Vertical phase and group velocities of internal gravity waves
derived from ionograms during the solar eclipse of 24
October 1995

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Abstract

A procedure is developed to derive the vertical phase and group velocities of waves from measurements of ionograms. We apply the developed procedure to a sequence of ionograms recorded by the digisonde portable sounder in Taiwan and find numerous waves occurring in the ionosphere during the solar eclipse of 24 October 1995. A detailed analysis of an 87-min period wave shows that the vertical phase velocities of the wave below and above the F1 ledge are about 100 m s\(^{-1}\) in the downward and upward directions, respectively. The associated group velocities below and above the ledge are found to be about 10 m s\(^{-1}\) in the downward and upward directions, respectively, which indicates that during the solar eclipse the wave source is near the F1-ledge. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

Ionospheric eclipse observations make a worthwhile contribution to study transient properties due to decreasing ionizing radiation from the Sun. One of the scientific goals in solar eclipse campaigns is to study the source-response relation between the ambient rates of production, chemical loss and motion of ionization, and the internal atmospheric gravity waves (AGWs). Chimonas and Hines (1970) suggested that, as the lunar shadow sweeps at supersonic speed across the Earth, the cooling atmosphere acts as a contributor of gravity and builds up a bow wave. Many attempts have been made to detect such waves with varying degrees of success (for references, see the papers listed in Davies, 1990). Meanwhile, a number of investigators found that the nature and magnitude of the effects of internal atmospheric gravity waves are significantly affected by the ambient rates of production, chemical loss and motion of ionization. Hooke (1967) applied a perturbation treatment and concluded that, at heights at or below the height of the F1-ledge, chemical effects, in particular the effect of gravity waves on the rate of photoionization, are quite important. Although the causal mechanisms are not well understood, scientists (Walker et al., 1991; Cheng et al., 1992; Tsai and Liu, 1997) recently showed direct evidence for the induced AGW by the solar eclipse, obtaining periods of tens of minutes.

In previous work, the ionosonde techniques were often employed to derive the apparent (or phase) velocity of internal AGW in the ionosphere (Morgan et al., 1978; Tedd et al., 1984; Walker et al., 1988; Huang and Chen, 1991; Chen and Huang, 1992; Wan and Li, 1993); however, they have not been applied to obtain vertical group velocities. In this paper, we mainly follow the procedure employed by Liu (1996), but assisted with the true height analysis developed by Tsai et al. (1995), to examine in detail the vertical phase and group propagation of
gravity waves in the ionosphere during the eclipse of 24 October 1995.

2. Methodology

Liu and Berkey (1993) examined oscillations in virtual height, echo amplitude and Doppler velocity of a fixed sounding frequency obtained from ionosondes and found the power spectra of these phase parameters to be nearly identical. With careful studies in theoretical development and data analysis, they concluded that several different parameters measured by or derived from ionospheric soundings can be used to study ionospheric waves. It can be seen that, if a single sounding frequency is applied, we can only monitor ionospheric waves at a particular height. However, when many sounding frequencies are transmitted, ionospheric waves at various heights can be simultaneously observed. On the basis of Liu and Berkey (1993), we can reveal signatures of ionospheric waves at various heights by extracting time series of virtual heights from a sequence of ionograms.

To obtain the phase velocity along the ionosonde beam direction, we simply adopted the method developed by Kuo et al. (1993). Following their idea, the Fourier analysis of time series of virtual height fluctuations extracted from the sequence of ionograms at a fixed radiowave (sounding) frequency \( f_r \), \( h_i, i = 1, 2, 3, 4, \ldots, N \), with time resolution \( \Delta t \) and frequency resolution \( \Delta f \), can be written as

\[
h_i = A_0 + \sum_{j=1}^{N} \left( A_j \cos \sigma_j t_i + B_j \sin \sigma_j t_i \right)
\]

(1)

Since the virtual height and true height are different (Titheridge, 1985; Liu et al., 1992), to determine the true height for each time series of virtual height fluctuations properly, we further applied the method developed by Tsai et al. (1995) converting the recorded ionograms into their corresponding true height traces. With a similar procedure to the virtual heights, the time series of true height fluctuations and the mean value for each sounding frequency are obtained. Our idea of obtaining the correct phase velocities is to consider that, for each sounding frequency, the time series of virtual height fluctuates at an averaged true height which is the mean value of the associated true height fluctuations. Note that, unlike Kuo et al. (1993), the height resolutions \( \Delta z \) in the current study is not necessarily a constant.

If the fluctuations are caused by gravity waves in the ionosphere, we can express them as the combination of plane waves

\[
h_i = A_0 + \sum_{j=1}^{N} \left( c_j \cos (\sigma_j t - k_j x - l_j y - n_j z) \right)
\]

(2)

and

\[
\sigma_j = 2\pi j/N
\]

(3)

where \( \sigma_j \) represents the observed frequency of the \( j \)th harmonic, and \( k_j, l_j, \) and \( n_j \) are the wave numbers of the \( x \)-, \( y \)-, and \( z \)-components, respectively. For the routine observation of ionosondes, the ionograms being obtained by vertical sounding (the \( z \)-component), and for studies of a long-period AGW, the horizontal wavelength being much greater than the horizontal range of ionosonde volume, the \( x \)- and \( y \)-components of the observed targets do not change along the ionosonde beam. Therefore, \( k_x + l_y \) is constant, which results in the following relation being obtained

\[
k_x + l_y + n_z = \tan^{-1} \left( B_j/A_j \right) = \Phi(z) = n_z
\]

(4)

If the \( j \)th harmonic is present in the physical quantity, then the Fourier analysis of the time series of successive heights should give a smooth function \( \Phi(z) \) and the vertical wave number \( n_j \) can be obtained by differentiating \( \Phi \) with respect to \( z \), that is,

\[
n_j = \frac{d\Phi}{dz} = \frac{d}{dz} \left( \tan^{-1} \left( \frac{B_j}{A_j} \right) \right)
\]

(5)

Consequently, the vertical phase velocity is given as

\[
\nu_v = \frac{\sigma_j}{n_j}
\]

(6)

Instead of a monochromatic wave, a wave packet centered at the center frequency is usually detected in the observed data. The wave packet propagates with the group velocity, that is the velocity at which energy is transmitted. To evaluate the group velocity, the different frequencies closely distributed within the packet must be identified by successively changing the length of the data. When the data changes from \( T = N \Delta t \) to \( T' = (N - \Delta N) \Delta t \), both the observed frequency of the \( j \)th harmonic \( \sigma_j \) and the vertical wave number \( n_j \) change. Then, the group velocity of the wave packet is simply the derivative of \( \sigma \) with respect to \( n \)

\[
\nu_v = \frac{d\sigma}{dn}
\]

(7)

Note that, to maintain the different frequencies \( \sigma \) closely distributed within the packet (or the bandwidth of the central frequency), \( \Delta N \) must be an integer much smaller than \( N \).

3. Observation and data analysis

The solar eclipse of 24 October 1995 at Chung-Li began at 0311 UT (LT = UT + 0800), reached a peak of 49% disk obscuration at 0435 UT, and ended at 0556 UT. Rapid sequence ionograms above the National Central University (NCU) Observatory (24.9 N, 121.5 E, 35.2 N
Magnitude dip) were recorded between 0100–0900 UT at 5-min intervals by the Digisonde Portable Sounder (DPS-1) (Reinisch, 1996). Figure 1 illustrates the O-mode trace of the ionogram sequence. Due to the solar eclipse effect, some echoes in the lower and upper ionosphere were not continuously observed and, therefore, we focus on echoes returned between the upper E- and lower F2-regions. Figure 2a reveals various time series of virtual height fluctuations at sounding (or radiowave) frequencies 4.1–7.0 MHz, \( \{h_i, i = 1, 2, 3, 4, \ldots, N\} \), with the total number of data points \( N = 108 \), time resolution \( \Delta t = 5 \) minutes and frequency interval 0.1 MHz extracted from the O-mode trace of the sequence ionograms. These time series of virtual height fluctuations characterize a downward trend. The power spectrum of the virtual fluctuations presented in Fig. 2b shows that numerous waves occur during the solar eclipse. To meet the analysis criteria of narrow beam and central frequency of eqns (4) and (7), an 87-min wave constantly existing at various heights is selected to be investigated. Figure 2c illustrates that the 87-min waves yield a stronger power density during the occurrence of solar eclipse.

Although a time series of true height fluctuations can be obtained from the converted true height traces, we find that the fluctuations and tendencies shown in the time series of true height and virtual height are very different, this indicates the applied true height analysis possibly smooths the signature of the fluctuations. Figure 3 shows the mean (averaged) profiles of virtual height of O-mode trace of the ionograms and converted true height traces. It is obvious that the two heights near the F1-peak are significantly different. To preserve the fluctuation signatures and to derive the vertical velocities properly, we assume that each time series of virtual heights shown in Fig. 2a fluctuates at its mean true height.

With the Fourier analysis, via eqns (1), (2), and (4), of time series of virtual height fluctuations (data illustrated in Fig. 2a), we obtain the phase vs true height relation of the fluctuations. The solid-circle line in Fig. 4 shows that the phase vs true height relation of the harmonic with a
Fig. 2. (a) Virtual height, and (b) power spectra of fluctuations at 30 fixed sounding frequencies 4.1–7.0 MHz extracted from the ionograms shown in Fig. 1; (c) Power density of the 87-min waves derived from Fig. 1.
Fig. 3. The mean profiles from O-mode traces of the ionograms and converted true height traces.

Fig. 4. Phase vs true height diagrams from the data presented in Fig. 2a.
period of 87 min, which corresponds to Mode 5 of 87 data points, increases and decreases with respect to height below and above 176 km, respectively.

We further apply eqns (3), (5), and (6) to the data of the solid-circle line of Fig. 4 to find the phase velocities of each of 5 successive heights from the 29 fixed-sounding-frequency 4.2–7.0 MHz layers. Notice that the derived phase velocity should meet the first selection rule (Rule No. 1: the phase angle Φ is linearly dependent on the height for no less than four successive heights) given by Kuo et al. (1993). The open circles in Fig. 6 show the phase velocities to be about 100 m/s in the downward and upward directions for below and above 174 km, respectively. To derive the group velocities at various heights, we repeat the procedure obtaining the phase velocities but successively reduce the data length from 95-81 points (see various symbol-lines in Fig. 4). Figure 5 reveals that the group velocities of the fluctuations of sounding frequencies 5.4–5.9 MHz, around the F1 ledge 174–195 km, are very complex and difficult to obtain. The zooming plot shows the group velocities to be about 10 m/s in the downward and upward directions for below (sounding frequencies 4.3–5.3 MHz) and above (sounding frequencies 6.0–6.7 MHz) the ionospheric F1 ledge, respectively. Figure 6 summarizes the phase and group velocities shown in Figs 4 and 5, where open and solid circles, respectively, represent the phase and group velocities. Note that the group velocities denoted the solid triangles shown in the same figure were obtained in an approximate manner, which does not fully meet the second selection rule (Rule No. 2: the wave number is linearly dependent on the frequency for no less than four successive frequencies) given by Kuo et al. (1993).

4. Discussion and conclusion

To further understand the solar eclipse—AGW causality, ionograms recorded on one day before and one day after the eclipse day were also analyzed. A comparison of the results of the three days shows that various virtual height fluctuations exist on both eclipse and non-eclipse days. Therefore, it is rather difficult to determine the causality of these AGWs. However, unlike the eclipse-day fluctuations which are related to the solar obscuration (e.g., see Fig. 2c), the persistence and amplitude of the non-eclipse-day fluctuations are significantly different. These differences suggest that numerous waves observed in the F1 region during the solar eclipse may be either caused or enhanced by the photochemical and/or dynamic processes in the ionosphere.

We consider that the causality and/or enhancement of these waves are mainly attributed to changes of temperatures, and variations of the height of the transition

Fig. 5. Frequency vs wave number derived from Fig. 4. The inset magnifies the results derived from sounding frequencies 4.3–5.6 and 6.0–6.7 MHz.
level for the loss coefficient and the height of the peak of electron production (for details see Ratcliffe, 1974). When the photoionization is interrupted by an eclipse, the electron temperature falls rapidly, as the excess heat is drained away by conduction to lower heights. A little later the temperatures of the ions and neutrals also decrease. The decreases in the temperatures cause reductions of the scale height of the plasma and neutral gas which result in the plasma and neutral gas readily diffusing downwards. Meanwhile, due to the obscuration of solar radiation and the reduction of neutral gas, both the transition level and the height of peak production move downwards. After the maximum obscuration, owing to the increase of the solar radiation, the temperatures rise and, therefore, the plasma begins to diffuse upwards, and the heights of the transition level and the peak production move upwards. As a result, during the solar eclipse, the motions of the plasma and variations of the level and the height in the F1 region act as oscillation energy sources that generate numerous gravity waves in the ionosphere.

Results show that, below the altitude of 174 km, the vertical phase velocities are upward and the group velocities are downward, while above the altitude of 195 km, the phase velocities are downward and the group velocities are upward. In these two height ranges, the direction of the wave propagation is consistent with the AGW theory that the phase progression in the vertical direction is opposite to the energy transport. Results for the height range between the altitude of 174 km and 195 km are a little confusing: the phase velocities are downward while the group velocities appear to fluctuate between upward and downward. Notice that the group velocities at higher altitudes propagating in the upward direction and those at lower altitude traveling in the downward direction imply the energy and wave being possibly generated between 174–195 km. Within this energy wave source region, an upward propagating (phase downward) wave packet is superposed on a downward propagating (phase upward) wave packet; the phase velocities of the composite wave packet obtained by the method will be unanimously downward, and the apparent group velocities will reveal some pattern of fluctuation between upward and downward. The ionospheric models discussed above and all of these results suggest that during the solar eclipse of 24 October 1995, the energy source of AGW may lie in the height range of the ionospheric F1 ledge, between 176–195 km altitude.

References


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