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Infrasonic Oscillations in the F_2 Region Associated With Severe Thunderstorms

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Phase path variations of F_2 region echoes on 5.6 MHz over Waltair (17°43'N; 83°18' E) are found to exhibit prominent short-period reversals on some occasions during summer evening hours. The observed waves have periods in the range of 0.5 to about 5 min. The spectral content of the ionospheric waves is found to vary from one event to another. These disturbances are apparently associated with severe local thunderstorms in the troposphere and are interpreted as ionospheric manifestations of acoustic waves generated in the storm sources. The mechanical oscillations excited during the pulsating growth of a thundercloud are the likely source of the observed ionospheric disturbances. A simple model for the generation of acoustic waves by the developing thunderstorms is suggested.

1. INTRODUCTION

During the past five decades, meteorological phenomena have been correlated with ionospheric parameters. It was first suggested by *Wilson* [1925] that the electric field of a cloud may cause ionization changes in the ionosphere, and later, *Martyn* [1934] found that day-to-day changes in the *F* region ionization were associated with meteorological changes at the ground. An association between meteorological and ionospheric phenomena has also been reported by *Gherzi* [1950], *Beynon and Brown* [1951], and *Bauer* [1958]. *Rastogi* [1962], among others, has related ionospheric sporadic *E* with the occurrence of thunderstorms.

However, in recent years, more direct evidence for the coupling of energy from the troposphere into the ionosphere has come from the observations of temporal variations in the phase and frequency of ionospherically reflected radio waves. Thus disturbances at ionospheric heights have been observed both from natural sources [*Davies and Baker*, 1965; *Georges*, 1968*a*; *Baker and Davies*, 1969; *Davies and Jones*, 1971, 1972, 1973] and from artificial sources [*Barry et al.*, 1966; *Baker and Davies*, 1968; *Tolstoy et al.*, 1970]. The observed disturbances are successfully interpreted as manifestations of atmospheric waves that are generated in the earth's lower atmosphere and that propagate up to ionospheric heights. Among the various possible sources responsible for the observed disturbances, severe tropospheric weather phenomena gained much importance, and considerable experimental evidence has been accumulated in recent years to offer some theoretical explanations [*Jones*, 1970; *Chimonas and Peltier*, 1974].

From his HF Doppler studies, *Georges* [1968*a*] pointed out the existence of unusual fluctuations in the ionosphere, e.g., quasiperiods around 3 min, under severe weather conditions. He observed that the occurrence of severe weather is a necessary but not sufficient condition for the appearance of ionospheric effects. *Baker and Davies* [1969], and later *Davies and Jones* [1971, 1972, 1973], have reported the existence of infrasound in the F_2 region under severe thunderstorm activiy in the troposphere. From a study of the storm-associated ionospheric effects, *Baker and Davies* [1969] devised a severe weather index and found that this index was always high on days when infrasound was observed in the F_2 region. They have also observed that ionospheric effects associated with severe weather are maximum in June and are most prevalent in late spring and summer evenings. These studies have revealed that short-period fluctuations sometimes exist in the ionosphere when thunderstorms occur within a circle of about 250-km radius about the radio reflection point and when thundercloud tops exist above the tropopause level. *Georges* [1973] reviewed the severe-storm-associated infrasonic pressure fluctuations on the ground and short-period wavelike fluctuations in ionospheric phase height. He concluded that these two kinds of wave motions were different manifestations, in different parts of the acoustic spectrum, of the same emission mechanism. Recently, *Prasad et al.* [1975] suggested a geographical dependency in the occurrence of severe-storm-associated ionospheric disturbances. *Rao and Rao* [1977] reported the existence of acoustic waves in the F_2 region under cyclonic weather conditions from the low-latitude station, Waltair.

Thus most of the earlier investigations on troposphere-ionosphere coupling are confined to a few places in middle latitudes. The purpose of this paper is to report and present evidence for the occurrence of infrasonic waves in the F_2 region associated with severe local thunderstorms in a completely different part of the world. The supporting weather information is obtained from the India Meteorological Department (IMD), Waltair. Four events, which occurred on June 3, 4, 21, and 23, 1979, are analyzed and discussed here.

2. OBSERVATIONS

Phase height measurements of the F_2 region over Waltair have been made at a frequency of 5.6 MHz. The experimental details and the method of analysis of the records are the same as those described by *Reddy and Rao* [1967, 1971].

In all the samples of phase path records shown here, when

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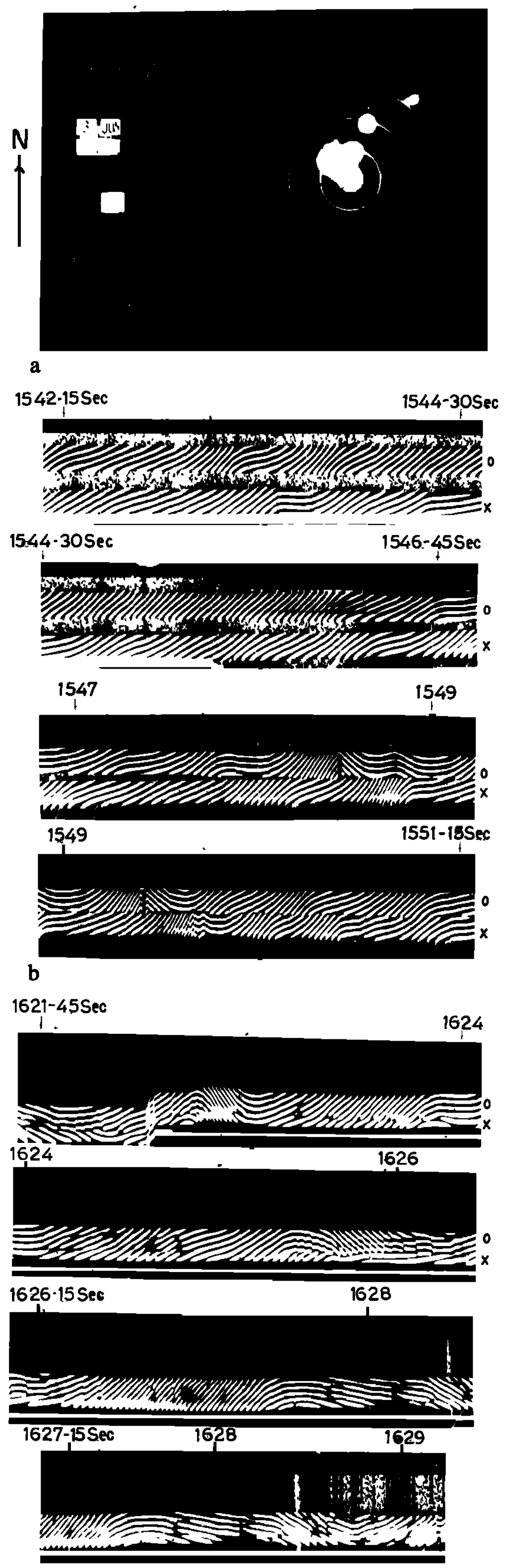

Fig. 1. (*a*) Radar weather picture of Visakhapatnam, taken at 2° elevation on June 3, 1979, at 1552 IST; observed maximum range of cloud cells is 200 km. (*b,c*) Samples of ionospheric phase path record taken on June 3, 1979, during the period from 1520 to 1630 local time (LT).

magnetoionic splitting is present, the fringe pattern at the bottom part of each sample indicates the phase path variations of the extraordinary (X) component and that above it indicates those of ordinary (O) component. The positive slope of the fringes indicates an increase in phase path and vice versa. Twice the time interval between the midpoints of the corresponding reversals in phase path gives the period of the disturbance that causes the oscillations at the radio reflection height. When the phase path increases are rapid, particularly during sunset periods, reversals in phase path are not normally observed. However, in all the events discussed here, although the phase path increases are rapid, short-period reversals did occur in pairs, sometimes characterized by well-defined wave groups, for a considerable length of time. In these well-defined wave groups the time interval between corresponding pairs of reversals is roughly constant during an event but varied from one event to another.

Samples of phase path record, corresponding to the June 3 event, are shown in Figure 1(*b, c*). Short-period reversals with different time periods can be seen in these figures. Slight perturbations in phase path, and sometimes sudden changes in phase path followed by smooth phase path reversals, are evident from Figure 1(*b*). From the similarities observed in corresponding reversals on the 'O' and 'X' records it is seen that they generally occur a few seconds earlier on the 'O' record than on the 'X,' indicating that the general direction of motion is from north to south. Sometimes the disturbances appear almost simultaneously on both the components, suggesting a west–east or east–west motion.

Figure 2(*b*) shows samples of a continuous phase path record obtained on the next day, i.e., June 4. This event lasted for about 1½ hours, and during this time a number of pairs of monochromatic phase height oscillations occurred in a series. Throughout the length of this event, the time delay in the occurrence of corresponding pairs of reversals on the two components is extremely small, with the disturbances appearing earlier on the 'X' component. It is interesting to note that the repetition period of these pairs of reversals is roughly constant around 1 min 15 s. On the average, the time delay between corresponding pairs of 'O' and 'X' reversals is around 6 s.

Samples of phase path records, corresponding to the ionospheric events that occurred on June 21 and 23, are shown in Figure 4(*a* and *b*, respectively). A series of pairs of prominent short-period reversals with symmetrical wave forms that occur one after another can be seen in these records. During these events, disturbances with longer periods as well as larger amplitudes occurred in series, undergoing a few cycles of phase change between pairs of reversals.

3. Data Analysis

All the phase path observations reported here are scaled at intervals of 15 s, except for the record that corresponds to June 3. The record of June 3 is scaled at 10-s intervals because, in this record, phase path reversals, sometimes with periods close to 0.5 min, are observed from a visual examination of the record. Continuous plots of total phase path changes with time that correspond to the four events are shown in Figures 5(*a*), 6(*a*), 7(*a*), and 8(*a*). The linearly increasing trend (diurnal variation), and any large-period variations present in the original phase height vs time series, are removed by a numerical filtering technique [*Holloway*, 1958] with a filter cutoff period of 9 min. The resulting filtered time series of the corresponding events are shown in Figures 5(*b*), 6(*b*), 7(*b*), and

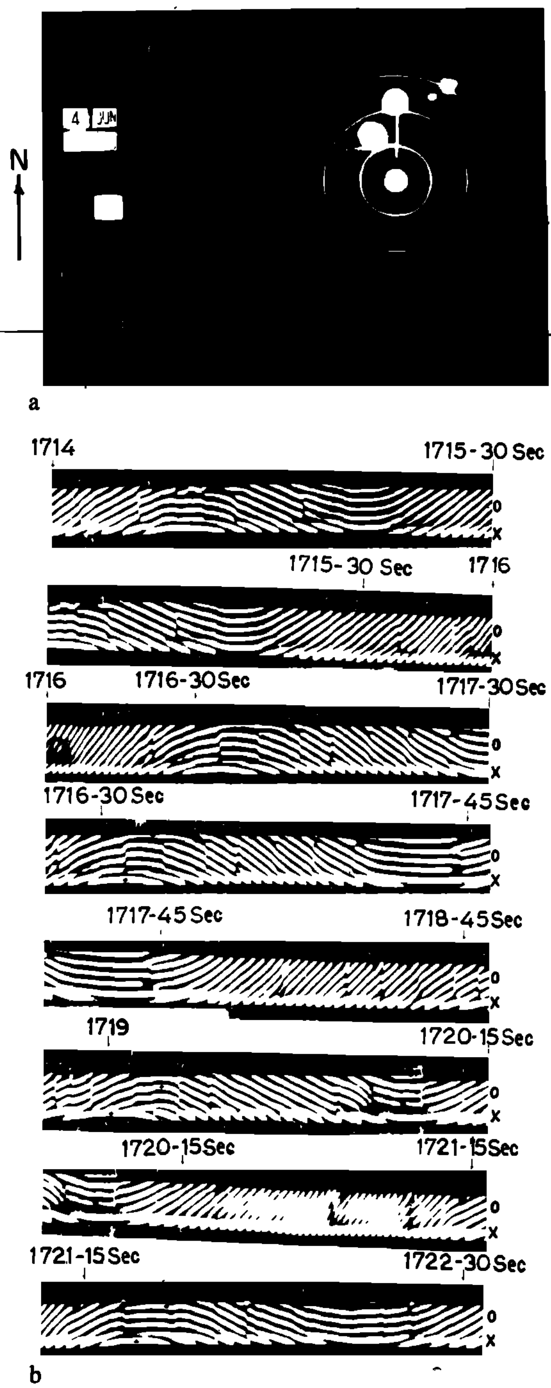

Fig. 2. (*a*) Radar weather picture of Visakhapatnam, taken at 4.5° elevation on June 4, 1979, at 1550 IST; observed maximum range of cloud cells is 200 km. (*b*) Samples of ionospheric phase path record taken on June 4, 1979, from 1630 to 1800 LT.

8(*b*), respectively. The filtered series thus obtained are subject to power spectrum analysis [*Blackman and Tukey*, 1959], and the powers of various frequency components in the spectra are smoothed by using Hanning weights [*Blackman and Tukey*, 1959] and then normalized [*Nagpal et al.*, 1974]. The power spectra are reduced to amplitude spectra, which show only the relative amplitudes of various periods because of normalization. The normalized amplitude spectra of the ionospheric phase height oscillations that correspond to the four events are shown in Figures 5(*c*), 6(*c*), 7(*c*), and 8(*c*), respectively.

Event of June 3, 1979. The IMD weather data show development of thunderclouds in the Visakhapatnam area by 1430 IST (Indian Standard Time). The clouds developed over a wide area by 1730. The cloud picture (Figure 1*a*) taken with *S* band radar at Visakhapatnam over 2° elevation at 1552 IST shows prominent thunderclouds that extend from Visakhapatnam area to the northeast, up to a distance of 175 km, with cloud tops exceeding 15 km. The Tephigram of Visakhapatnam for the third morning shows conditions favorable for thunderstorm activity, but moisture available in the atmosphere is low. This resulted in a thunderstorm without precipitation, from 1550 to 1720 IST.

The spectrum of ionospheric disturbances for this event is shown in Figure 5(*c*). It exhibits three peaks, at periods near 2.5 min, 1 min, and 0.5 min. It is interesting to note that this is the only event that exhibited three peaks. The peak at 2.5 min has also appeared in the spectrum of the next event, i.e., June 4.

Event of June 4, 1979. The weather charts show thundercloud development in the Bhubaneswar (20° 15'N; 85° 50'E)-Kalingapatnam (18° 20'N; 84° 08'E) area from 1430 to 1730 IST. The radar weather picture (Figure 2*a*) taken at Visakhapatnam at 1550 IST with 4½° elevation shows prominent thunderclouds to the north that extend over a 175-km belt oriented southwest–northeast and with the thunderheads reaching a height of over 14 km. The Tephigram of Visakhapatnam on the fourth morning shows conditions favorable for thunderstorm activity. The moisture available in the atmosphere on this day is much more than that on June 3. This resulted in prominent thunderstorm activity for a period of about 9 hours, from 1850 to 0400, in the Visakhapatnam area. The barogram of Visakhapatnam shows a marked rise of pressure at around 1630 hours because of downdraft from the thunderclouds. It may be mentioned that Bhubaneswar recorded thunderstorm activity at around 1430 hours.

The above evidence brings out the fact that the thunderstorm activity was more prominent in the Visakhapatnam area on June 4th than on June 3rd. It can also be inferred that the thunderstorms occurred to the northwest and north of Visakhapatnam earlier than the thunderstorm occurrence over Visakhapatnam, since the radar picture taken at 1550 shows thundercells to the northwest and north of Visakhapatnam.

The spectrum of ionospheric disturbances of this relatively intense event is shown in Figure 6(*c*). It exhibits a pronounced single peak near 2.5 min.

Event of June 21, 1979. On the morning of June 21, at 0830 IST, a feeble low-pressure area lay over the Bay of Bengal off the extreme north of Andhra and adjoining the south Orissa coast. On account of this system, in the afternoon/evening there was fairly widespread thunderstorm activity along the east coast, extending from north of Visakhapatnam up to Balasore (21° 30'N; 86° 56'E), as shown in Figure 3(*a*). Cumulonimbus clouds were also reported at Visakhapatnam. Thus there was intense convective activity from Visakhapatnam northeastward to Balasore, a distance of over 600 km.

This is another event in which the spectrum of ionospheric disturbances is monochromatic, as shown in Figure 7(*c*). It exhibits a prominent peak near 4.5 min.

Event of June 23, 1979. At 0830 IST, a depression, formed over north Bay of Bengal, centered about 350 km east of Puri (19° 48'N; 85° 49'E). Under the influence of this depression, intensive convective activity occurred in the afternoon/evening of the 23rd, over the land area north of Visakhapatnam

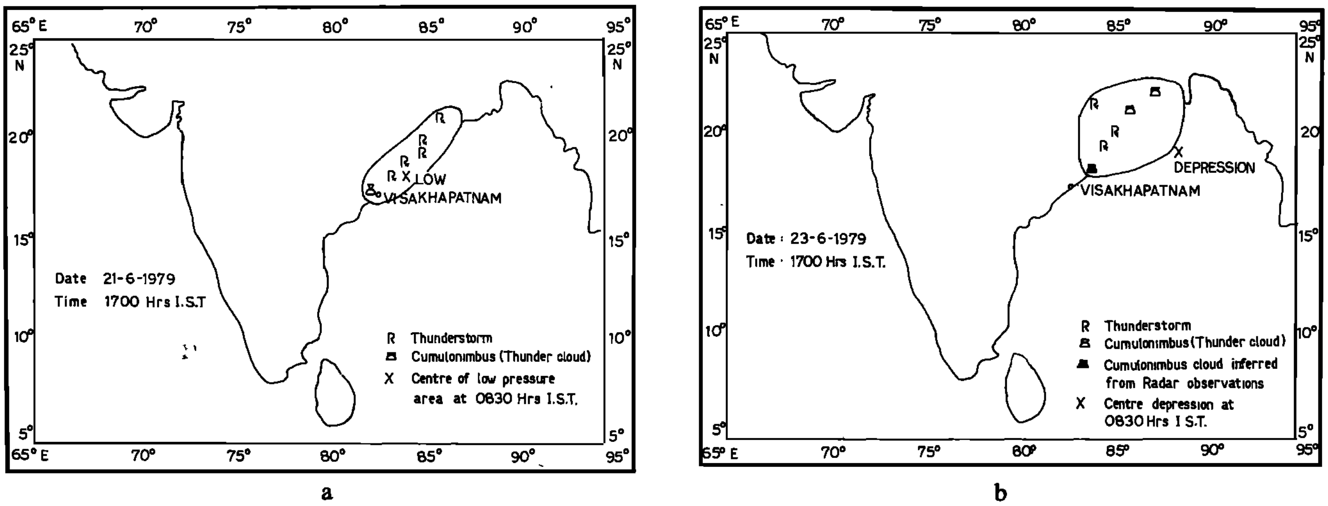

Fig. 3. Weather maps showing intensive convective activity (*a*) on June 21, 1979, and (*b*) on June, 23 1979, at 1700 IST.

(see Figure 3*b*). Good thunderstorm activity can also be inferred over the northwest bay, off the Orissa coast, on account of the depression over the north bay.

The spectrum of ionospheric phase height oscillations that corresponds to this event is shown in Figure 8(*c*). As is evident from the figure, the spectrum exhibits two peaks: a prominent peak near 4.5 min, and a minor peak near 2.5 min.

4. Simple Model for the Generation of Acoustic Waves by Thunderstorms

a. Generating mechanism. Convective activity over land can be initiated by differential heating. The rising air in a convective cloud goes in pulses. The size of a warm bubble in such a convective system can vary from a mere 1 km to about 10 km. The bubble of warm air rises, and condensation takes place through adiabatic cooling. Further feeding of warm air from below pushes the cloud upward in different turrets, and these turrets advance upward with different velocities at different intervals. Looking from the top, the cloud appears as a mushroom growth. The height of the cloud depends on the instability present in the atmosphere. A thundercloud often penetrates the tropopause and enters the lower stratosphere. Sometimes when the instability is weak, the cloud may end up at much lower heights.

The pulsating growth of a thundercloud can send compressional waves (longitudinal waves) into the atmosphere. These acoustic waves, originating in such a pulsating growth, can travel upward, provided the cloud top goes above the tropopause temperature inversion. Such longitudinal waves can generate ionospheric oscillations in the *F* layer. Even though these waves are excited above the tropopause, they have to pass through another temperature inversion at the base of the thermosphere. At late evening, when the zenith angle of the sun is large, the temperature inversion at the mesopause may be weak enough to permit at least a part of the energy spectrum to *F* region heights. Further, thunderstorms usually occur in the afternoon and sometimes extend into the late evening hours. In tropics the life of a thunderstorm is usually between 1 and 2 hours. The ionospheric oscillations typically recorded at Waltair show that they persist from 1 to 1½ hours only in the evening, supporting the above explanation.

A few azimuth determinations [*Georges,* 1973] that use

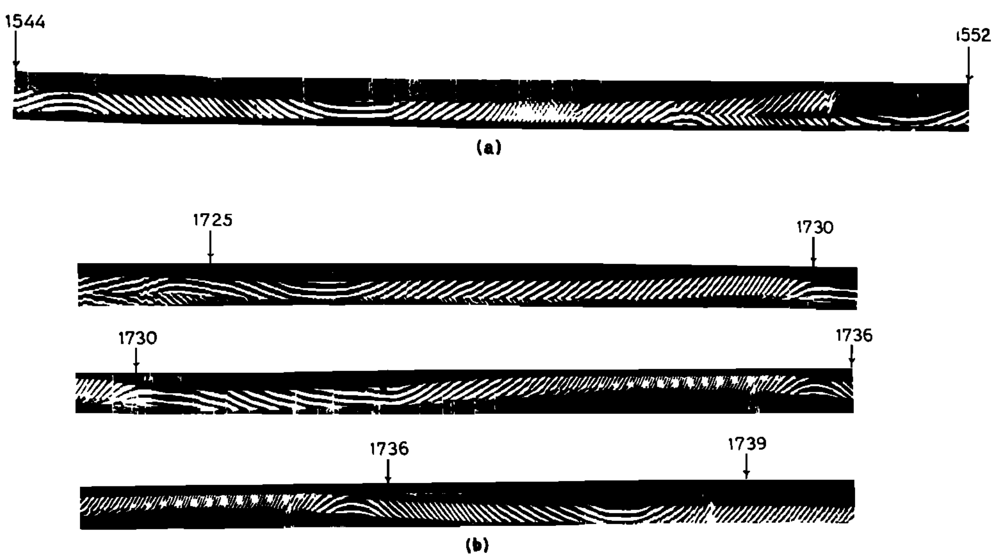

Fig. 4. Samples of phase path records taken (*a*) on June 21, 1979, during the period from 1515 to 1630 LT and (*b*) on June 23 1979, from 1630 to 1815 LT.

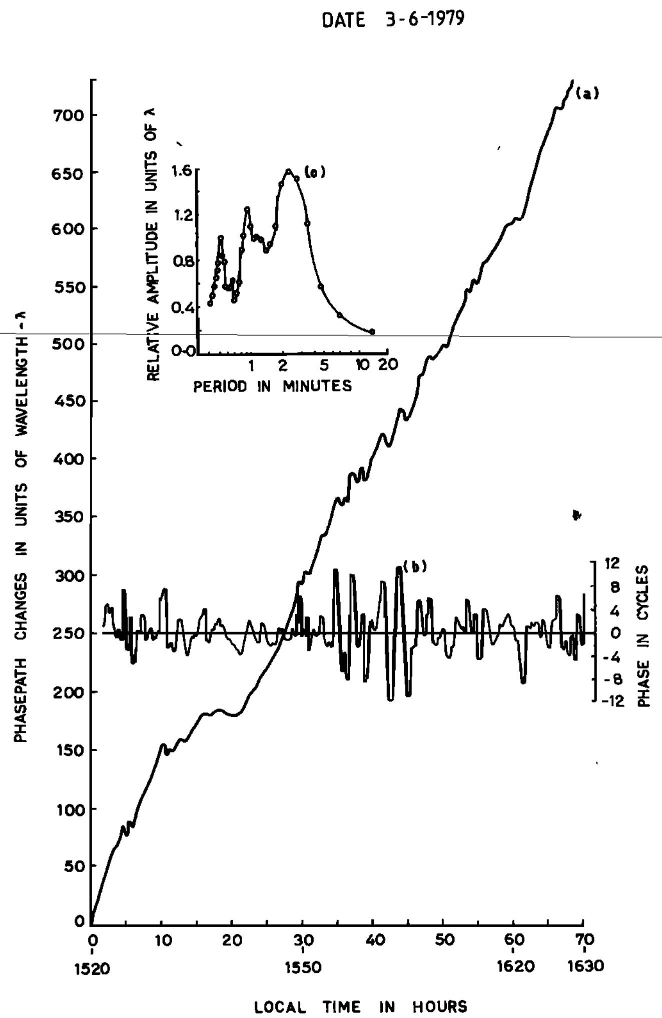

Fig. 5. (*a*) Phase height variations with time, (*b*) corresponding filtered time series, and (*c*) normalized amplitude spectrum of oscillations for the ionospheric phase path record of June 3, 1979.

spaced radio soundings made in the central United States show that the apparent source direction often shifts abruptly. This can be attributed to the rising and subsiding turrets of a thundercloud. Such growth is quite often observed in tropical regions.

b. Energy considerations. An acoustic wave carries energy as it propagates. Therefore, the mechanism that generates an acoustic wave must be capable of supplying it with the necessary energy, which can be estimated in a number of ways. It is well known, for example, that the energy released suddenly by a lightning discharge, about 10^{10} J, results in the production of acoustic waves [*Vonnegut,* 1963]. This is of the same order of magnitude as the estimate of 10^{10} J made by *Pierce and Coroniti* [1966] as the kinetic energy of the oscillations that might generate acoustic-gravity waves at the tops of cumulus clouds. This suggests that energies of the order of 10^8 or 10^9 J are necessary for the generation of acoustic-gravity waves by storm sources.

An order-of-magnitude estimate of the acoustic power of the source at the source region can be made in a simple way. It has been observed that ionospheric oscillations are almost always associated with nearby thunderstorm cells with tops above 12 km. This means that the temperature of the top of the cloud is around −40°C. At this temperature, all water particles change into ice crystals. Such a cloud moving with a velocity of 10 m/s (U) will possess energy, assuming mass of the matter in unit volume cell as 0.5 gm/cm^3, equal to $1/2 \times 0.5 \times 10^3 \times 10^3$ ergs. Taking the dimension of the cloud as 1-km radius (R), the energy associated with a moving cloud top will be equal to $0.25 \times 10^6 \times 2\pi R^2 \approx 1.5 \times 10^9$ J. This value compares well to the energy figures discussed earlier. The energy calculated by *Georges* [1973], based on an acoustic wave traveling into the ionosphere to create a typical oscillation there, requires a power of about 2.8×10^7 W. This is about 2 orders of magnitude smaller than the energy associated with a moving cloud top. The values of R and U used in the present calculation are typical of convective cells of moderate strength and could be expected to be larger for severe thunderstorms. It is therefore reasonable to assume that acoustic wave generation by such a convective system is energetically possible.

5. ESTIMATING SOURCE POWER FROM IONOSPHERIC PHASE PATH OBSERVATIONS

Following a model similar to the one adopted by *Georges* [1973], an average estimate of the severe weather source

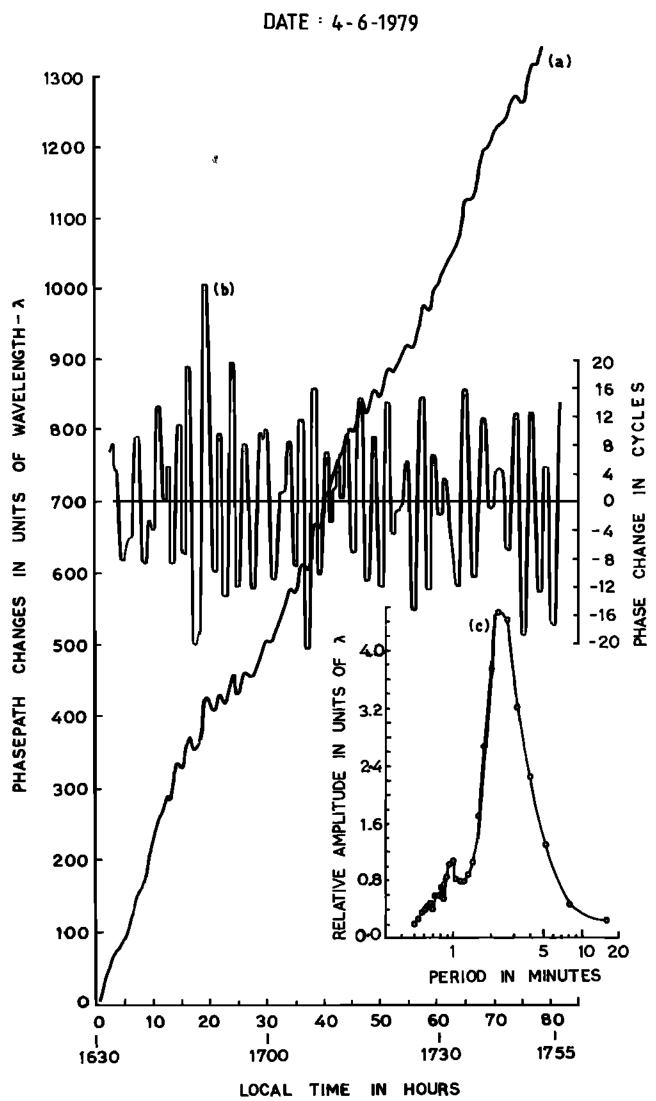

Fig. 6. (*a*) Phase height variations with time, (*b*) corresponding filtered time series, and (*c*) normalized amplitude spectrum of oscillations for the ionospheric phase path record of June 4, 1979.

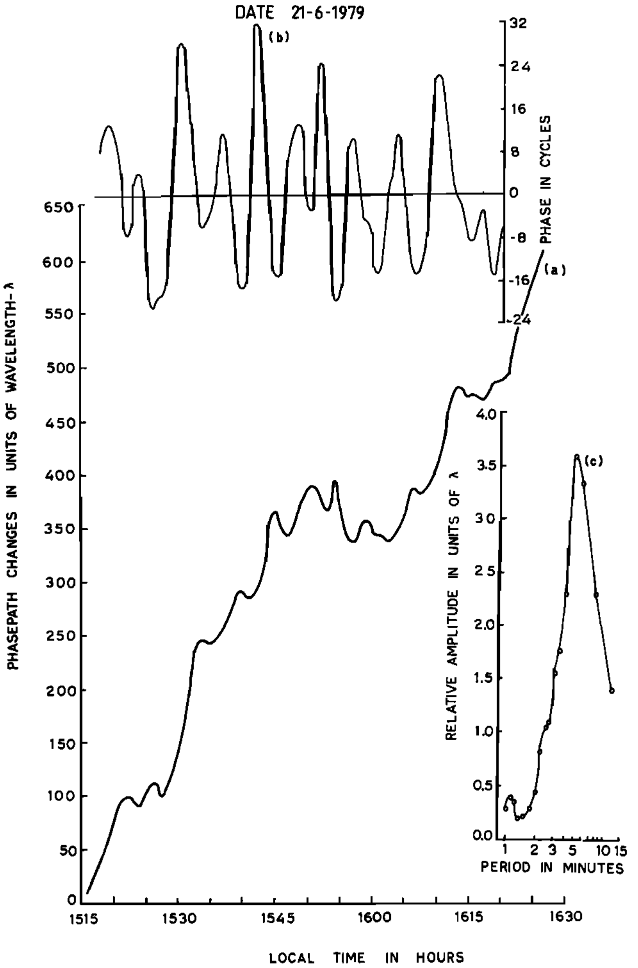

Fig. 7. (*a*) Phase height variations with time, (*b*) corresponding filtered time series, and (*c*) normalized amplitude spectrum of oscillations for the ionospheric phase path record of June 21, 1979.

power can also be obtained from the ionospheric phase path observations. For this purpose, a point source of spherical, monochromatic, acoustic waves is assumed to be located near the ground, at a typical distance of 150 km from the observing station. In the upward propagation, only a portion of the wave within a narrow cone of 30°–45° about the vertical penetrates into the thermosphere, while the rest is refracted back into the lower atmosphere because of the large temperature gradient at the base of the thermosphere. The waves propagating in that narrow cone are not refracted very much, and in their vertical propagation they remain essentially spherical.

When the acoustic wave travels through the ionosphere, the motions of the neutral particles are transferred to the free electrons via collisions. The ionization movement results in up and down motion of the level of radio reflection, which in turn causes phase path increases and decreases in the received radio echo. In the presence of the earth's magnetic field, only the component of the neutral particle motion U_B parallel to the field is communicated to the ionization as shown in Figure 9. The average time interval between collisions is short enough that, for the wave periods of interest here, the ionization moves in phase with the neutral wave.

Let U be the wave-associated neutral-air velocity and U_Z be the vertical ionization velocity, then assuming an elevation angle of $\theta°$ between the direction of propagation and the horizontal, we have

$$U_Z = U \sin I \cos(\theta - I) \qquad (1)$$

where I is the inclination of the local magnetic field. The expression reduces to $U \sin^2 I$ for the case of vertical propagation [*Georges*, 1968*b*].

Now the neutral-wave amplitude is linked to the phase height oscillations of the reflecting layer, which in turn can be simply related to the rate of change of phase path. Assuming specular reflection of the probing radio wave of frequency f_0, it can be written mathematically as [*Georges*, 1973]

$$-\frac{c_0}{f_0}\Delta f = \frac{dP}{dt} \cong \frac{2dh}{dt} \cong 2U_Z = 2U \sin I \cos(\theta - I) \qquad (2)$$

where c_0 is the free-space velocity of light, Δf is the induced Doppler shift, P is the radio phase path, and h is the radio reflection height.

Now if dP/dt is estimated from the phase path records at the time when an acoustic wave is causing phase height oscillations of the reflecting layer, U, the velocity amplitude of the neutral acoustic wave, can be calculated with the help of (2). Corresponding to the June 4, 1979, event, which exhibits a monochromatic spectrum near 2.5 min, dP/dt, on the average, is found to be 20 m/s for a transmitted frequency of 5.6 MHz. Thus for $I = 20°$ (for Waltair) the velocity amplitude of the neutral acoustic wave is then

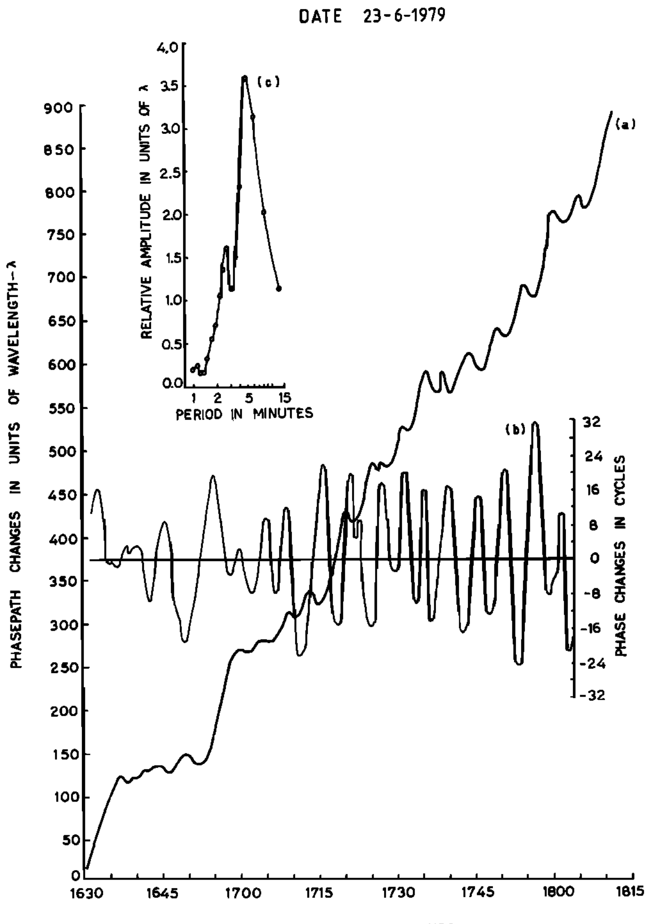

Fig. 8. (*a*) Phase height variations with time; (*b*) corresponding filtered time series, and (*c*) normalized amplitude spectrum of oscillations for the ionospheric phase path record of June 23, 1979.

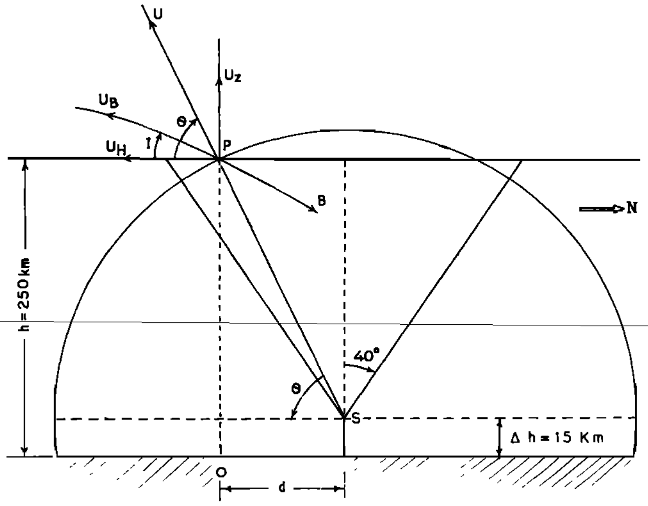

Fig. 9. A simple model of the acoustic wave propagation from a source near the ground to the overhead ionosphere at a low-latitude observing station: d—ground range of the source from the station; θ—angle between propagation direction and the horizontal; P—radio reflection point; S—source; O = observing station; and the cone angle of energy propagation to the ionosphere is 40° (typical value) from the vertical.

$$U = \frac{dP/dt}{2 \sin I \cos(\theta - I)} \approx 38 \text{ m/s} \quad (3)$$

where θ is about 60° for a typical ground range d = 150 km.

The corresponding source power can be estimated by calculating the average power flux density P_d in these waves across a surface situated at a slant range R_s

$$P_d = \frac{1}{2} \rho_0 v U^2 \text{ W/m}^2 \quad (4)$$

where ρ_0 is the ambient air density and v is the ambient sound speed appropriate to the ionospheric height h, which is typically of the value 250 km. Since the dimension of the source (≈1 km radius) is very much less than the wavelength of the acoustic waves (≈50 km), a spherical radiation from the source can be assumed. Hence the total emitted power of the source can be obtained by integrating P_d over a spherical surface of radius R_s and is given by

$$W = (2\pi R_s^2 + 2\pi R_s \cdot \Delta h)\, P_d \quad (5)$$

where Δh is the height of the source above the ground, typically of the order of 15 km.

Assuming the atmospheric density $\rho_0 = 7.2 \times 10^{-11}$ kg/m³ [*COSPAR*, 1972] and the sound speed v = 800 m/s that corresponds to the radio reflection height h = 250 km, the source power is estimated to be about 2.31×10^7 W.

While evaluating the total power radiated by the source according to (5), it will be useful to consider to what extent the above represents the true state of affairs. The above equation assumes uniform flux density across the entire surface under consideration, which is evidently a gross approximation, as revealed by the following facts. It is known that acoustic energy propagating through a cone described by an angle of about 30°–45° from the vertical will reach the ionosphere, and the rest is refracted back and would ultimately flow past the surface under consideration, at lower altitudes. The estimated power would be low to the extent that loss processes, namely, transmission loss in the process of a series of partial reflections between layers of different atmospheric densities, are due to viscosity and heat conduction. The transmission coefficient α_t given by *Kinsler and Frey* [1962]

$$\alpha_t = \frac{4\rho_2 v_2 \rho_1 v_1}{(\rho_2 v_2 + \rho_1 v_1)^2}$$

where $\rho_1 \rho_2$ and $v_1 v_2$ refer to densities and sound velocities in two adjacent layers of the atmosphere, varies between the maximum value of unity for the energy propagating in a horizontal direction to a minimum value in the case of vertical propagation for a horizontally stratified atmosphere. The flux density obtained from phase height oscillations of the ionospherically reflected radio wave, and used in the evaluation of total power, is what is actually measured after the energy has been subjected to a considerable transmission loss wherein the wave undergoes repeated partial reflections and is dissipated. In view of the above the actual power radiated by the source would be greater than that obtained for a near-vertical direction. Because the transmission coefficient is maximum in the horizontal direction, considerable energy flows horizontally. If a proper account were taken of the above losses and other effects, the source power would be more than the present estimated value of 2.31×10^7 W and would be closer to the value 1.5×10^9 W estimated from the meteorological data in section 4(*b*). The present estimated value also compares well with that of *Davies and Jones* [1972] and *Georges* [1973], who obtained the source power by using Doppler shift observations under severe weather conditions in mid-latitudes and neglecting the acoustic losses and the effects of refraction and reflection.

6. DISCUSSION

The observed periods of disturbances in all the events discussed here range from 0.5 to about 5 min. This range falls within the narrow band of periods of acoustic waves expected at ionospheric heights [*Georges*, 1968*a*]. The predominantly evening occurrence of these ionospheric effects, and the range of observed periods of disturbances, also agree well with those of earlier investigators [*Baker and Davies*, 1969; *Davies and Jones*, 1971]. The striking appearance of these short-period waves, which occur in pairs, sometimes characterized by well-defined wave groups, for a considerable length of time on the records, with their characteristic symmetrical signatures, suggests that these are not horizontally traveling waves like the medium-scale traveling ionospheric disturbances (TIDs) that are normally observed at this station during daylight hours. Further, the extremely small time delays between the occurrence of corresponding pairs of reversals on the 'O' and 'X' components suggest that the observed disturbances are caused by waves that propagate upward with much faster speeds than the usually occurring normal TIDs. Acoustic waves that originate in thunderstorms and propagate upward from below could be responsible for the observed disturbances. The localized nature of these ionospheric disturbances is consistent with the behavior of freely propagating acoustic waves in a thermally stratified atmosphere [*Baker and Davies*, 1969]. That these disturbances are acoustic waves is reinforced by multifrequency radio soundings that reveal vertical phase speeds comparable to the local speed of sound [*Georges*, 1968*a*].

The spectral range of the observed disturbances varied from one event to another, an observation that is also consistent with those of earlier investigators [*Prasad et al.*, 1975]. It is interesting to note that in all the four ionospheric events discussed here, the thunderstorms lie to the north of the observing station within a circle of about 200-km radius. This observation is in agreement with the condition discussed by *Davies and Jones* [1971] that, under such circumstances, the energy transfer from the neutrals to the electrons via collisions is maximum because of the way the waves move the ionization under the influence of the geomagnetic field.

The exact emitting mechanism associated with severe penetrative convection that radiates these subaudible acoustic waves is not yet clearly known. *Pierce and Coroniti* [1966] suggested that the oscillating tops of cumulus clouds could generate atmospheric waves that propagate upward. In a study of the vertical velocity of cumulus clouds, *Anderson* [1960] found that the velocity pulsates with a pronounced longer-period component of about 10 min, and also with shorter-period components of the order of 1 min. It is possible that the source, during its pulsating growth, produces a spectrum of oscillations and that the rather narrow band of periods observed at the *F* region heights is a consequence of atmospheric filtering as suggested by *Georges* [1968*a*]. On the other hand, *Baker and Davies* [1971] favored that the narrow band of periods observed at ionospheric heights is a characteristic of the source. However, more storm-associated ionospheric effects, as well as a study of the spectra of ionospheric oscillations during the lifetime of a single storm, may lead to a better understanding of the nature of oscillations generated by storm sources.

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