3.4B ACCURACY OF VERTICAL VELOCITY DETERMINATION

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Typical wind spectra taken at Poker Flat, Alaska, using the vertically oriented antenna show velocities of 10's of cm to meters per second and spectral widths winds of 0.5 to 1 m/s. The potential errors in such measurements can be broken down into three categories: (1) those due to instrumental parameters and data processing, (2) those due to specular returns from non-horizontal surfaces, and (3) those due to other physical effects.

At Poker Flat the typical vertical velocity spectrum has data points every 10 to 20 cm s^{-1}. This spacing is small enough to prevent velocity determination errors. The central point in the spectrum (0 velocity) is replaced by the average of the two adjacent points in order to avoid dc offset problems. For small velocities and narrow spectral widths, this could cause systematic errors of ~ 1 cm/s. However, since the errors are symmetric with respect to zero velocity they will not cause noticeable errors in velocities averaged over significant times ($\geq 1/2$ hr). Hence we expect no significant errors due to instrumental parameters or data processing.

On the other hand, for finite width antenna beams, specular returns from nonhorizontal surfaces can occur. We have no real estimate of the errors caused by this effect. However, we do expect it to be a random effect with zero mean and hence again we expect no errors in long-term averages of vertical velocity. These expectations are borne out in the mesosphere where vertical velocities derived from turbulent echoes and vertical velocities at higher altitudes from meteor echoes show the same general trend. Since the meteor echoes cannot be so affected we assert that, on the average, specular returns in the mesosphere from tilted surfaces cause no systematic error.

There are a number of potential effects in the third category. First we consider the possibility that the beam is not vertical. For a typical horizontal velocity of ~ 50 meters per second to cause an error of less than 10 cm/s it is essential that the beam is no more than 0.1° off vertical. At Poker Flat the typical monthly mean vertical velocity in the troposphere is less than 1 cm/s and hence the beam is considerably less than 0.1° off vertical.

In the mesosphere several physical effects could cause an error in the vertical velocity measurements that should increase with height. We have considered beam bending by the magnetic field, beam bending by nonvertical ionospheric gradients, phase shifts (interpreted as velocities) introduced by changing electron density and electric fields in the ionosphere (REID, 1983). Even under extreme conditions only the latter mechanism could introduce measurable effects. The similarity of Poker Flat mesospheric vertical monthly averages over 25 km range (70 to 95 km) indicate that none of these potential error sources are significant.

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3.5A IMPLICATION ON DATA INTERPRETATION BY SHORT- AND LONG-PERIOD OSCILLATIONS

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OBSERVATION OF HORIZONTAL VELOCITY VARIATIONS

Measurements of horizontal velocities in the upper atmosphere have been attempted using a multitude of techniques with associated assumptions about the wind field. One example is the Doppler beam swinging radar where line-of-sight wind measurements are made with the antenna positioned in three different directions and then the three-dimensional wind field is calculated under the assumption that the wind field is constant over time and space spanning these measurements. This assumption is reasonable when tidal oscillations and the mean wind are considered. Tides have wavelengths of thousands of kilometers and periods that are integral fractions of a solar day (24-12-8 hours). For the mean wind the scale of the temporal and spatial variations are even larger. Thus it is concluded that there are no problems in measuring the mean wind and tides using the Doppler beam swinging (DBS) technique, or any other technique based on the assumption of stationary wind fields.

The problem arises when short-period horizontal oscillations are measured. COUNTRYMAN and BOWHILL (1979) using the Jicamarca radar in a DBS experiment have shown that the horizontal wavelength of short-period gravity waves are of the order of 20 km. This agrees well with observations of gravity waves in the OH layer observed by MOREELS and HERSE (1977) showing horizontal wavelengths as short as 20 km. It is thus clear that a DBS radar with angular separation in beam directions of about 5° or more will span a substantial fraction of the horizontal wavelength in the mesosphere and thus the assumption of similar wind fields is violated. So it appears that short-period horizontal velocity oscillations can not be easily measured by the use of the DBS technique. This appears to be generally accepted in the MST radar community.

Similar considerations are valid for the spaced antenna drifts technique (SAD). However, there have been claims in the literature that this technique should be able to measure short-period horizontal oscillations, so it is reasonable to discuss this technique in more detail. The SAD technique is based upon the recognition of an interference pattern drifting across a set of spaced receiving antennas (ROYRVIK 1983a).

Under ideal conditions, it is clear that the velocity of the interference pattern over the ground can be measured with reasonable accuracy. However, it remains to be shown that this velocity is related to the bulk horizontal motion of the ionosphere at the altitude probed. It is reasonable to expect to find short-period gravity waves in the mesosphere that have approximately the same amplitude in the horizontal and vertical wind component, and horizontal wavelength as short as 20 km. The effect of such short-period waves upon the SAD experiment's ability to measure wind has not previously been taken into account.

Consider the simplified situation given in Figure 1 where only two scattering irregularities are present in the antenna beam at equal but opposite angular distances away from the zenith. The same amount of power is scattered from each irregularity. The electric fields on the ground resulting from scattering from each of the two irregularities may be written

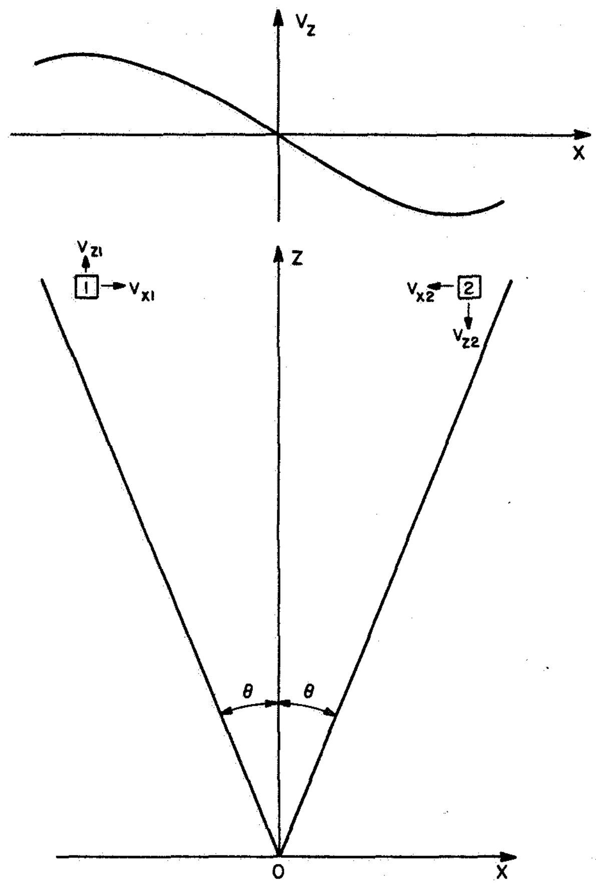

Figure 1. Radar situation with two scattering irregularities moving under the influence of a short-wavelength gravity wave.

$$E_1 = E_0 \exp i[(\omega_0 + \omega_1)t - \frac{2\pi \ x \sin\theta}{\lambda} + \frac{2\pi \ z \cos\theta}{\lambda}]$$

$$E_2 = E_0 \exp i[(\omega_0 + \omega_2)t + \frac{2\pi \ x \sin\theta}{\lambda} + \frac{2\pi \ z \cos\theta}{\lambda}]$$

In these equations E_0 is the amplitude of the scattered wave, ω_0 the angular frequency of the transmitted radar wave, ω_1 and ω_2 the Doppler shifts in frequency, and $\lambda = \frac{2\pi c}{\omega_0}$ is the free space wavelength. Generally, ω_1 and ω_2 are independent, and we can express them as a function of a mean frequency shift ω_m and a differential frequency shift ω_d so that

$$\omega_1 = \omega_m - \omega_d \text{ and } \omega_2 = \omega_m + \omega_d$$

Since the antenna beam width is generally small we may add the electric fields without accounting for polarization effects. The total electric field on the ground then becomes

$$E = E_1 + E_2 = E_0 \exp i \ [(\omega_0 + \omega_m)t + \frac{2\pi \ z \cos\theta}{\lambda}]$$

$$2\cos(\frac{2\pi \ x \sin\theta}{\lambda} - \omega_d t)$$

The exponential part of this function represents a wave propagating vertically in the negative z direction with a frequency $(\omega_0 + \omega_m)$. The amplitude of this wave is modulated in the horizontal plane in the form of a propagating wave given by

$$A(x,t) = 2E_0\cos\left(\frac{2\pi\ x\ \sin\theta}{\lambda} - \omega_d t\right)$$

where the frequency of the wave is given by $\omega_d = (\omega_2 - \omega_1)/2$. The two Doppler shift frequencies ω_1 and ω_2 resulting from the action of an internal gravity wave can be expressed as a function of the two line-of-sight velocities

$$\omega_1 = \frac{2\omega_0}{c}(V_{1z}\cos\theta + V_{1x}\sin\theta)$$

and

$$\omega_2 = \frac{2\omega_0}{c}(V_{2z}\cos\theta - V_{2x}\sin\theta)$$

For radars with half beam width θ less than 15° it is a good approximation to set $\cos\theta = 1$ thus simplifying the expressions for ω_1 and ω_2. Using the asymptotic relationships for internal gravity waves we can express ω_1 and ω_2 as a function of amplitude, frequency and wavelength of the gravity wave giving

$$\omega_1 = \frac{2\omega_0}{c}(V_z\sin\Omega\ t + V_x\cos\Omega\ t\ \sin\theta)$$

and

$$\omega_2 = \frac{2\omega_0}{c}[V_z\sin(\Omega\ t - \theta_d) - V_z\cos(\Omega\ t - \theta_d)\sin\theta]$$

Here it has been assumed that the vertical and horizontal velocity components are 90° out of phase. This may not be very realistic under all circumstances, but leads to simplifications of the result and will not affect the basic conclusions. Ω is the frequency of the internal gravity wave, and V_z and V_x are the vertical and horizontal components of the wind field, respectively. θ_d is the phase difference between the oscillations in the two scattering volumes which can be approximated by

$$\theta_d = \frac{4\pi z\ \sin\theta}{L}$$

where L is the horizontal wavelength of the gravity wave. Combining these equations give the expression

$$\omega_d = \frac{\omega_0}{c}\{V_z[\sin(\Omega\ t - \theta_d) - \sin\Omega\ t]$$

$$-V_x\sin[\cos(\Omega\ t - \theta_d) + \cos\Omega\ t]\}$$

and

$$\omega_m = \frac{\omega_0}{c}\{V_z[\sin(\Omega\ t - \theta_d) + \sin\Omega\ t] + V_x\sin\theta[\cos\Omega\ t - \cos(\Omega\ t - \theta_d)]\}$$

It is clear from the expression for ω_d that the horizontal velocity of the ground pattern will be a quite complicated function of several physical parameters unless $\theta_d \approx 0$. However, consider a not unreasonable situation of an antenna half beam width of 5°, two scattering irregularities at 85 km as shown in Figure 1, a horizontal wavelength of 30 km and a wave period of 10 minutes. Then $\theta_d \approx \pi$ and ω_d reduces to

$$\omega_d = \frac{\omega_0}{c} V_z(-2\sin\Omega\ t)$$

Thus it is seen that for this, and other similar choices where $\theta_d \approx \pi$ the horizontal motion of the pattern over the ground is caused by the horizontal variations in the vertical velocity only. However, even for other values where $0 \ll \theta_d < \pi$, ω_d will be dominated by vertical velocity differences because of the additional factor $\sin\theta$ in the contribution from the horizontal velocity.

The preceding calculations show that small spatial variations in the vertical velocity within the antenna beam can drastically affect the horizontal velocity measured. It was shown that if the antenna beamwidth is of the order of 10° such vertical velocity variations could be caused by short-period gravity waves. For an antenna beamwidth of the order of 1° large-scale turbulent motion is more likely to cause erroneous horizontal wind measurements. As is shown in another paper (ROYRVIK, 1983b) there are indications of large-scale (200-400 m) Kelvin-Helmholtz billows with a circular motion in the mesosphere. These occur intermittently and may cause large disturbances in the calculated horizontal velocities when a narrow beam antenna is used.

Thus it appears that both the SAD and the DBS techniques require integration over several periods of the short-period oscillations to obtain a horizontal velocity measurement. Estimates show that integration over approximately one hour gives reasonably accurate horizontal velocity estimates.

Two other less known techniques may be better suited to measure short-period horizontal velocity oscillations. These are the interferometer (IFR) technique and the cross-beam drift (CBD) technique. Both these techniques are based upon the horizontal drift of spatially limited scattering volumes. In the IFR mode the horizontal motion of the irregularities could be traced as a change in relative phase between the signals received in a set of spatially separated receivers. In the CBD mode the horizontal drift would manifest itself as a lagged maximum in the cross correlation of signal amplitudes received in a set of antennas in looking different directions.

The use of these techniques will depend on a proper spatial and temporal distribution of the scattering irregularities in the upper atmosphere, and as far as is known it has not been shown that these distributions exist.

ACKNOWLEDGMENT

The work described was supported by the National Science Foundation under Grant ATM 80-19563.

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