

(*g*) *Independence of Phase Path of* o- *and* x-*Rays*

We may utilize the fact that the rate of change of phase path is often markedly different for the two magneto-ionic components, to give increased resolution above the normal *h't* records. In Figure 5 for example the *o*-ray shows a phase-path increase whilst the *x*-ray simultaneously shows a decrease in phase path. Such " herring-bone " patterns are not at all uncommon.

(*h*) F-*Region Phenomena*

(i) *Extra Traces*.—Group-path records of F_2-region night-time reflections often show spreading in range, and at times show a main trace and a number of discrete extra traces. Phase-path records have been made to find the rate of change of phase path of these traces (McNicol, Webster, and Bowman 1956).

(ii) *Sudden Height Rises*.—From time to time at night, travelling disturbances in the ionosphere cause distortion of the F_2-region ionization contours. If a large disturbance occurs, it shows itself on group- or phase-path records as a fairly abrupt rise in the virtual height of the reflection level at any given frequency. The *o*-ray is affected first, followed after a short interval (of a few minutes) by the *x*-ray. If the working frequency is well below the critical frequency of the region, the *o*- and *x*-rays at quiet times are normally not resolved at night on $h't$ records, so the effect of the disturbance is to produce a temporary separation of the *o*- and *x*-ray traces. A typical example of the phase-path behaviour during such an occurrence is shown in Figure 6. McNicol, Webster, and Bowman (1956) have made measurements on a number of such records and point out that the change in group path is always much more marked than the change in phase path of either the *o*- or *x*-rays.

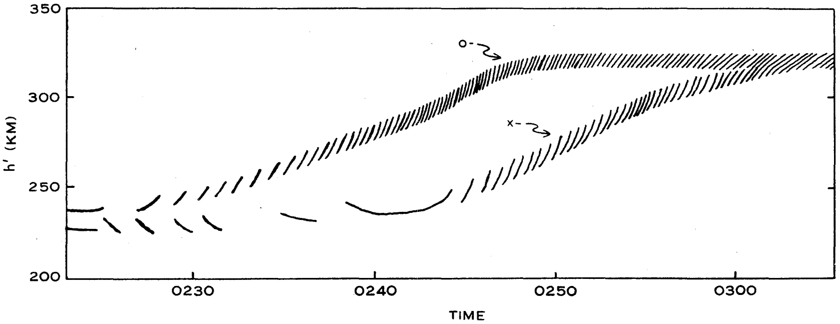

Fig. 6.—Phase-path record showing different behaviour of *o*- and *x*-reflections from F_2 region during an F_2-region sudden height rise. (Only every fifth fringe is shown.)

(*i*) E_S-*Region Phenomena*

(i) *Isolated Clouds of Ionization.*—One of the most striking types of phase-path record is obtained when we have reflections from isolated patches (clouds) of E_s ionization drifting horizontally at a fixed height of about 100 km. Findlay (1951) has discussed such records, an example of which is given in Figure 7.

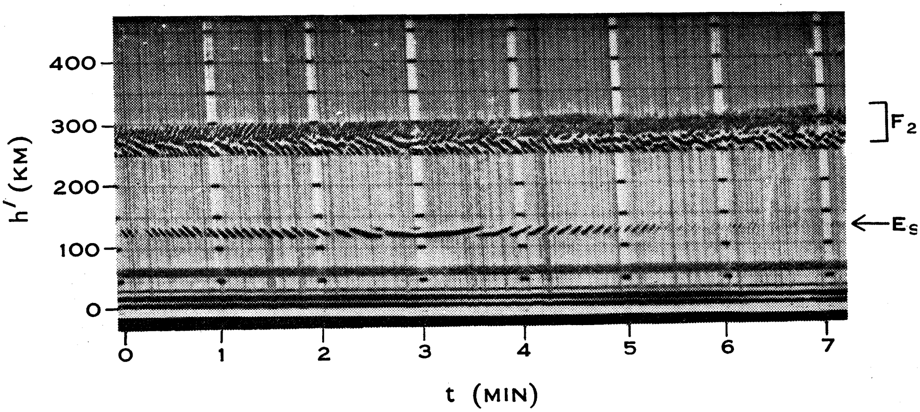

Fig. 7.—Phase-path record showing drifting E_s cloud at 120 km.

Measurements of the rate of change of phase path agree with the measured rates of decrease and increase of slant group path within the limits of error, and good estimates can thus be made of the speed of movement of such patches.

We might hope to find out something about the ionization density in E_s clouds by observing the effect the passage overhead of such clouds has on the phase-path records of reflections from the F_2 region. In particular, if the ionization density in the cloud were greater than that of its surroundings, we would expect the phase path from a stationary F_2 region to show a temporary decrease as the E_s cloud passes overhead. In practice, however, the picture is considerably complicated by the fact that the F_2-region echo is usually changing in phase path quite independently of the presence of any observable E_s region. Also, on many of the occasions on which we can be sure that an observed E_s cloud has passed exactly overhead (say, by direction of arrival measurements or by noting the behaviour of multiple E_s reflections), the F_2 region is blanketed, and on such occasions we lose the F_2-region echo and so cannot observe its changes of phase path. Accordingly, no definite conclusion could be drawn from the records as to whether E_s echoes are associated with any increase in total electron content in the E region or not.

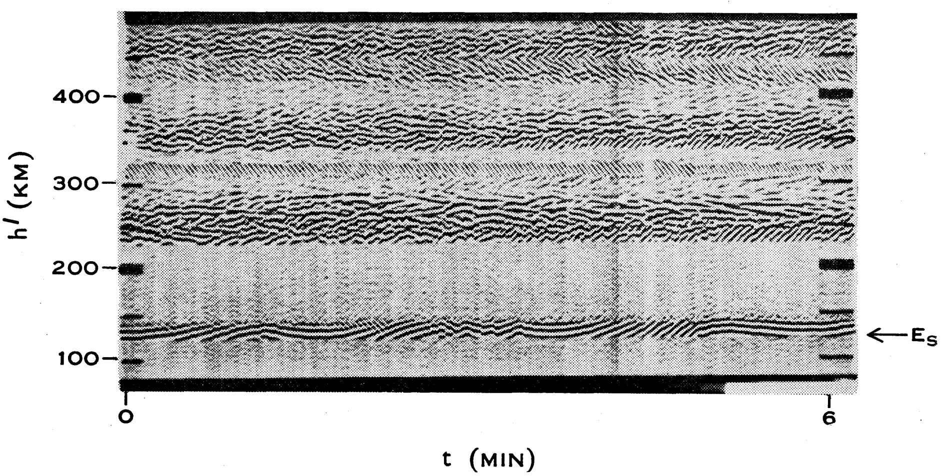

Fig. 8.—Phase-path record showing overlapping E_s clouds at 125 km.

Figure 8 illustrates a rather more common event—at 125 km we have the obvious overlapping of echoes from a series of E_s clouds to form a trace which on group-path records would give no such definite indication of structure.

Occasionally the leading and trailing edges of such cloud echoes extend to ranges beyond that of the main echo, giving rise to converging and diverging traces on group-path records and decreasing and increasing phase paths on P,t records as discussed by Thomas and Burke (1956).

Sometimes the recorded trace presents a completely jumbled appearance, as shown in Figure 3 above, i.e. we have phase incoherence, as discussed in (*a*) above. This jumbled appearance is probably due to the fact that a large number of clouds are present simultaneously and the traces due to echoes from individual clouds are no longer separately discernible.

(ii) *Simultaneous Occurrence of Several Different Types of* E_S *Region*.—Quite frequently phase-path records were obtained which show smooth and irregular E_s regions to be present simultaneously. Figure 2 shows a very smooth

E_s region at 95 km, together with a more irregular E_s region at 110 km. A more complex example is shown in Figure 9, where the E_s echo is clearly divisible into three parts, at 95, 110, and 130 km respectively. The phase-coherent central portion shows up again at 220 km on the double-hop path with twice the rate of change of phase path of the single-hop echo. These latter facts make it probable that the E_s region responsible for the echo at 110 km is overhead, at a height close to 110 km, rather than being displaced to one side and being at a slant range of 110 km but at a smaller actual height. If this is true, the smooth E_s region at 110 km must be completely embedded in some quite separate, irregularly distributed, E_s ionization.

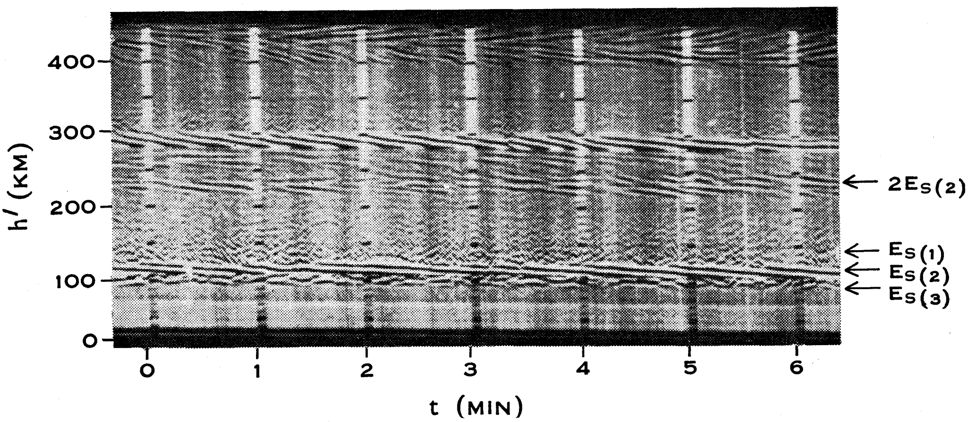

Fig. 9.—Phase-path record showing three different E_s reflecting regions, at 95, 110, and 130 km respectively, and an F_2 region at 280 km.

(iii) *Distinction between Sequential and Constant-height* E_s *Regions.*—It can be stated generally that the type of sporadic-E echo classified as " sequential E_s " is consistently more phase coherent and stable than the type designated as " constant-height E_s " (McNicol and Gipps 1951). This feature has been used as an aid in distinguishing between these two types of E_s (Thomas 1956).

(*j*) *Effect on* F_2*-region Phase-path Records of Underlying Irregular* E_s *Ionization*

One interesting effect is sometimes noticed when echoes from a partially reflecting E_s layer are observed simultaneously with F-region echoes. Normally one would expect incoherent E_s echoes to be accompanied by incoherent F echoes and this is often so. However, in certain cases, such as the one illustrated in Figure 3 above, the E_s echoes are mainly incoherent, while the F_2 echoes (which involve waves passing twice through the E region) are phase coherent. In addition it will be noted that, in this case, the M echo, i.e. the $2F_2$-E_s echo, is also phase coherent. These observations suggest that, whatever the mechanism by which the E_s region produces reflection of radio waves at normal incidence may be, the region on such occasions has the peculiar property of looking rough and irregular when viewed from beneath, of looking relatively smooth when viewed from above (as in M reflections), and of being virtually invisible, in so far as variations of phase are concerned, to radio waves passing right through it.

(k) *Phase-path Changes during Penetration of a Layer*

Although in this paper no direct experimental method of recording phase path as a function of radiated frequency is described, nevertheless some penetration information has been gained by operating on a fixed frequency and by taking advantage of the fact that on certain occasions the ionospheric changes are such as to cause the penetration frequency of one or other of the reflecting layers to pass through the operating frequency of the phase-path equipment. The value of this procedure is somewhat reduced by the fact that it may take quite a few minutes for the complete record to be made and changes in the height of the reflecting layer as a whole may occur during this time, as also may changes in the distribution of ionization at levels well below the reflecting layer, and either of these changes will give rise to changes in the phase path other than those specifically due to the penetration of the layer.

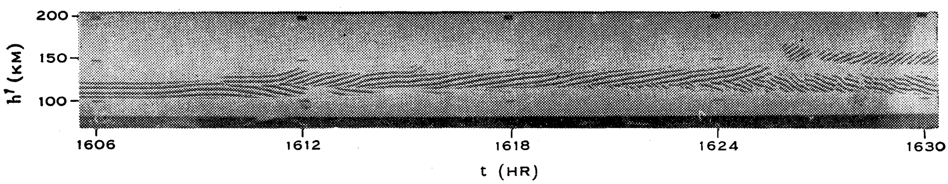

Fig. 10.—Phase-path record showing penetration of E_s region at 1610 hr and penetration of normal E region at 1626 hr.

Figure 10 illustrates two aspects of such penetrations. Near the start of the record, at 1610 hr, there is a sudden reflection " jump " from E_s to normal E, and the phase-path fringes show no consistency from the one region to the other. At 1626 hr, we have, on the other hand, a penetration of the normal E region, and here the phase-path fringes tend to carry over across the penetration to the F region.

Computations of phase path as a function of frequency carried out by Lander (personal communication) for E-region penetrations show a smooth increase of phase path with frequency. Correspondingly it has been noted that the fixed-frequency phase-path record always shows a continuing increase whenever the wave penetrates a region.

IV. Conclusion

Phase-path records are easy to make and provide a very useful supplement to the information obtained about the ionosphere in other ways. Their good signal-to-noise properties and their potentialities for the resolution of overlapping echoes are especially valuable.

V. Acknowledgments

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