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Acoustic waves in the ionosphere

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Abstract—An unusual traveling ionospheric disturbance has been detected from Faraday rotation observations of 40- and 41-MHz signals from the radio beacon satellite BE-B, inclination 80°, observed simultaneously at Urbana, Illinois, (40·1°N, 88·2°W); Danville, Illinois, (40·1°N, 87·6°W); London, Ontario, (43·0°N, 81·3°W) and Hamilton, Massachusetts, (42·6°N, 70·8°W) three of which are widely spaced. The fluctuations in the total electron content deduced from these observations are interpreted as a superposition of long—about 3·5 min—and short period—about 15–50 sec—acoustic waves. The magnitudes obtained for horizontal velocities of propagation averaged about 4·5 km/sec at 350 km height and indicate wavefront tilts averaging about 10° from the horizontal if the waves are assumed to travel at the speed of sound at 200 km height.

1. INTRODUCTION

TRAVELING ionospheric disturbances have been studied for a number of years using a variety of techniques (see GEORGES, 1967 for an extensive bibliography). The periods of these disturbances have been known to vary from a few seconds to several minutes and even a few hours. The time resolution permitted by several of these techniques is not sufficient to observe very short period disturbances, i.e. periods of few seconds. Examples of techniques which are capable of detecting such very short period waves are those utilizing continuous sounding of the ionosphere at fixed frequencies provided recording is done at a fast speed. Recently, RAO and YEH (1968*a*) demonstrated the utility of Faraday rotation observations of orbiting satellite signal transmissions at three closely spaced stations for deducing all three characteristics, i.e. velocity of propagation, wavelength and period of traveling ionospheric disturbances. From observations at stations situated approximately at the corners of an equilateral triangle of sides about 50 km, they were able to detect a traveling disturbance of period about 3 min.

In this paper, this technique is applied to observations at widely spaced stations and the results for an event characterized by periods of the order of only a few seconds are presented and discussed. The three stations of interest are Urbana, Illinois, (40·1°N, 88·2°W); London, Ontario, (43·0°N, 81·3°W); and Hamilton, Massachusetts, (42·6°N, 70·8°W). In addition, observations at Danville, Illinois, (40·1°N, 87·6°W) are used to resolve an ambiguity created due to the wide spacing of Urbana, London and Hamilton. The satellite is beacon explorer-B(BE-B) which has an orbital inclination of about 80°. 40- and 41-MHz signal Faraday rotation

data recorded during revolution 11618 on February 2, 1967, are analyzed for total electron content up to the satellite height (about 1000 km) using the well-known differential Faraday method (e.g., LYON, 1967; RAO and YEH, 1968*b*). A value of 350 km is assumed for the mean ionospheric height used for computing the geometric-magnetic factor $\overline{M}$ which relates the Faraday rotation to the total electron content.

2. ANALYSIS

Figure 1 shows the total electron content vs. Eastern Standard Time curves for the three stations: Urbana, London and Hamilton. The variations in content depicted by these curves may be interpreted as a superposition of short and long

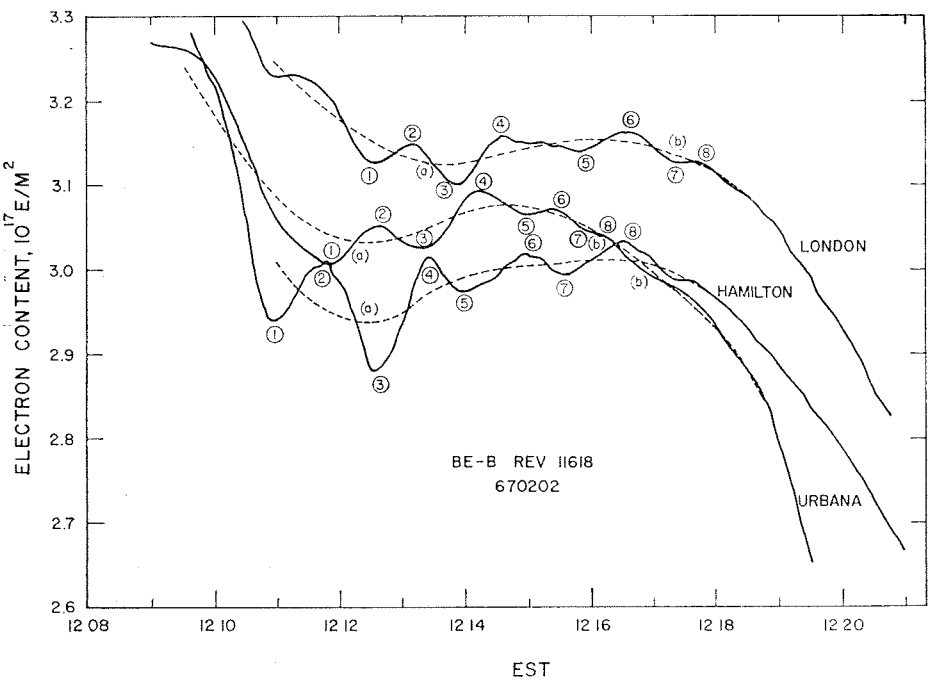

Fig. 1. Electron content versus E.S.T. curves for BE-B revolution 11618 on February 2, 1967, observed at Urbana, London and Hamilton stations.

wavelength fluctuations. Smooth curves are drawn by inspection to identify the long wavelength fluctuations. These are shown dashed. Two sets of times denoted (a) and (b), one corresponding to maxima in content and the other corresponding to minima in content are identified from the dashed curves by inspection. The times of maxima and minima in the actual content curves are determined on the basis of maximum percent deviation from the smoothed curves. These groups of times are denoted 1 through 8.

Figure 2 shows the subionospheric paths of the satellite for the three stations using 350 km for the mean ionospheric height. The times corresponding to maxima and minima in content are indicated beside the squares and circles which represent the co-ordinates of the subionospheric points for the respective times. The squares correspond to groups (a) and (b) and the circles correspond to groups 1 through 8.

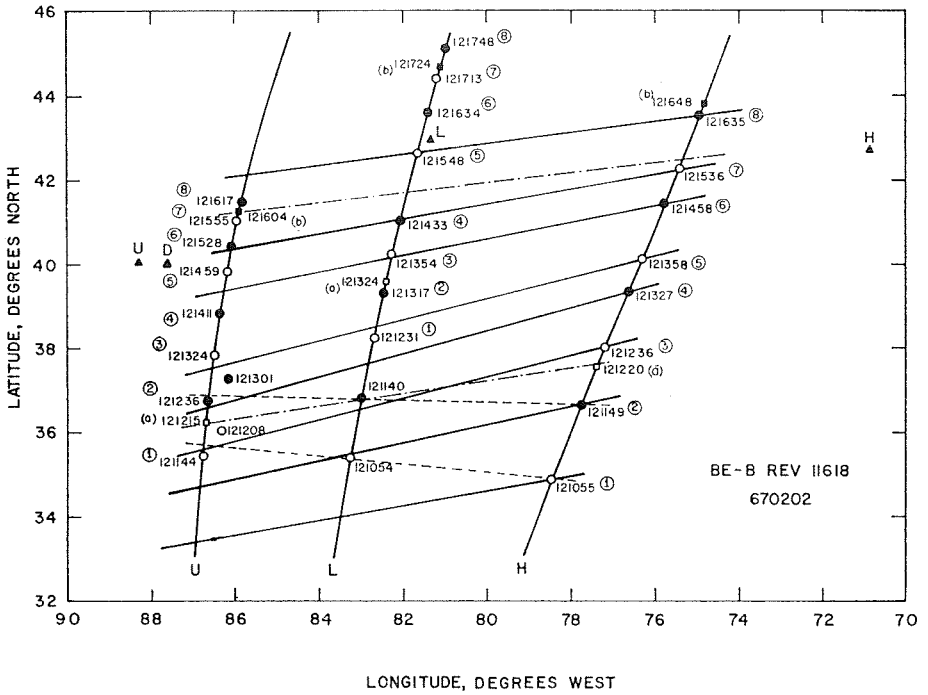

Fig. 2. Geometry pertinent to the fluctuations in electron content for revolution 11618 on February 2, 1967, observed at Urbana (U), Danville (D), London (L) and Hamilton (H). The curved lines represent subionospheric paths of the satellite and the straight lines represent wavefronts. The wavefront orientations shown correspond to the times at the Urbana station for groups (a) and (b) and to the times at the Hamilton station for groups 1 through 8.

Solid squares or circles represent maxima and hollow squares or circles represent minima in content. For the London subionospheric path, two additional times, namely, 121054 and 121140 are shown. Locations of the stations are indicated by the triangles.

Following the method outlined by Rao and Yeh (1968*a*), the characteristics for both the long wavelength and the short wavelength fluctuations are obtained. Briefly, this consists of constructing a wavefront and determining the horizontal phase velocity for each set of three points assuming plane wave propagation. The wavefront orientations thus obtained are shown by the alternately dashed and dotted lines for groups (a) and (b) and by the continuous lines for groups 1 through 8. For each adjacent pair of wavefronts, a value of wavelength is obtained from which the period is computed. The results are shown in Table 1 for the long wavelength fluctuations and in Table 2 for the short wavelength fluctuations. Note that the periods in Table 2 are in seconds whereas that in Table 1 is in minutes.

If the times 121144, 121054 and 121055 are chosen to represent group 1 instead of the times 121144, 121231 and 121055, the resulting wavefront orientation is shown by the dashed line passing through 121054 and 121055. Similarly, the wavefront orientation due to the grouping of 121236, 121140 and 121149 instead of 121236, 121317 and 121149 is shown by the dashed line passing through 121149.

Table 1. Characteristics of long wavelength fluctuations (Assumed height is 350 km)

Group	Phase velocity Magnitude (km/sec)	Phase velocity Direction (°N of E)	Wavelength (km)	Period (min)
(a)	4·40	99	915	3·45
(b)	4·10	98		

Table 2. Characteristics of short wavelength fluctuations (Assumed height is 350 km)

Group	Phase velocity Magnitude (km/sec)	Phase velocity Direction (°N of E)	Wavelength (km)	Period (sec)
1	4·78	104	212	44
2	4·85	103	252	52
3	5·03	104	195	39
4	5·48	106	136	25
5	4·03	104	90	22
6	3·90	102	78	20
7	3·85	100	60	16
8	4·06	99		

The velocities of propagation corresponding to these and other wavefronts formed by successive groups of points vary from 0·27 to 1·1 km/sec and are directed southward in contrast to the northward propagation for the results of Tables 1 and 2. The corresponding wavelengths vary from 180 to 410 km and the periods from 4 to 15 min. Thus, there is an ambiguity since both sets of results are physically reasonable.

However, this ambiguity is resolved by examining the content results for the fourth station, i.e. Danville. The first maximum and minimum in the Danville content curve are found to occur at 121208 and 121301 respectively. The subionospheric points corresponding to these two times are shown in Fig. 2. It is immediately apparent that these points are consistent with the wavefront orientations shown by the continuous lines and not with those shown by the dashed lines. Thus, the solutions corresponding to the wavefront orientations shown dashed are rejected. Only two points for the Danville station are shown to avoid congestion in Fig. 2. Other points lead to the same conclusion. Also, the wavefront orientations

and the resulting characteristics for groups 1 through 8 are more internally consistent than those for the rejected groupings.

3. Discussion

Previous observations of acoustic waves in the ionosphere having periods of the order of magnitude reported here are very few. Using a high-frequency Doppler sounding technique, Baker and Davies (1968) observed waves with periods about one minute generated by nuclear explosions. Using the same technique, Georges (1967) reports of short period Doppler fluctuations (about a minute) during magnetic sudden commencements but he finds these to be apparently simultaneous at widely spaced stations and hence not traveling in the usual sense. He also observed occasional geographically localized and vertically propagating wavelike disturbances with a characteristic period of about three minutes seemingly associated with severe surface weather activity (see also Georges, 1968). Perhaps the only previous observation of periods less than a minute has been by Shrestha (1967) who reported oscillations in virtual height-time records at fixed frequencies ranging from 10 to 50 sec.

The event reported here can also be explained on the basis of acoustic waves propagating nearly vertically. The computed velocities of propagation are horizontal velocities at an assumed height of 350 km. However, the actual heights of occurrence could be below 350 km and probably different for the long and short period waves. Also, the almost sinusoidal (although decreasing in magnitude) nature of the content curves seems to imply that the bulk of the perturbation was confined to a region small in vertical extent. For acoustic waves of periods reported here, this can be explained since although much of the acoustic energy is confined to lower heights, the ambient electron density is too small at these heights to give appreciable content perturbation whereas at greater heights, the waves are attenuated rapidly. For example, the shortest periods observed here fall into the range within which the waves are attenuated by more than 1 dB/km above about 300 km and by more than 0·1 dB/km above about 200 km (Georges, 1967). Assumption of a height between 200 and 350 km does not alter the periods significantly since the maximum values of only about 1–2 min and 8 min for the short and long wavelength fluctuations respectively are reached for zero height.

If a value of 700 m/sec (approximately equal to the speed of sound at 200 km) is assumed for the velocity of propagation, the wavefront tilts range from about 7° to about 15° from the horizontal. The fact that the horizontal velocities of propagation are greater than the satellite velocity projected to 350 km implies that the waves associated with increasing numbers of the groups in Fig. 2 actually originated in that order timewise. It is also of interest to note that the amplitude of the perturbation increases with the period which is in the same sense as the frequency squared dependence of acoustic wave attenuation.

It is not known if the 3·45 min for the long wavelength perturbation has any relation to the characteristic period of three minutes observed by Georges in connection with severe weather activity. A check of daily weather map published by the ESSA weather bureau for 1300 E.S.T. on that day indicated some precipitation in a major portion of the area covered in Fig. 2. There was a cold front in the southeastern half of the area advancing to the southeast and a warm front in the northeastern portion of the area advancing towards northeast. The two fronts met at a

point not far from the Hamilton station. No other details were shown and hence a definite conclusion cannot be drawn as to whether or not the observed disturbance was due to surface weather activity.

The foregoing discussion is based on the assumption of a source below the ionosphere i.e., vertical velocity of propagation is directed upward. However, since the Faraday rotation technique gives only the horizontal velocity, it is equally probable that the vertical velocity is directed downward. In support of this alternative, one can argue that it is difficult to accept the hypothesis of a plane wave excitation over such a wide geographic area if the source is below the ionosphere. Also, a downward vertical velocity tends to orient the direction of propagation along the magnetic field lines which seems to be attractive.

However, the plane wave assumption used in the method of analysis does not imply that the actual phenomenon observed is due to plane wave propagation. If the source is indeed below the ionosphere, it only means that the plane wave assumption is not strictly valid. Nevertheless, the results based on this assumption exhibit a high degree of internal consistency. Also, one might expect that the ray direction corresponding to the maximum content deviation approximates the angle of wavefront tilt. Since the content deviations in Fig. 1 are in general greater when the ray path is low to the south, the computed 10° average value for the wavefront tilt is such that the irregularity height is greater towards the equator and lower towards the pole. This feature favors the upward direction for the vertical velocity of propagation.

Other geophysical data were examined for possible correlations with the observed event and clues regarding the causative mechanism. Rapid run magnetograms recorded at Boulder, Colorado; Fredericksburg, Virginia and Great Whale River, Ontario, near the time of the satellite passage showed no significant correlation with the event. Ionograms from Washington, D.C., and Ottawa, Ontario, showed evidence of perturbations, especially at the underside of the F-region, although not in the form of series of cusps reported by Shrestha (1967). It has not been possible to obtain further useful information since the ionograms were recorded only at 15-min intervals. The day of observation was characterized as one of the five magnetically quiet days. The sum of K_p index for the 24 hr prior to the time of satellite passage was 3-.

4. CONCLUSION

In conclusion, the reported event fits well with the phenomenon of acoustic waves propagating in a near vertical direction in the ionosphere. The phenomenon is complex; however, of necessity and for lack of sufficient correlative data, the analysis and discussion are simplified. Since the method of observation does not yield the vertical velocity of propagation, arguments for and against the two directions are presented. If the source was below the ionosphere, the observed electron content fluctuations must be due to the coupling of neutral-acoustic waves to the ionized medium whereas if the source was above the ionosphere, the event could be an experimental evidence of ion-acoustic waves.

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