Vertical group and phase velocities of ionospheric waves derived from the MU radar


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[1] The middle- and upper-atmosphere (MU) radar (34.85°N, 136.10°E) was operated in the incoherent scatter power-only mode to observe the ionosphere during 17 June 2001. Pronounced 200- to 300-min. waves in the echo power appeared in the F\textsubscript{2} region during 0240–1250 local time on 17 June 2001. A procedure of Fourier analyses is conducted to derive power spectra, vertical phase, and group velocities of the pronounced waves. Results show that the center frequency of the waves is a function of the wave number. The opposite directions of the vertical phase and group velocities imply the presence of atmospheric gravity waves.


1. Introduction

[2] Ionospheric wave features have been observed by various sounding techniques ranging from VLF to UHF bands [see papers listed, Davies, 1990; Hunsucker, 1991]. However, most of the studies focus on phase changes of the observed quantities and simply derive the associated phase velocities of waves. Kuo et al. [1993] developed a procedure of Fourier analyses deriving the phase and group velocities of atmospheric gravity waves from measurements of radial Doppler velocities at various range gates recorded by the Chung-Li VHF radar. On the basis of the work of Kuo et al. [1993], Liu [1996] for the first time developed a procedure deriving the vertical phase and group velocities of the quasi 16-day waves in the ionosphere from a sequence of ionograms.

Since then, scientists adopted the work of Liu [1996], examining sequences of rapid-run ionograms and obtaining the vertical phase and group velocities of gravity waves during solar eclipses [Liu et al., 1998; Altadill et al., 2001] as well as those of traveling atmospheric disturbances during geomagnetic storms [Lee et al., 2002]. However, the shortcomings of the ionosonde sounding technique are that ionograms simply provide the information below the altitude of the F\textsubscript{2} peak and often have data gaps due to the shortwave fadeout [Davies, 1990]. Therefore sounding frequencies greater than the ionospheric critical frequency foF\textsubscript{2} are essential to be employed to further probe vertical propagations of waves above the F\textsubscript{2} peak.

[3] In this paper, we adopt the procedure of Kuo et al. [1993] and Liu [1996] to investigate incoherent scatter measurements in the ionosphere observed by the 46-MHz middle and upper atmosphere (MU) radar (34.85°N, 136.10°E). First, the observation and the analysis procedure are briefly reviewed. Later, pronounced waves are isolated from the observation, and the associated vertical phase and group velocities are computed. Finally, we discuss the wave characteristics, search the location of wave source, and propose some possible causal mechanisms.

2. Methodology

[4] Based on the Fourier analysis, a time series of the received echo-power variations \( p(z, t) \) observed at a...
certain altitude \( z \) by vertical sounding can be expressed as [Kuo et al., 1993]

\[
p(z, t) = C_0 + \sum_{j=1}^{N/2} C_j(z)(\cos \omega_j t - \Phi_j(z))
\]

\[
= C_0 + \sum_{j=1}^{N/2} C_j(z) \cos(\omega_j t - k_j z) \tag{1}
\]

where \( N \) is the number of data points, and \( C_j, \omega_j, \Phi_j, \) and \( k_j \) are the amplitude, angular frequency, phase, and vertical wave number of the \( j \)th harmonic, respectively. The angular frequency of the \( j \)th harmonic can be expressed as \( \omega_j = 2\pi j/(N\Delta t) \), where \( \Delta t \) is the sampling time. If the \( j \)th harmonic is present in the wave fluctuation, then the Fourier analysis of the time series of successive heights should give a smooth function \( \Phi_j(z) \), and the corresponding vertical wave number \( k_j \) can be written as

\[
k_j = \frac{d\Phi_j}{dz} \tag{2}
\]

By definition, the vertical phase velocity \( v \) is given as

\[
v = \frac{\omega_j}{k_j} \tag{3}
\]

In most cases, instead of a monochromatic wave, a wave packet centered at certain frequency (center frequency) is observed in the data. To evaluate the group velocity, \( v_g \), the different frequencies near the center frequency of the wave packet can be derived by successively changing the data length from \( T = N\Delta t \) to \( T = (N \pm \Delta N)\Delta t \), where \( \Delta N \) is the change of the number of data points. Note that the \( \Delta N \) is an integer much smaller than \( N \). If the wave packet does exist, such a process of consecutive analysis will generate a smooth relation between the \( \omega_j \) and the \( k_j \). Then we can obtain the group velocity of the wave packet, which is simply the derivative of \( \omega \) with respect to \( k \)

\[
v_g = \frac{d\omega}{dk} \tag{4}
\]

3. Observations and Analyses

[5] The MU radar was operated with a standard IS echo-power (= electron density) experiment mode observing vertically throughout the \( E \) and \( F \) regions on a geomagnetic quiet day (Dst \( \sim 0 \); Kp sum < 10) of 17 June 2001. In that experiment, the range resolution was 9.6 km while data were oversampled at every 4.8 km. Data are recorded about every 12.5 s during this experiment but averaged to 1-min. resolution (\( \Delta t = 1 \) min.). Figure 1 illustrates the overall and the median echo power profiles during 0000–1600 local time (LT) of 17 June 2001. The significant fluctuations near and below 150 km might be related irregularities of the lower ionosphere. Meanwhile, the \( F \)-region signal offers become unusable beyond 600 km owing to weak signal strength [Oliver et al., 1988]. For simplicity, we focus on temporal variations of the echo power around the \( F2 \) peak ranging from 254 to 542 km (Figure 2). It can be seen that a large disturbance (or the fast dissipation process) occurs between 0000 and 0240 LT, and some sinusoidal waves appear after 0240 LT.

[6] Figure 3 displays the periodogram (dynamic power spectra, calculated by Fourier analysis) at 353 km with a time window of 600 min. shifting by 1 min. The window is denoted by its beginning time. The contour shows that pronounced 200- to 300-min. waves appear from 0240 LT. Figure 4 displays the spectra of temporal variations in the echo power at various heights during 0240–1250 LT. It can be found that pronounced waves at second harmonic (mode 2) with the center frequency (period) of about 224.5 min. (0.0045 min.\(^{-1}\)) appear around 438 km altitude and gradually yield lower frequencies toward the higher altitude (232.5 min., 0.0043 min.\(^{-1}\) at 529 km altitude) and the lower altitude (264.5 min., 0.0038 min.\(^{-1}\) at 276 km altitude).

[7] Previous studies reported the center frequency to be a constant value [Kuo et al., 1993; Liu, 1996; Liu et al., 1998; Altadill et al., 2001; Lee et al., 2002]. By contrast, the center frequency (or period) in this study is not a constant but gradually changes with height (Figure 4). We therefore adjust the data length \( N \) and apply equations (1) and (2) to calculate the phase near...
the center frequency (the heavy lines in Figure 5a), and we then compute the associated vertical phase velocities by equations (2) and (3) accordingly. The lines in Figure 5 show the phases versus altitude for successive period change from 224.5 to 280.5 min. Since the slope of the phase $\Phi_j$ versus height $z$ represents the vertical wave number, the monochromic increase and decrease in the phases of the center frequency (the heavy lines in Figure 5) below and above 437 km indicate the vertical phase velocities to be in the upward and downward directions, respectively.

To derive the group velocity at a certain height, we further shorten the data length $N$ by $\Delta N = 0, 16, 32, 48,$ and 64 (the time resolution is $\Delta t = 1$ min.) at each of the

**Figure 2.** The variations of the echo power at fixed heights between 254 and 542 km.

**Figure 3.** The periodogram of the echo power at 353 km altitude between 0000 and 1600 LT. The time window is 600 min. shifting by 1 min. The window is denoted with its beginning time in local time hour.

**Figure 4.** The selected spectra of the echo power from 276 to 529 km altitude. The dotted symbols denote the center frequencies.

**Figure 5.** The phase versus height for mode 2. (a) The phase versus height for various center frequencies. The heavy segmented line denotes the center frequencies (periods) at the associated heights.
seven successive altitudes (the target altitude together with its six adjacent altitudes, i.e., three above and three below) and repeat the procedure of calculation of the vertical wave number of each associated period by equations (1) and (2). Note that the changes of data length result in \( \omega_j \) and the associated \( k_j \) changing accordingly. Therefore the group velocities can be obtained from equation (4). The slopes in Figures 6a, 6b, and 6c show the group velocities within 520–497, 493–434, and 429–299 km being in the upward direction, complex, and the downward direction, respectively. The complex (or mixed) slopes shown in Figure 6b indicate that the group velocities of the 493- to 443-km altitude cannot be derived. By contrast, the monochromic increase and decrease in slopes in Figures 6a and 6c show that the group velocities within 520–497 and 429–299 km are around 4.7 m/s in the upward and 19.1 m/s in the downward directions, respectively. Figure 7 summarizes the phase velocities, group velocities, center frequencies, and spectral power of the pronounced waves as well as the median echo power of the MU radar during 0240–1250 LT. It can be seen that the peak of the echo power is at about 371 km altitude where it is close to the maximum spectral power of the waves at about 375 km altitude (see left panel). Meanwhile, the greatest center frequency 0.0045 min. (224.5 min.) appears around 420 km (midway of 380–460 km) altitude (see left panel) where it is near the direction change of the vertical phase and group velocities (see right panel).

4. Discussions and Conclusions

[9] For the incoherent scatter power observation, the echo power is proportional to the ionospheric electron density [Sato et al., 1989]. Results show that the peak of the spectral power of the waves at 375 km is near that of the echo power at 371 km altitude. This indicates the amplitude of the pronounced waves to be related to the ionospheric electron density.

[10] On the other hand, the directions of the phase velocities of the pronounced waves change at 437 km altitude (Figure 7, right panel), which is near the height of 420 km at the midpoint of the maximum center frequency (Figure 7, left panel). The features seem to be consistent with Doppler-shifted waves generated by wave sources located at altitude, \( z_0 \) (about 420–437 km in this paper), of the maximum of the center frequency (and/or the direction change of the phase velocities). The Doppler-shifted frequency is given by [Scheffler and Liu, 1985]

\[
\omega = \Omega - kv
\]

where \( \Omega \) is the source frequency at \( z_0 \), and \( v \) and \( k \) denote the vertical phase velocity and wave number, respectively. Since the phase velocities above and below \( z_0 \) are in the downward and upward directions, respectively, we then express

\[
v = v_0 - a(z - z_0), \quad a > 0
\]
where \( v_0 \) is the phase velocity at \( z_0 \). From equations (5) and (6), the center frequencies \( \omega_0 \) at \( z = z_0 \) and \( \omega \) at various altitudes \( z \) can be respectively expressed as

\[
\omega_0 = \Omega - kv_0 \tag{7a}
\]

and

\[
\omega = \Omega - kv_0 + ka(z - z_0) = \omega_0 + ka(z - z_0) \tag{7b}
\]

For \( z > z_0 \), we have downward phase propagation from the center, so \( k = -|k| \), and the center frequency and its gradient are, respectively,

\[
\omega = \omega_0 - |k|a(z - z_0) \tag{8a}
\]

and

\[
d\omega/dz = -|k|a < 0 \tag{8b}
\]

For \( z < z_0 \), \( k = +|k| \), and those two are, respectively,

\[
\omega = \omega_0 + |k|a(z - z_0) \tag{9a}
\]

and

\[
d\omega/dz = +|k|a > 0 \tag{9b}
\]

Equations (8) and (9) show that the nonstationary center frequency is related to the wave number.

Results show that the phase velocities above and below 434–493 km altitude are in the upward and downward directions, respectively. The opposite directions of the vertical group velocities demonstrate that the energy source of the pronounced waves is located at 434–493 km altitude where it is near the F2 peak, upper F2 region.

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\omega = \omega_0 + |k|a(z - z_0) \tag{9a}
\]

and

\[
d\omega/dz = +|k|a > 0 \tag{9b}
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Results show that the phase velocities above and below 437 km altitude are in the downward and upward directions, respectively, while the group velocities above and below 434–493 km altitude are in the upward and downward directions, respectively. The opposite directions of the vertical group velocities demonstrate that the energy source of the pronounced waves is located at 434–493 km altitude where it is near the F2 peak, upper F2 region.

It is interesting to speculate possible source mechanisms in a region of such high viscosity. In the midlatitude ionosphere, such as the MU (Arecibo) radar observatory, the near 55° (45°) dip angle allows each of the four important forces, plasma pressure, neutral wind, gravity, and electric field, to be in control of the F-region dynamics. If any of these terms dominate the dynamics, the F layer seeks out an altitude where a balance between these factors is reached (for detail, see the paper of Kelley [1989]). In the Arecibo radar observatory, some features are common to all nights. The F peak itself displays undulations with a period of 2 hours. The F layer rose and fell many tens of kilometers during these long-period oscillations (also see the study of Kelley [1989]). Similarly, the MU radar observation shown in this paper reveals the F-layer electron density undulations with a period of 3–5 hours.

In the midlatitude ionosphere, external factors, such as traveling ionospheric disturbances, atmospheric gravity waves, neutral winds, plasma flows, etc., could easily disturb the balance of the four forces and generate long-period undulations. For example, northward (polarward) motion of the neutral atmosphere and/or the westward E field causes downward motion of ionospheric plasma in the Northern Hemisphere. In the topside
ionosphere, the downward motion causes decrease of electron density (echo power) at a certain altitude since the plasma density decreases with altitudes. By contrast, in the bottomside ionosphere, the downward motion causes increase of electron density (echo power). Thus the waves seen in the perturbation of echo power should have opposite phase above and below the $F_2$ peak (see Figure 5) even if the gravity wave in the neutral atmosphere has a uniform phase progression throughout the ionosphere. The opposite directions of the vertical phase velocity could be explained by the downward motion of ionospheric plasma; however, it is difficult to consider a continuous localized energy source of waves at such a high altitude around the $F_2$ peak in midlatitudes. Note that the high molecular viscosity in the thermosphere prevents the localization of energy source at high altitudes [Richmond, 1978; Hocke and Schlegel, 1996].

[15] Although the candidate of causal mechanisms could not be identified, previous and current observations show a common nighttime feature of undulations with periods of few hours in the midlatitude $F$ region. The observed phase velocity and group velocity have opposite directions, indicating that the pronounced signature is likely to be caused by atmospheric gravity waves [e.g., Hines, 1960].

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References


S. Fukao and M. Yamamoto, Research Institute for Sustainable Humanosphere, Kyoto University, Kyoto, Japan.

C. C. Hsiao, Institute of Space Science, Chung-Li, Taiwan.

F. S. Kuo, Department of Electro-Optics Engineering, Vanung University, Chung-Li, Taiwan.

C. H. Liu, National Space Organization, Hsin Chu City, Taiwan.

J. Y. Liu, Institute of Space Science, National Central University, Chung-Li, Taiwan. (jyliu@jupiter.ss.ncu.edu.tw)

H. Y. Lue, Department of Physics, Fu-Jen University, Hsing-Chuang, Taipei, Taiwan.