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3.4B IMPROVEMENT OF VERTICAL VELOCITY MEASUREMENTS

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Vertical velocities are assumed to be measurable with vertically pointing antenna beams. An exact horizontal levelling and good phase calibration of the radar antenna system can yield real main-beam directions which do not significantly differ from calculated patterns. It is, thus, anticipated that antenna beams can be pointed exactly vertically. Because of area size and near-field limitations, VHF radar antennas have typically beam widths of more than several degrees.

It is known that most of the reflectivity structures detected by vertically beaming VHF radars in the troposphere, stratosphere and lower mesosphere are aspect-sensitive. It cannot a priori be assumed that these structures are exactly horizontally stratified, they are rather inclined according to the atmospheric flow pattern in which they are embedded. This flow pattern is mostly not exactly horizontal. We have collected a few examples to support this statement.

In synoptic-scale disturbances the isopleths of temperature and humidity are inclined and correspondingly the isopleths of the vertical gradient of the potential refractive index are inclined, too. This is shown in Figure 1 which compares the radiosonde-deduced and the VHF radar-deduced results obtained during the successive passages of a cold front and a warm front. Another illustrative example of passage of a warm front is shown in Figure 2 which very clearly indicates layers sloping downwards and upwards with time. Since these disturbances propagate and have lifetimes of a day or more, layers ascending or descending with time over a fixed (radar) location have to be tilted. Typical tilt angles of these frontal structures are a fraction of a degree to some degree.

Whereas synoptic-scale disturbances have characteristic horizontal scales of some 1000 km and vertical scales of the height of the troposphere ($\approx$ 10 km), the corresponding baroclinicity (tilt angle) is fairly small but not negligible. For illustration of tilted cross section see also Figure 4. Larger tilt angles occur in smaller scale disturbances such as orographically influenced flow patterns, namely mountain lee waves (Figure 3). Here tilt angles of several degrees or more can occur.

This generally holds for any kind of gravity waves. For example, it was pointed out by GAGE et al. (1981) that the specular reflection point changes its direction with respect to the vertical antenna beam at different phases of a gravity wave (Figure 5). This results in a modulation of the radar return power if the radar beam is narrower than the offset range of the direction to the specular point (2, 4). It can also result in defocussing (1) or focussing (3) for wider antenna beams. More crucial, it changes the direction of incidence, and even with an exactly vertically oriented antenna beam the ray direction is off-vertical. This has an obvious effect on the measurement accuracy of the vertical velocity. The possible error can be reduced by applying a technique to measure the incidence angle and correct the estimated horizontal and vertical velocities.

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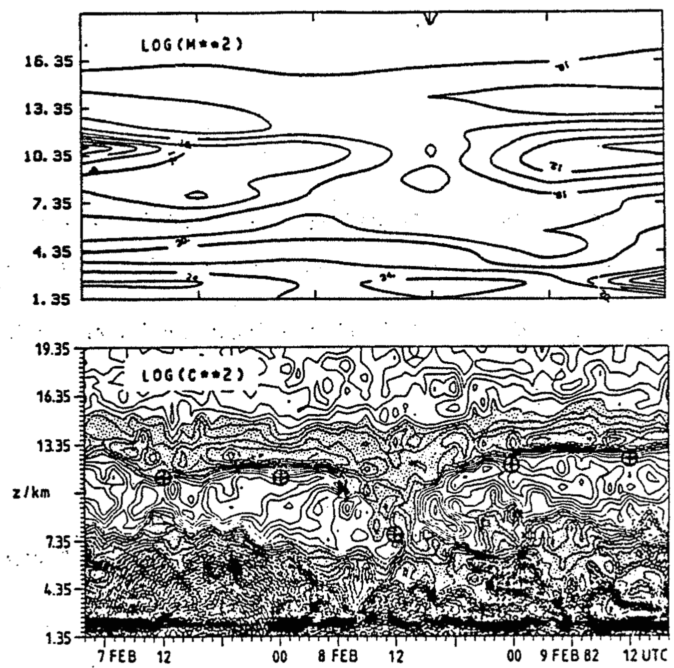

Figure 1. Logarithms of the vertical gradient of potential refractive index M^2, deduced from radiosonde data, and of the corresponding effective reflectivity C^2, measured with a vertically beaming VHF radar (from LARSEN and ROTTGER, 1983).

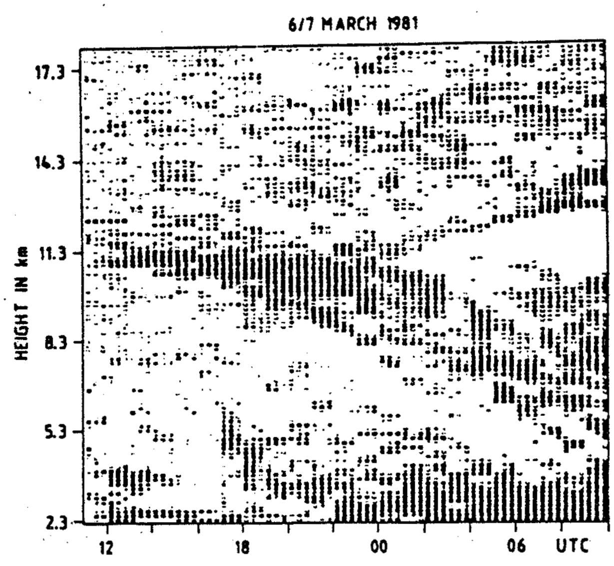

Figure 2. Modified (mean profile subtracted) height-time intensity plot showing sloping layers of enhanced radar reflectivity due to frontal boundaries and tropopause (after ROTTGER, 1981), observed with the SOUSY-VHF Radar.

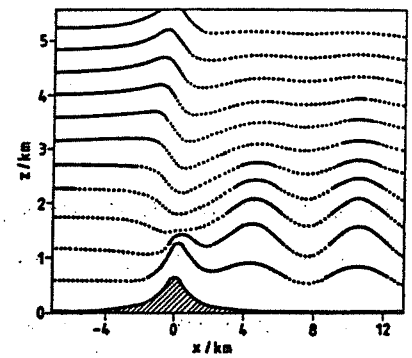

Figure 3. Displacement of streamlines of lee waves, resulting in equivalent structures of the potential refractive index.

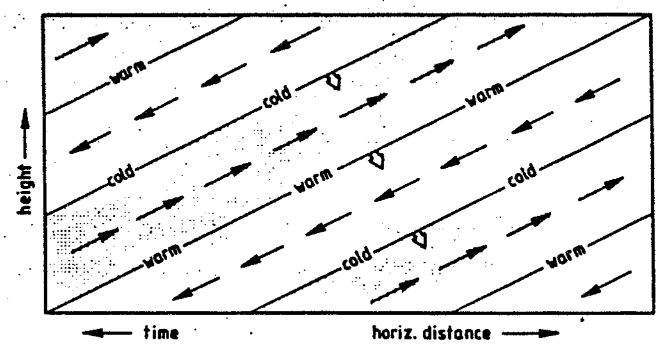

Figure 4. Idealized cross section for internal gravity wave (after HOLTON, 1972).

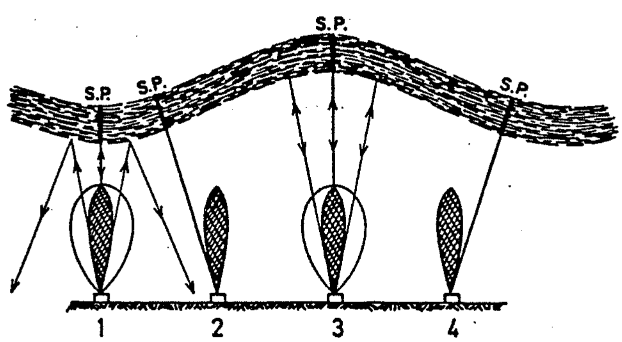

Figure 5. Schematic diagram showing changes in the specular point with respect to the vertical angenna beam at different phases of the gravity wave (after GAGE et al., 1981). Additionally, wide beam widths are inserted to show the effect of focussing (3) and defocussing (1).

The Doppler and the spaced antenna drifts method do not separately evaluate the spatial distribution of the phases of the field pattern at the ground. With the spaced antenna set-up the amplitudes and the phases can be measured. Combining in a suitable procedure the complex signals from different antennas is in a wide sense the application of the interferometer technique. In the first spaced antenna measurements with VHF radars, ROTTGER and VINCENT (1978) and VINCENT and ROTTGER (1980) applied this method to measure the angular spectrum of tropospheric returns. The vertical velocity measurements can also be improved by using a spaced antenna interferometer. The basic principle of the technique is sketched in Figure 6. Let us assume diffuse reflection from a rough surface or structure S which is sufficiently far from the radar antenna and which is slightly tilted to the horizontal by an angle δ'. This structure moves with a velocity given by the horizontal component U and the vertical component W. A radar with vertically pointing antenna A_o with beam width larger than δ' measures the radial velocity

$$V' = W^* - U^* = W\cdot\cos\delta' - U\cdot\sin\delta'.$$

Thus, even when knowing the horizontal velocity U, the vertical velocity is still incorrect if δ' is unknown.

The reflected signal can also be received at two separate antennas A_1 and A_2, and the complex cross-correlation function ρ_{12} be computed. Its amplitude $|\rho_{12}|$ and phase ϕ_{12} are sketched in the lower part of Figure 6. From the displacement τ_{12} of the maximum of $|\rho_{12}|$ and the horizontal sepa-

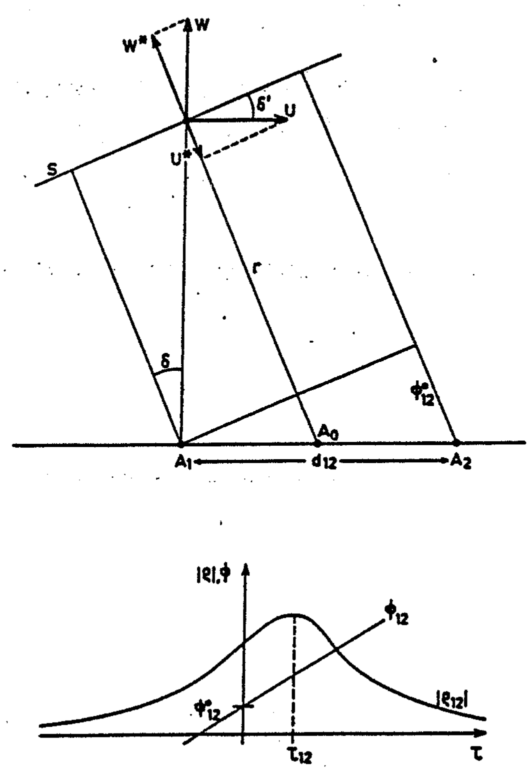

Figure 6. The principle of phase measurements at antennas A_1 and A_2, and determination of time delay τ_{12}.

ration d_{12} of the receiving antennas, the apparent velocity $V_a = d_{12}/2\tau_{12}$ is calculated with the spaced antenna drifts method. We assume here for simplification that $V_a = U$ (instead of V_a, the true velocity has to be calculated according to full correlation analysis). The radial velocity is calculated from the time derivative of ϕ at $\tau = 0$:

$$V = \lambda/4\pi \cdot d\phi\ (o)/dt.$$

The tilt angle δ', which is similar to the incidence angle δ, is

$$\delta' = \arcsin(\phi_{12}(o) \cdot \lambda/2\pi d_{12}.$$

This yields the corrected vertical velocity

$$W = (V' + V_a \sin\delta)/\cos\delta.$$

For a typical ratio $U/W = 100$ and $\delta = 0.6°$, for example, the vertical velocity estimate would be incorrect by a factor of 2 (0.5) if this correction were not applied. The angle δ' is equivalent to the inclination of the reflecting structures. Its average can give an estimate of the inclination of isentropic surfaces (baroclinicity), which is evidently of interest for meteorological applications (GAGE, 1983).

The phase lag between two antennas can also be introduced instrumentally, either by including a delay line between the antennas and the receiver or by adding a phase lag to the complex signal samples received at the different antenna channels. In the first case (preselected beam direction) the signals from both antennas would be added in an analogue coupler, and in the second case (post-selected beam direction) the digital samples would simply be added as vectors during data processing. This procedure is equivalent to electrically swinging the beam to different angles δ. The addition (distribution) of signals from (to) different antenna modules is used to swing the receiver (transmitter) beam of a phased array. For separate transmission and receiving antennas, the transmitter antenna beam can be kept fixed and the receiving antenna beam be swung by post-selection as long as the angle δ is narrower than the beam of the transmitter antenna. The advantage of this latter method is the post-selection of all possible angles δ, whereas the former method preselects an angle which cannot be changed after the data were taken. Of course, this method is easily extendable from the explained 1-dimensional example to a 2-dimensional application as well as to an array of more than two antenna modules.

This radar interferometer method not only allows the measurement of the horizontal wind components by the Doppler method, but also the tilt, the aspect sensitivity and the horizontal phase velocity and wavelength of atmospheric waves (see ROTTGER, 1983).

Another application, which originally was used to study ionospheric plasma turbulence (FARLEY et al., 1981), was recently applied also to MST radars to trace discrete structures, such as blobs of turbulence moving through the antenna beam (ROTTGER and IERKIC, in preparation). By making use of a cross-spectrum analysis and observing the change of δ and V' as a function of time. not only the location of the blobs but also their vertical and horizontal velocities can be measured more accurately (see also paper 2.2A by ROTTGER, this volume).

The measurements of δ and its temporal variations are very useful to avoid erroneous interpretations that the radial velocities measured with vertical antenna beams are really vertical velocities.

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