SPORADIC E STRUCTURES AND PRESSURE OSCILLATIONS AT GROUND LEVEL

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Abstract

This paper describes a method for obtaining rapid measurements of the phase differences between signals from the ionosphere at two pairs of aerials. Measurements were made, during quiet ionospheric conditions, on the first hop near-vertical reflections using a pulsed 1·98 MHz radiowave transmitter. Evidence is presented to suggest that a relationship exists between wavelike disturbances of a period of 3 min in the E_s layer and pressure oscillations at ground level. From ionosonde records of six ionospheric stations around Australia it was found that a large-scale travelling ionospheric disturbance was moving in the F region with a speed of 350 m sec^{-1} towards the south-west. It was overhead at Brisbane at the time the small-scale structure was observed in the E region. Two other cases are also presented to show correlation between E_s layer structures and ground pressure oscillations.

I. INTRODUCTION

Previous attempts have been made by several workers to correlate ionospheric events with ground pressure oscillations. The passage of gravity waves from one region to the other is thought to link the two regions (Hines 1960; Gossard 1962). Atmospheric waves are known to exist at ionospheric heights due to the Alaskan earthquake of March 28, 1964 (Davies and Baker 1965; Leonard and Barnes 1965; Row 1966, 1967). More recently Yuen *et al.* (1969) have reported that the Japanese earthquake of May 16 generated seismic waves, which in turn produced upward travelling acoustic waves that propagated over a large front and penetrated into the atmosphere to at least 300 km, producing an oscillatory disturbance there. The effect on the microbarograph at ground level was not recorded, as it was believed that the ground pressure fluctuations would be too small to be distinguished from the noise. Baker and Davies (1968) have shown that thermonuclear explosions cause waves of a similar nature, with a period of about 1 min, at ionospheric heights and at ground level. Similarity of the period (recorded by a 5 MHz Doppler sounder) and the speed of the disturbances observed in the ionosphere and at ground (recorded by a microbarograph) allow them to conclude that the ionospheric disturbances are also caused by ducted acoustic waves.

Baker and Davies (1969) have reported the existence of certain types of waves like ionospheric disturbances which are characterized by a periodicity that is always around 3 min. These disturbances are suggested to be associated with severe local storms in the troposphere and are interpreted as the result of acoustic waves generated by the storms. Also, Bowman and Shrestha (1966) have described short period

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oscillations that occured at ground level at the same time as the passage of a large ionospheric disturbance.

In the present work using a somewhat novel method of rapidly obtaining the angular coordinates of the arrival of signals reflected from the ionosphere, it has been possible on a few occasions to detect a wavelike disturbance passing through the E_s region. On these occasions the disturbances were found to occur simultaneously with pressure oscillations at ground level recorded by a microbarograph. In one case a travelling ionospheric disturbance in the F region was also recorded.

II. Experimental Details

(a) *Principles of Operation*

The direction of arrival of radio waves reflected by the ionosphere may be determined by measuring the phase differences of signals received in an assembly of aerials. If two similar pairs of aerials are erected on lines perpendicular to each other and the phase differences between signals received at each pair are measured, the angles of elevation and azimuth of arrival of the signals may be determined (Bramley and Ross 1951).

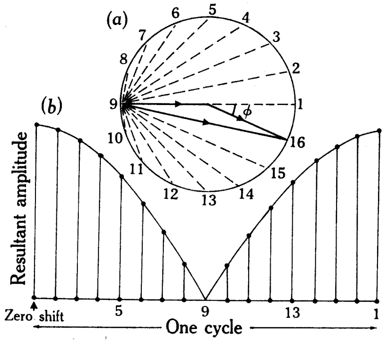

Fig. 1.—Vector summation (*a*) and resultants (*b*) of the amplitudes received at each aerial pair for various positions of the phase-shifting capacitor.

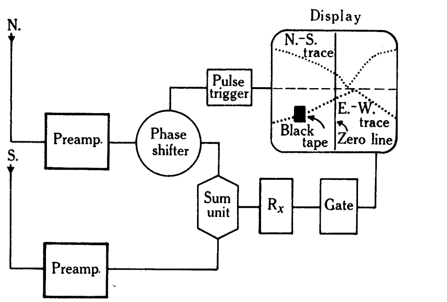

Fig. 2.—Schematic diagram of the essential equipment used for each aerial pair.

(b) *Equipment Used*

The signals were emitted by a transmitter with a pulse duration of 100 μsec (rounded pulses), a pulse-repetition frequency of 50 Hz, and a peak output of 2 kW, located close to the receivers.

The signals received at one pair of aerials were added by a sum unit. One signal went straight to the sum unit while the other passed through a phase shifter (Morrison 1937). The phase shifter advanced the phase of the signal by an amount which increased at a constant rate when the capacitor in it was rotated at constant speed. The maximum advance was 360°.

With this arrangement, when the received signals are in phase and the phase shifter is set at zero, a maximum in amplitude is obtained from the sum unit. As the amount of advance increases, the amplitude of the resultant signal decreases, reaching a minimum for a 180° advance. Hence it is expected to get a minimum at the centre of the traverse of the phase shifter as shown in Figure 1. If the two signals arrive at the aerials with a difference in phase, the position of the minimum will be shifted from the centre and the measurement of this shift will yield the phase difference between the two signals.

A block diagram of the receiving equipment is shown in Figure 2. The phase shifter was rotated at a constant speed by a synchronous motor. The period of rotation was set at 2 sec, i.e. the phase advance increased from 0° to 360° in 2 sec. The resultant signal from the sum unit went to a modified Loran receiver (An/APN–4).

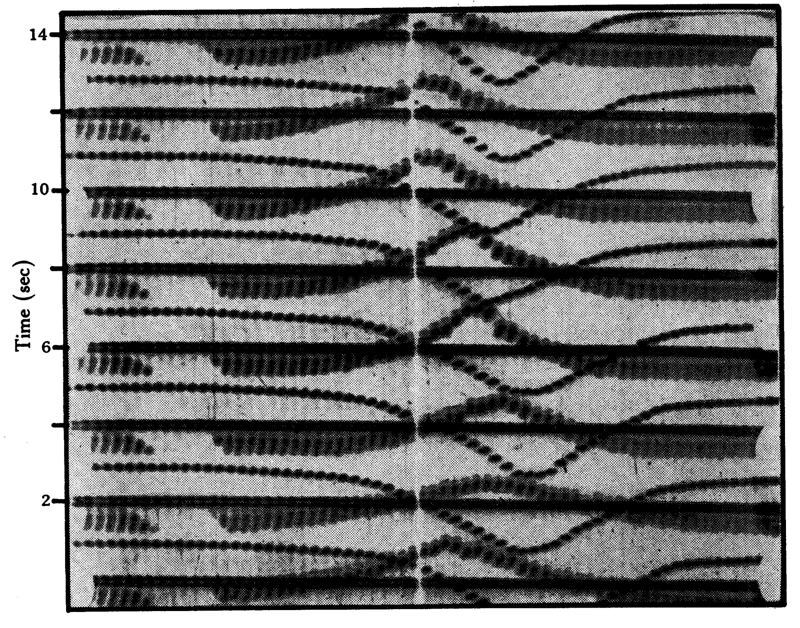

Fig. 3.—A 14 sec sample of the direction-finding records. The thick and thin traces represent respectively the east–west and north–south amplitude variations and the white central line is the zero reference.

The leading edge of the video signal was gated with a narrow square pulse of width 30 μsec. The gate unit used the same square pulse of 50 Hz repetition frequency as was employed to trigger the transmitter. The gated video signal then entered the display unit. In the display unit the vertical deflection was proportional to the gated signal amplitude while the horizontal deflection was produced by a phantastron time base locked to the phase shifter by a phototransistor relay system, which triggered it at zero phase shift.

The amplitudes of north–south and east–west combinations were displayed simultaneously on a cathode ray tube. Records were taken on 35 mm film which moved at right angles to the time base at a rate of $0 \cdot 127$ cm sec^{-1}. An example is shown in Figure 3. Successive dots on each trace were separated by $0 \cdot 02$ sec, representing $3 \cdot 6°$ in phase. The vertical distance of each dot from the near-horizontal line represented the amplitude. A vertical central line was obtained by placing a black thread over the cathode ray tube at the zero position of the minimum. This was used as a reference when reading the film. The north–south trace was displayed on the top half of the tube and the east–west on the bottom, a phase inverter unit reversing the direction of the deflection. The east–west amplitude trace was made thicker than the north–south one and was also marked by placing a piece of black tape in the third quadrant of the tube (see Fig. 2) to distinguish it on the film. The phase shifters for both pairs of aerials were so set that a minimum was obtained at the centre of the display under the shadow of the black thread for in-phase radio waves at the aerials.

(c) *Ambiguity*

When the position of the minimum moves to either edge of the display, the phase difference ϕ between the signals will be π (i.e. a path difference equal to one half wavelength). Any positive value of ϕ greater than π (but less than 2π) would normally be interpreted as a negative value of ϕ $(=2\pi-\phi)$. Thus pairs of values of azimuth α and angle of elevation δ which give either ϕ_1 (the difference in phase between the north and south aerials) or ϕ_2 (the difference in phase between the east and west aerials) greater than π (or less than $-\pi$) will be wrongly interpreted from the records.

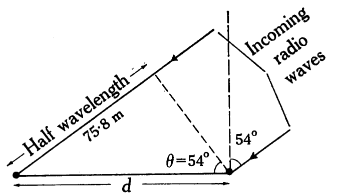

Fig. 4.—Phase lag in the incoming radio waves due to the aerial spacing *d*.

From Figure 4 we see that

$$\phi=\pi=(2\pi d/\lambda)\sin\theta \qquad \text{or} \qquad \sin\theta=\lambda/2d,$$

where d is the spacing between the two aerials of each pair, λ is the wavelength, and θ is the maximum zenith which can be read without ambiguity. As the spacing between the two aerials of each pair is 93·7 m and λ is 151·6 m then θ is 54°, and hence the equipment at this frequency can only measure a zenith up to 54° without any ambiguity. However, with the transmitting and receiving aerials housed at the same site, it is found that the zenith angles are never in practice greater than 30°. Hence it can be taken that the records are free from any ambiguity.

(d) *Accuracy of the Records*

The phase differences ϕ_1 and ϕ_2 are found by determining the position of the minimum on the film by counting the number of spots lying between the zero reference position and the minimum. Miscounting of the spots would produce errors in the zenith and azimuth estimates. If we consider the maximum possible error as the mislocation of a minimum by one spot length, and as this is equivalent to 3·6°, then the errors in the determination of ϕ_1 and ϕ_2 can be taken as $\pm 3\cdot 6°$. This estimate leads to an overall error of 0·9° in the determination of the zenith (Bramley and Ross 1951). It is impossible to set any general limits on the error in the azimuth due to a $\pm 3\cdot 6°$ error in the determination of ϕ_1 and ϕ_2; for large zenith angles the error is quite small (at zenith 30° the error is 2°), but for small zenith angles the error tends to infinity.

III. Results

The equipment described was only operated during quiet conditions in the ionosphere. It has been reported (Bowman 1968) that at Brisbane very little amplitude fading of the signals occurs at such times, suggesting that few components are present in the returning energy. If more rays than one are received from directions relatively close to one another, then it can be shown that the equipment records the average direction. From the mass of data observed, three cases have been selected for special study because of the quasi-periodic nature of the movements of the reflected ray.

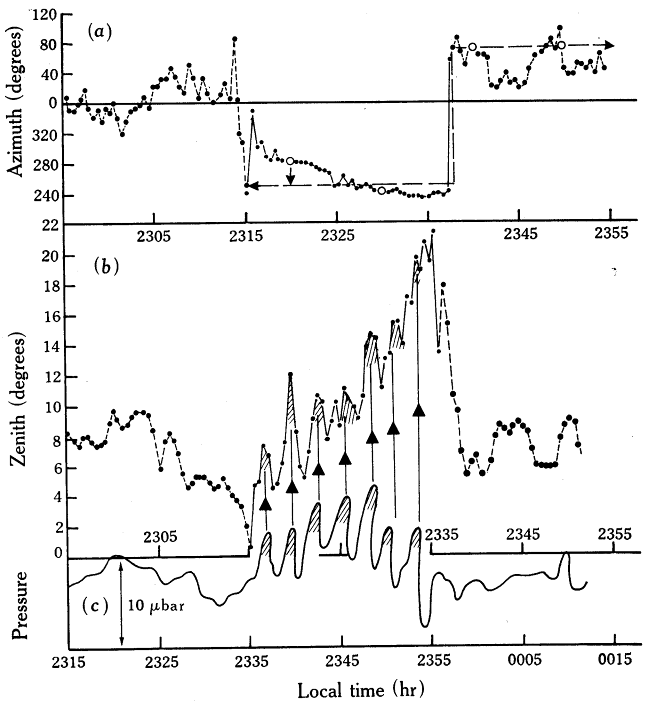

Fig. 5.—Variations of (*a*) azimuth, (*b*) zenith, and (*c*) pressure at ground level during the travelling disturbance recorded on October 26, 1968.

Case 1

This was the most clear-cut example observed of periodic variation of zenith angles, which is fairly rare in occurrence. The computed zenith angles and azimuths are plotted in Figure 5. This figure is derived from a record of E_s reflections obtained on October 26, 1968 commencing at about 2315 hr E.A.S.T. (E.A.S.T. = U.T.+10 hr). Seven well-defined cycles were recorded. Each point on the diagram is an average of 15 readings, and is thus effectively separated from the adjacent points by 30 sec (as the readings were taken every 2 sec).

Prior to the onset of the disturbance, the azimuth was on average about 20° E. of N. (geographic) but after onset it changed abruptly to the south–west quadrant where it remained until the disturbance had passed. It then reverted sharply to the north–east quadrant (Fig. 5(*a*)). The zenith angle prior to onset was 8° on average. At onset, it was reduced to 1° but during the passage of the disturbance it increased gradually to about 21° before falling to an average value of 8° after the disturbance had passed (Fig. 5(*b*)).

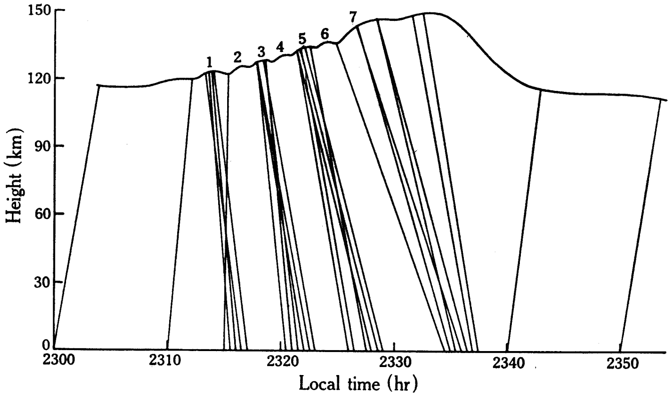

Fig. 6.—Approximate profile of the reflecting E_s layer during the passage of the disturbance on October 26, 1968. To avoid confusion, ray directions are shown only for alternate cycles during the passage of the disturbance.

Information relating to the shape of the reflecting E_s layer at the time of the passage of the disturbance has been determined on the assumption that specular reflection occurs and the refractive index of the ionospheric medium below the reflecting layer is unity. In constructing this theoretical model the distances between the ground and the reflection points were obtained from ionograms (taken every 10 min), recorded at the same site as the direction of arrival records. At first the lines joining reflection and receiving points were drawn every 10 min (as zenith angles and heights were known every 10 min). The position of such mirror points gave a gross picture of the reflecting E_s layer. To obtain an approximate picture of the reflecting E_s profile during the period in which zenith angles showed cyclic

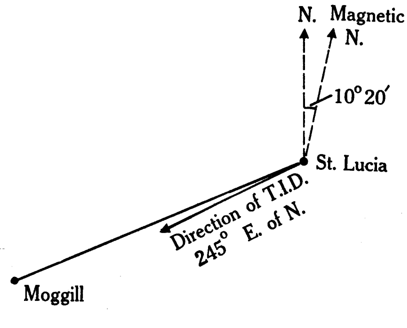

Fig. 7.—Relative positions of St. Lucia and the Moggill Radio Research Station. The bearing of Moggill from St. Lucia is 247°30′ and the distance between the two stations is 10·2 km.

patterns, lines were drawn at each instant at the receiving point with the known zenith angle and a best-fitting profile was then drawn across these lines. In such a profile a wavelike structure was evident (Fig. 6), each wave corresponding to a cyclic variation of the zenith angle.

Figure 6 represents a section of the model based on the assumption of a constant-azimuth reflecting E_s layer (i.e. two dimensional only), and hence is of significance only if the assumption remains true during the period of interest. The computed values of the azimuth appear to be reasonably constant, except for the first few measurements (for which zenith angles are fairly low and the error in azimuth could be large). The azimuth values were adjusted to produce a smooth curve for the reflection points (the adjusted azimuth is shown by a dashed line in Fig. 5(*a*)). The speed of the disturbance was calculated by computing the zenith angle values of the

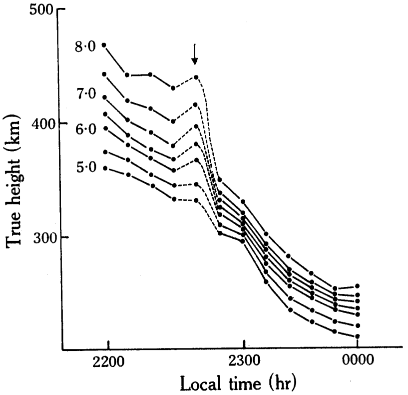

Fig. 8.—Variation of contours of equal ionization density showing an anomalous rise in height (arrowed) at 2240 hr (150 E.M.T.) in the *F* region on October 26, 1968. The values to the left of the contours indicate the plasma frequency in megahertz.

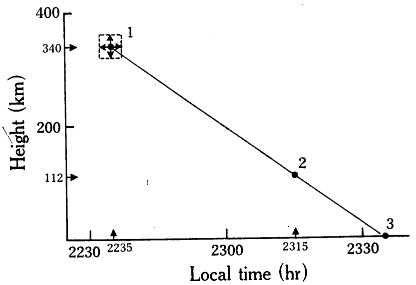

Fig. 9.—Plot of onset times of the disturbance on October 26, 1968 at three levels:

1, *F* region (the square indicates the maximum uncertainty)

2, *E* region

3, ground

reflection point at each instant and its distance (measured from the ionograms). The average speed so determined was approximately $5 \cdot 0$ km min^{-1}. The principal change in the zenith angle occurred between 2310 and 2320 hr, which is consistent with the azimuth pattern.

At ground level remarkably similar pressure oscillations of the same periodicity were recorded 20 min later for the same length of time (i.e. 20 min or about seven oscillations) by a microbarograph stationed at St. Lucia ($10 \cdot 2$ km from the direction-of-arrival recording site at the Moggill Radio Research Station; see Fig. 7). These oscillations are shown in Figure 5(*c*).

A true height analysis of the Brisbane ionograms for the period (2200–0000 hr E.A.S.T.) was performed using Schmerling's (1967) 10 points method. It showed (Fig. 8) an anomalous increase in height of the *F* region which was falling 40 min prior to the onset of the disturbance in the E_s layer. In an attempt to correlate events at the three levels (i.e. *F* region, E_s layer, and ground) the onset times were plotted at each level (Fig. 9). The three points were almost collinear.

At Brisbane on the night in question the critical frequency showed a marked variation from the normal pattern. Hence further studies were made using ionograms taken at six other ionospheric stations in and near Australia. A plot of the departure of the critical frequency, $\Delta f_0 F_2$, from the average October and November 1968 values for all seven stations (Fig. 10) shows a marked variation with a systematic delay in time. This systematic delay in the occurrence of a large peak in $\Delta f_0 F_2$ at different stations suggests that a large travelling ionospheric disturbance may have been passing over Australia. To calculate the velocity of propagation, a graphical method was employed which depended on the estimation of the time delays between the occurrence of recognizable features of the phenomenon at different stations,

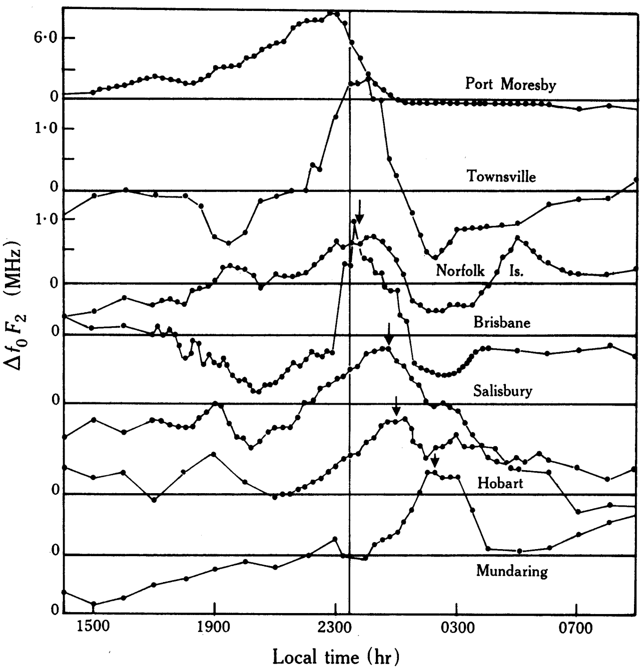

Fig. 10.—Variation of $\Delta f_0 F_2$ for seven stations. (Note that the ordinate scale for Port Moresby is six times that for the other stations.)

together with a knowledge of the separations of the stations. It was found convenient to compare each of the other stations with Townsville. By overlaying a plot of $\Delta f_0 F_2$ patterns from each station on the Townsville plot and shifting until the best fit was obtained, the time delay was estimated and hence the apparent velocity along the line joining the pair of stations. These data were then fitted to a model in which a frontal disturbance of fixed configuration moves with uniform speed over the several stations. To this end, all velocity vectors were plotted as in Figure 11, the ends of the vectors falling roughly along a straight line and thus justifying the model. It will be noted that the time delay Townsville–Norfolk Island is zero, indicating that the front is approximately aligned in this direction. The point for Port Moresby falls a considerable distance from the frontal line. Port Moresby alone is on the northern side of Townsville and the frontal velocity could well have changed as the front moved south. From the diagram, the velocity of the front, if perpendicular to its length, is approximately 350 m sec^{-1} in a direction 218° E. of N. This velocity is in good agreement with that found by Bowman (1965) for travelling ionospheric disturbances associated with magnetic sudden commencement. However, no sudden commencement occurred in the case cited, in fact it was fairly quiet magnetically ($K_p = \bar{1}$). The direction of movement of the travelling ionospheric disturbance seems to correspond approximately to the azimuth of the reflected ray from the E_s layer during the passage of the disturbance through it. It appears that the two events may have been associated in some way.

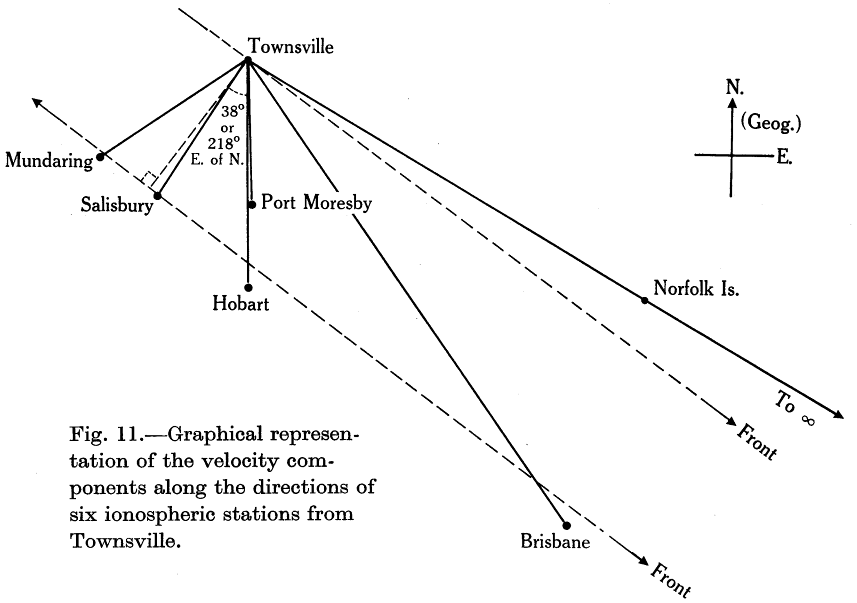

Fig. 11.—Graphical representation of the velocity components along the directions of six ionospheric stations from Townsville.

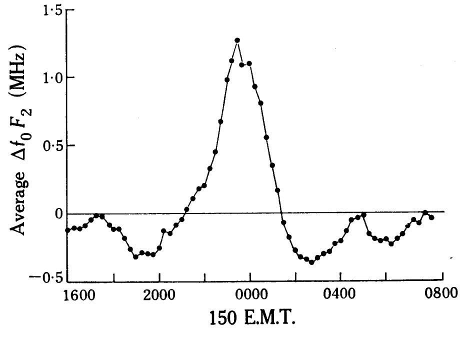

Fig. 12.—Average variation of the $\Delta f_0 F_2$ values (excluding Port Moresby) obtained after appropriate adjustment of the time scales.

The $\Delta f_0 F_2$ values of the six stations were averaged after advancing by the respective time delay, determined as stated previously. Port Moresby was not included in the averaging as the $\Delta f_0 F_2$ value for it was three times that for most of the other stations. Such a plot gives a more reliable estimate of the shape of the $\Delta f_0 F_2$ variation (Fig. 12).

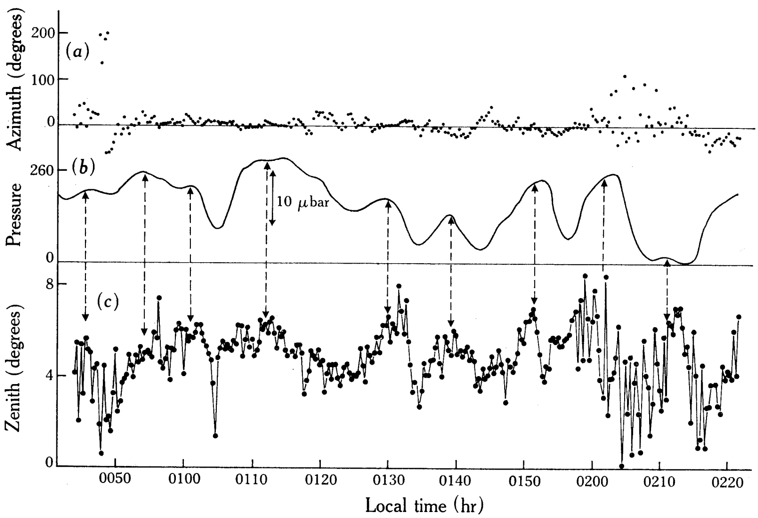

Fig. 13.—Variations of (*a*) azimuth and (*c*) zenith from the records of November 4, 1969 compared with (*b*) the pressure oscillations at ground, which have been fitted to match the zenith variations.

Case 2

In quiet periods, the zenith angles for E_S reflections show shallow structures, of which Figure 13(*c*) obtained from records of November 4, 1969 is typical. The pressure oscillation at ground level (Fig. 13(*b*)) can also be free from noise under such conditions. The time delay in the occurrence of similar patterns between E_S-layer structures and pressure oscillations at the ground can be obtained by plotting time lag crosscorrelations. Different values of crosscorrelations can be obtained by shifting zenith angle time series with respect to the pressure amplitudes. The occurrence of a maximum in the values of crosscorrelations so obtained gives the time delay (Fig. 14). In the case of the November 4 data, a similar pattern was registered at the ground 9 min 40 sec later to that registered in the E_S layer. In Figure 13 the plots are shown with the time displacement from the crosscorrelogram introduced. A reasonable degree of similarity between the patterns is visible.

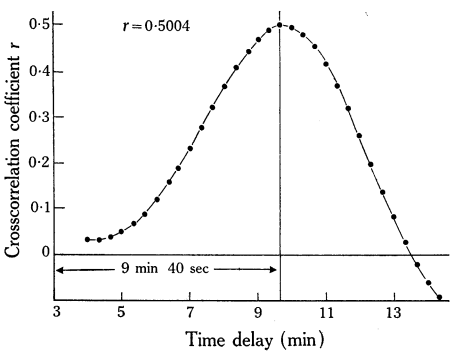

Fig. 14.—Estimate of the time delay by crosscorrelation analysis between the zenith variations and the pressure variations at the ground for November 4, 1969.

Case 3

In disturbed conditions, the zenith angles for E_s reflections show a short-period structure superimposed on a deep structure, of which Figure 15(*b*) obtained from records of October 28, 1968 is typical. The pressure oscillation at ground level can also have noise under such circumstances (Fig. 15(*a*)). The time delay between the occurrence of similar patterns at the two levels can be obtained using the time lag

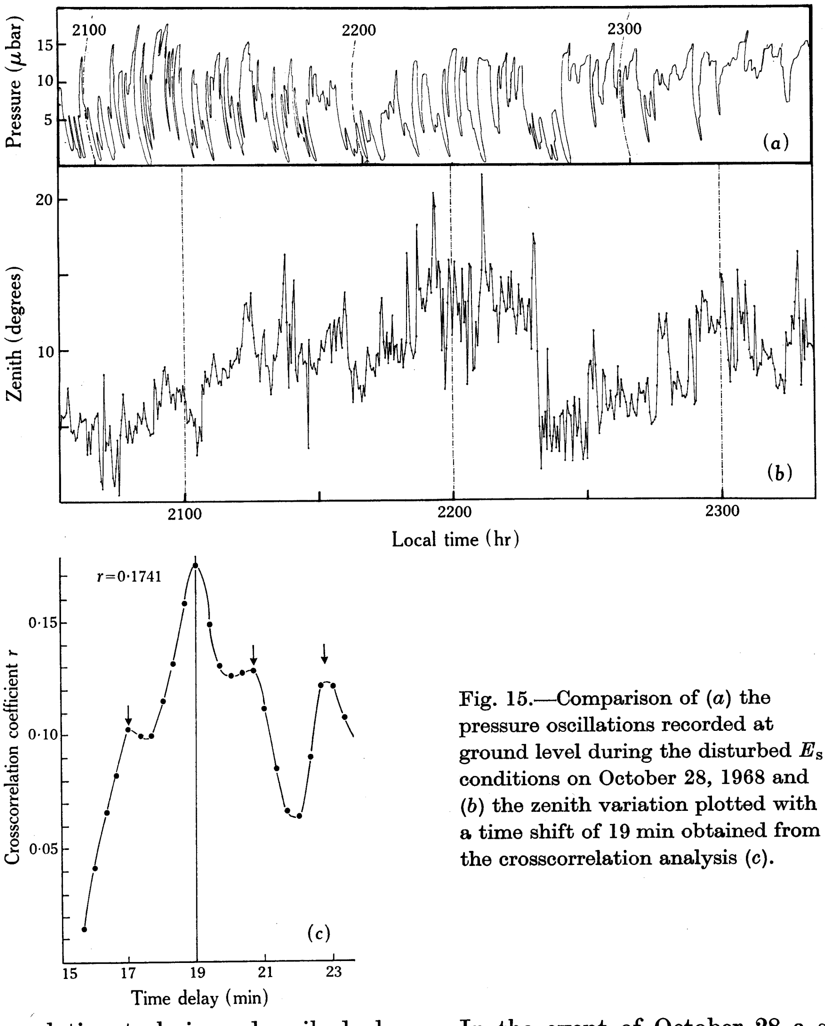

Fig. 15.—Comparison of (*a*) the pressure oscillations recorded at ground level during the disturbed E_s conditions on October 28, 1968 and (*b*) the zenith variation plotted with a time shift of 19 min obtained from the crosscorrelation analysis (*c*).

crosscorrelation technique described above. In the event of October 28 a similar pattern was found to occur at the ground 19 min later than that registered in the E_s layer (Fig. 15(*c*)). The side humps in the crosscorrelogram suggest an approximate periodicity of 2 min.

IV. Discussion

In the ionosphere, perturbation of the ionization density by waves in the neutral atmosphere can cause disturbances which can be detected by using direction-finding equipment in conjunction with spaced ionosondes. Many disturbances observed at ionospheric heights are attributed to internal gravity waves (Hines 1960, 1963, 1967; Row 1967). The characteristic of such waves is amplification as they progress upwards (Hines 1963). Hence if energy is transported vertically this could possibly result in a pronounced linkage between troposphere and ionosphere through the pressure waves, which can be detected at ionospheric heights by direction-finding equipment and at the ground by a microbarograph.

MacKinnon (1969), assuming a theoretical model of an inviscid gas above a flat non-rotating Earth, has shown for a transient ground disturbance that the waves of nearly all periods can contribute significantly to the energy flux at great heights (below the F region). The acoustic spectra of waves contribute most to the net mean vertical energy flux. At short periods (1–5 min), acoustic modes are found to be good vertical transporters of energy and also to be affected very little by the presence of winds. However, the effects of thermal conduction and viscosity become increasingly severe as waves approach the F region, and wavelengths shorter than the mean free path of molecules are removed from acoustic disturbances travelling upwards.

The results presented here showing the existence of correlations between pressure oscillations at the ground and variations in the E_s region suggest that there is an acoustic coupling between these levels.

V. Acknowledgments

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