3. TECHNIQUES FOR MEASUREMENTS OF HORIZONTAL AND VERTICAL VELOCITIES (Keynote Paper)

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Techniques to measure velocities with radars make use of spectrum analysis or correlation methods, either in the time or in the space domain. The autocorrelation function of a coherently detected radar echo signal $E(t)$ is $C(\tau) = \langle E(t)\, E^*(t + \tau)\rangle$. The power spectrum of the signal is $F(\omega) = \frac{1}{2\pi} \int C(\tau) \exp(-i\omega\tau)\, d\tau$. Here: t = time, ω = angular frequency, τ = temporal displacement, and * denotes complex conjugate.

The three first moments m_0, m_1, m_2 of the spectrum yield the essential parameters of the radio echo, namely the power P, the Doppler offset of the spectrum ω_d and the spectral width ω_s. These are

$$P = m_0 = \int F(\omega)\, d\omega,$$

$$\omega_d = \frac{m_1}{m_0} \text{ with } m_1 = \int \omega F(\omega)\, d\omega,$$

$$\omega_s = \sqrt{\frac{m_2}{m_0} - \left(\frac{m_1}{m_0}\right)^2} \text{ with } m_2 = \int \omega^2 F(\omega)\, d\omega,$$

Since $F(\omega)$ and $C(\tau)$ are related through Fourier transformation, the three moments can also be deduced directly from the autocorrelation function (WOODMAN and GUILLEN, 1974), yielding

$$P = C(\tau_0), \quad (\tau_0 = 0)$$

$$\omega_d = \frac{\phi(\tau_1)}{\tau_1}$$

$$\omega_s = \left(\frac{2\,(1 - A(\tau_1)/A(\tau_0))}{\tau_1^2}\right)^{1/2}$$

where $A(\tau)$ is the amplitude and $\phi(\tau)$ is the phase of the autocorrelation function

$$C(\tau) = A(\tau) \exp(i\phi(\tau)).$$

The power is proportional to the intensity of the refractive index fluctuations and/or the reflection coefficient.

The Doppler shift $\omega_d = \underline{k}' \cdot \underline{V}$; the vector $\underline{k}' = \underline{k}_0 - \underline{k}_1$ defines the "mirror direction" for the direction of incidence ($\underline{k}_0$) and scattering ($\underline{k}_1$), see Figure 1. The angle ϕ is the scattering angle. We find

$$|\underline{k}'| = \frac{4\pi}{\lambda} \sin\phi/2 = \frac{2\pi}{\lambda'}$$

where λ is the radar wavelength. For backscatter, $\phi = 180°$, and $\lambda' = \lambda/2$; λ' is the Bragg wavelength, which the the important spatial scale in the

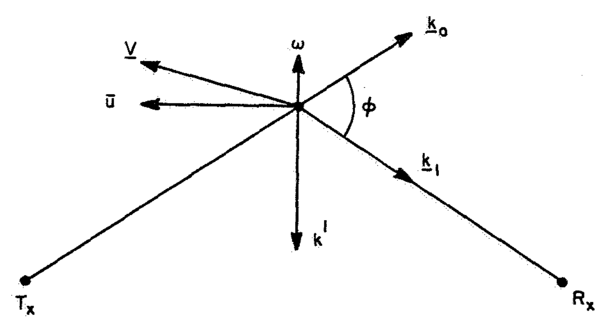

Figure 1. Scattering/reflection geometry.

scattering medium governing the radar echo intensity. For reflection, $\underline{k}'$ has to be perpendicular to the vector normal to the reflecting surface.

The bulk velocity of the scattering/reflecting target is $\underline{V} = (u,v,w)$. Measuring ω_d for different subsets of $\underline{k}'$, allows to determine $\underline{V}$. The spectral width

$$\omega_s = \frac{2 \langle \Delta v^2 \rangle \cdot \omega_0}{C}$$

is proportional to the rms velocity fluctuations $\langle \Delta v^2 \rangle^{1/2}$ of or in the radar target. ω_0 is the angular frequency of the radar and C the speed of light.

Great care has to be taken to actually extract only the wanted atmospheric signal component from the correlation functions or the spectra. Contaminations occur due to noise (cosmic, receiver or interference) or clutter (ground, seasurface, ships, cars, aircraft or satellites), each having different characteristics. Also antenna sidelobes may pick up unwanted signals from other parts of the atmosphere. These problems are treated under another topic.

There are basically two methods to measure velocities. One method uses a narrow radar beam pointed into various directions to measure the 3-dimensional velocity vector $\underline{V}$. Another method uses three or more spaced antennas and the received signals are cross-correlated to determine the offset of the cross-correlation functions yielding the horizontal velocity component. The complex cross-correlation function is

$$\zeta(\underline{r}',\tau) = \langle E_k(\underline{r},t) \cdot E_1^*(\underline{r} + \underline{r}', t + \tau)$$

where k and 1 denote the different antennas and τ and $\underline{r}'$ denote the temporal and spatial displacements. Knowing the spatial displacements (i.e. the antenna separations), and measuring the temporal displacements of the cross-correlation functions allows to determine the drift speed of the field pattern on the ground, which is given by the drift speed of the scattering/reflecting radar targets. This method is the so-called "spaced antenna drift" method, whereas the former is called "Doppler method". It was shown by BRIGGS (1980) that both these methods are basically the same.

In Figure 2 both methods are compared schematically. Turbulence structures in the atmosphere scatter and reflect radar signals transmitted by a transmitter TX. Structures drifting through the antenna beam cause a drifting field pattern on the ground. The drift velocity is determined by the full correlation analysis (e.g., BRIGGS, 1977; ROTTGER, 1981). In the Doppler method the radial velocities from at least three pointing directions of the radar beam are measured. Under the assumption that the turbulence structures are advected with the background wind (Taylor hypothesis), the velocities deduced with these two methods correspond to the wind velocity.

Since these techniques have been used intensively at various places for many years, they will not be described in detail. We rather will briefly discuss some peculiarities, capabilities and limitations.

MONOSTATIC VERSUS BISTATIC OPERATION

Bistatic operations employ separate antennas for transmission and reception, and these are separated by a distance comparable to the distance to the radar target (viz. scatter volume or reflecting structure). The height resolution is achieved by the intersection of the two beams and can be improved by applying pulse coding with short baud lengths. If the beams are matched, the echo power varies inversely as the distance of the scatter volume from the receiving antenna, instead of inversely as the square of the distance in the monostatic case. The signal-to-noise ratio does not depend on the gain of the transmitting antenna. It is proportional to the effective aperture of the receiving antenna if the horizontal width of the receiver beam at the scatter volume is larger than the width of the transmitter beam. The ideal dimensions of the two antennas are those where the two beams match. Any further improvement in gain of either antenna improves the resolution but not the signal-to-noise ratio.

Because of the change of the Bragg wavelength with incidence angle, the spatial scales to which bistatic forward scatter radars are sensitive are larger than for monostatic or bistatic backscatter radars. The forward scatter cross

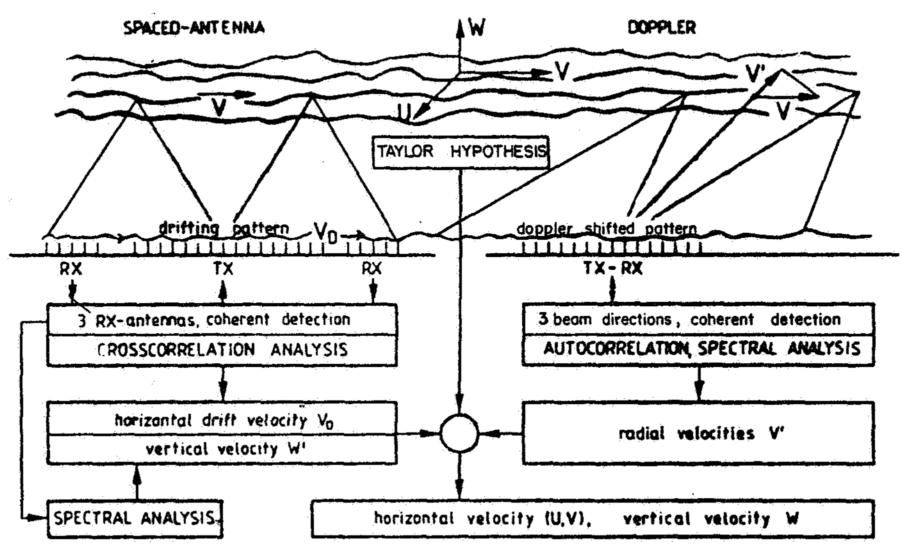

Figure 2. Scheme of spaced antenna and Doppler methods.

section mostly is larger than the backscatter cross section which significantly improves the detection capability. This on the other hand needs the scattering angle ϕ to be almost exactly 180°. This mostly is only the case if the target or scattering volume lies half the way along the line joining the transmitter and receiver. As a consequence, only vertical velocities can be measured.

The total velocity vector can be measured only with maintaining three receiving stations. A disadvantage of a bi- or multistatic system is further that it only observes one height at a time, although this limitation can partly be offset by antenna beam scanning or by using multi-beam receiving antennas.

SPACED ANTENNA MEASUREMENTS

Spaced antenna measurements of wind velocities in the troposphere and stratosphere until today were carried out only with the SOUSY-VHF-Radar. These were discussed in detail in earlier papers (e.g., ROTTGER, 1981), but still questions existed on the accuracy of these measurements. Traditional calibration standards to prove the validity of radar wind measurements were always radiosonde winds. These comparisons obviously have to take into account that the winds decorrelate with distance between the sensors, but even comparisons of very close-by measurements did not yield exact equality, neither with the Doppler nor with the spaced antenna method. FUKAO et al. (1982) have shown that most of the difference between radar and radiosonde data in the lower stratosphere is caused by errors of the radiosonde winds, while the spatial and temporal variations in the wind field seem to dominate the difference in the upper troposphere. We now also take into account that the winds are modulated by propagating synoptic-scale disturbances, and calculate cross-correlation functions for radar/radiosonde and radiosonde/radiosonde data to show that very reasonable agreement exists.

A first example of winds at levels close to the tropopause height is shown in Figure 3. The radiosonde Essen is 250 km west and radiosonde Berlin 220 km east of the radar. The periodical oscillation of the meridional wind component v, seen in all three data series, is caused by planetary waves (synoptic-scale disturbances) with periods of 3-4 days, propagating from west to east.

It is evident that the radar time series is delayed with respect to the western radiosonde and advanced with respect to the eastern radiosonde station. The cross-correlation functions ζ_{xy} in Figure 4 are significantly similar in maximum amplitude for all three data sets, which proves the validity of the spaced antenna radar winds. Whereas Figure 3 shows winds in the lower stratosphere (having a fairly broad autocorrelation function, i.e., high persistency), Figure 5 shows winds of the upper troposphere which have a much lower persistency (i.e., narrower autocorrelation function). Even here the radiosonde and radar wind cross-correlations are similar, of course the correlation between the radar and the closest radiosonde (2-4) is almost 1. The similarity of wind directions is even more convincing.

One may use these results as final evidence for the equality of both methods -- the radiosonde and the spaced antenna radar. It has to be noted also that the radar winds can easily be measured in a continuous series, which is far more difficult and very impractical with radiosondes. The radar winds of Figure 5 were measured every hour during a four-minute period only, and one may accept this value as sufficient for obtaining a very reliable wind velocity estimate.

RADAR INTERFEROMETER

The spaced antenna system that measures the quadrature components of a signal at different locations can be used as a simple form of a multielement or grating interferometer. Assume an array of N antenna modules at an equal

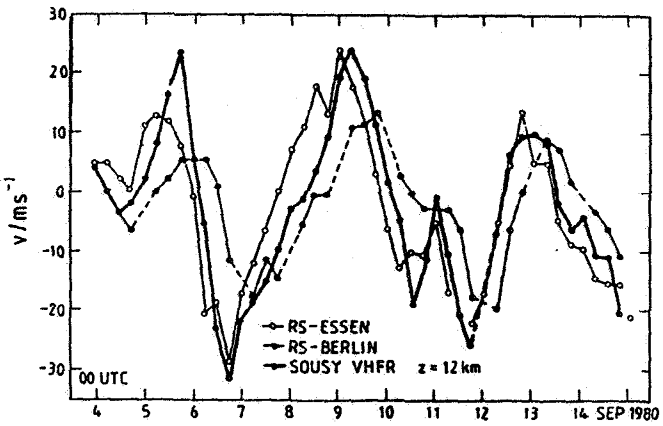

Figure 3. Meridional wind component v, measured over the period 4-15 September 1980 with radiosonde Essen, radiosonde Berlin and spaced antenna method with the SOUSY VHF radar.

spacing d to be lined up in the east-west direction. If each module with individual pattern $E_0(\phi,\theta)$ is fed with equal amplitude and phase the far field of this array is

$$E_R = \sum_{n=1}^{N} E_0(\phi,\theta) \exp(i\ (n - 1)\psi)$$

with

$$\psi = 2\pi\ d/\lambda \cos\phi \sin\theta \qquad i = (-1)^{1/2}$$

where ϕ is the zenith angle and λ is the wavelength. The azimuth angle θ is 90° only if the pattern in the east-west plane is considered. If the center of the array is chosen as phase reference, the array pattern in the east-west plane

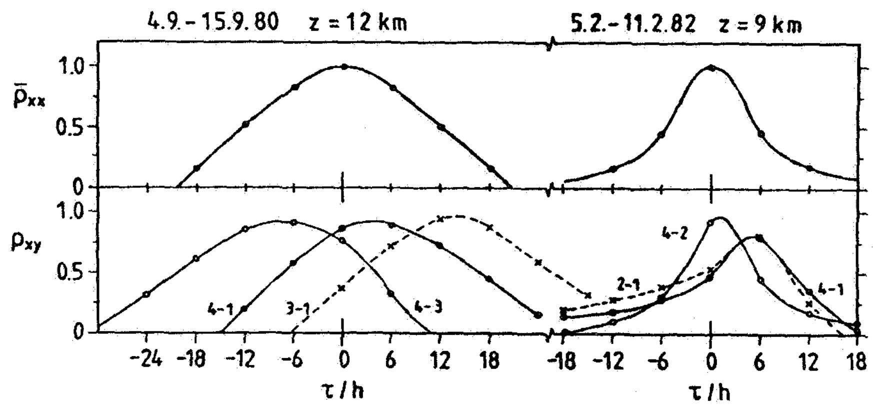

Figure 4. Auto- and cross-correlation functions for time series of wind velocity measurements with radiosondes: 1 = Essen, 2 = Hannover, 3 = Berlin, and 4 = spaced antenna radar (SOUSY near Lindau).

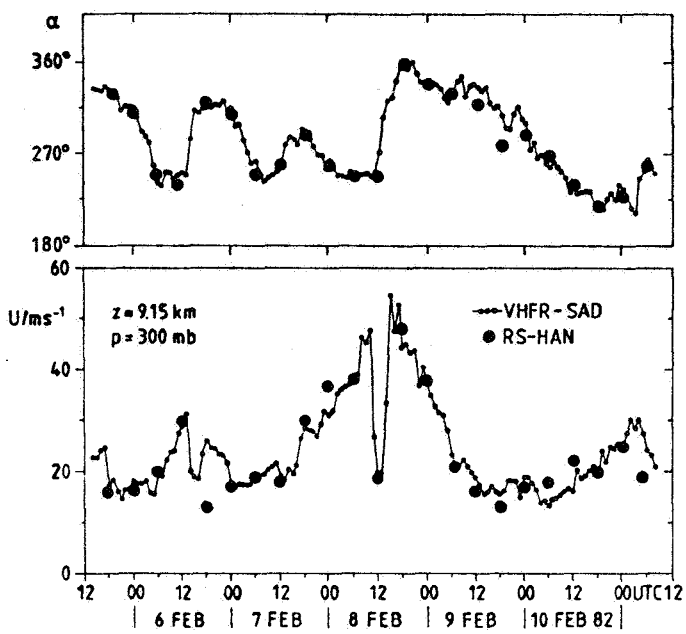

Figure 5. Wind speed U and direction α measured with the spaced antenna VHF radar method and the radiosonde of Hannover (RS-HAN).

becomes

$$E_R = E_0(\phi)\ \frac{\sin(N\psi/2)}{\sin(\psi/2)}$$

By reciprocity the array pattern is identical when the array is either used as a transmitting or receiving antenna.

In radar investigations an antenna with pattern $E_T(\phi)$ can be used for transmission and a grating interferometer with pattern $E_R(\phi)$ for reception. The effective pattern is

$$E(\phi) = E_R(\phi) \cdot E_T(\phi)$$

The transmitter antenna with half power beam width $\phi_T{}^h$ is assumed to point into zenith direction ($\phi = 0°$). The interferometer beam with half power beam width $\phi_R{}^h$ can be steered within the transmitter beam by changing the phase shift ψ between the receiving modules. This acts like swinging the radar beam to different elevation angles and can be used to measure the aspect sensitivity, the tilt of reflecting or scattering layers and also the velocity. Since any phase shift ψ can be inserted to recorded data during the evaluation process, the interferometer method appears to be more flexible than steering the antenna beam during transmission.

It has to be assured by appropriate spacing of the modules that only the main lobe of the interferometer is in the transmitter beam. This means that the spacing $\phi_R{}^g = \arcsin \lambda/d$ (with $d > \lambda$) of the grating lobe from the main lobe has to be larger than $\phi_T{}^h$. This yields

$$\sin \phi_T{}^h < \frac{\lambda}{d}$$

To obtain a reasonable angle resolution, ϕ_R^h should be equal to or smaller than ϕ_T^h. Since $\phi_R^h = 57.3° \lambda/Nd$, the extent of the whole array in wavelengths should be

$$L = \frac{Nd}{\lambda} > \frac{57.3°}{\phi_T^h}$$

In Figure 6 an example is shown of an interferometer pattern which could be obtained for the spaced antenna set-up of the SOUSY-VHF-Radar (e.g., ROTTGER, 1981). This example also takes into account an angular dependence or aspect sensitivity A of diffuse reflecting structures with about 2 dB per degree decrease of received signal power. The phasing between the antenna modules was optimized to obtain a best suppression of the grating lobe. Because only three receiving modules were used, a better suppression than 5 dB was not obtained and the interferometer set-off was 1.2° only and the beam width was fairly broad. However, this system allowed to measure horizontal phase velocities and wavelengths of gravity waves in the stratosphere (described in the working paper "Determination of vertical and horizontal wavelengths of gravity waves", topic 4). It also allowed to measure horizontal wind velocities when averaging over a longer period of an hour, as is shown in Figure 7. The comparison of wind speed U and direction α of the three methods interferometer, drift and radiosonde appears convincing. Better sidelobe suppression and narrower beam width of course can be obtained by using more than three receiving antenna modules.

Another approach to use a spaced antenna set-up as a radar interferometer was introduced earlier to study ionospheric irregularities at Jicamarca (e.g., FARLEY et al., 1981). They used a cross-spectrum analysis, which allows determination of the phase difference between different antennas at different Doppler frequencies. This method works properly when irregularity patches or blobs are present. Since we assumed that some of the mesospheric structures, detected with the VHF radars, are blobs drifting through the antenna beam, we have applied this method, too.

The height-time intensity plot of Figure 8 shows a fairly thin and short-lived structure at about 65 km altitude after 0710 UT. Analyzing this event with the cross-spectrum interferometer technique yielded the results of Figure 9. Here P_1, P_2, P_3 are the power spectra measured over 30 s at the three different spaced antennas. They clearly show a change of Doppler shift from positive values at the beginning to negative values at the end of the event. In the lower diagrams the coherence C_{13} and phase ϕ_{13} between signals measured at antennas 1 and 3 are depicted. These indicate that the phases changed during this event, which would not be expected if the scattering target would have remained overhead and moved up and down, according to the Doppler shift. The only explanation of these results is that a small scattering blob moved horizontally through the antenna beam. The combination of the interferometer and Doppler measurements yielded a zonal velocity of 43 m s^{-1} and a meriodional velocity of 7.5 m s^{-1} but a negligible vertical component. This analysis evidently proves the great advantage in applying the interferometer technique to avoid misinterpretation of velocity measurements.

DOPPLER METHOD

BALSLEY and GAGE (1982) and LARSEN and ROTTGER (1982) have recently reviewed the application of radars for atmospheric wind profiling and synoptic research. Both, the spaced antenna and the Doppler method, were discussed by them and in several earlier papers referenced therein. Since the application of the Doppler method has meanwhile become a standard part of textbooks, we only discuss here two items which are specific to MST radars, namely those which operate in the VHF band. It is accepted that the scattering/reflecting structures are anisotropic, which for instance led to the suitable application

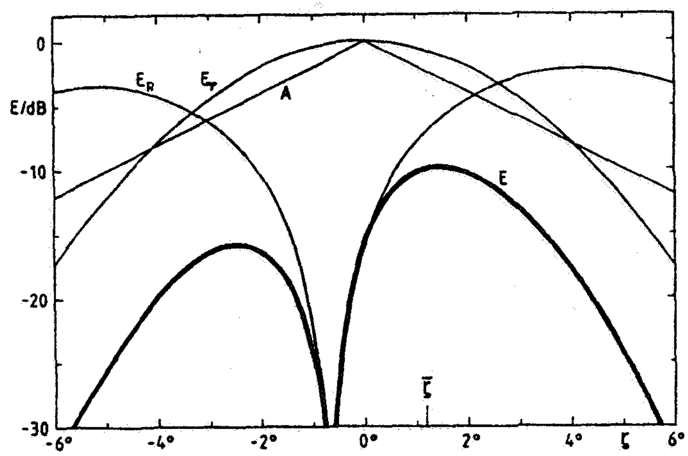

Figure 6. Interferometer pattern E, deduced from pattern of transmitter antenna E_T, three spaced antennas E_R, and angular dependence A of reflecting structures.

of the spaced antenna method. Evidently the anisotropy also leads to limitations of which the two most important shall be briefly discussed here.

ACCURACY OF VERTICAL VELOCITY DETERMINATION

Let us assume Fresnel reflection from a refractivity structure which is slightly tilted to the horizontal. It shall be tilted by an angle ψ around a horizontal rotation axis which forms an angle θ to the north direction. Let the tilted structure move with velocity $\underline{V}$, where $\underline{V}$ is given by its zonal (u), meridional (v) and vertical (w) components. A radar with vertically

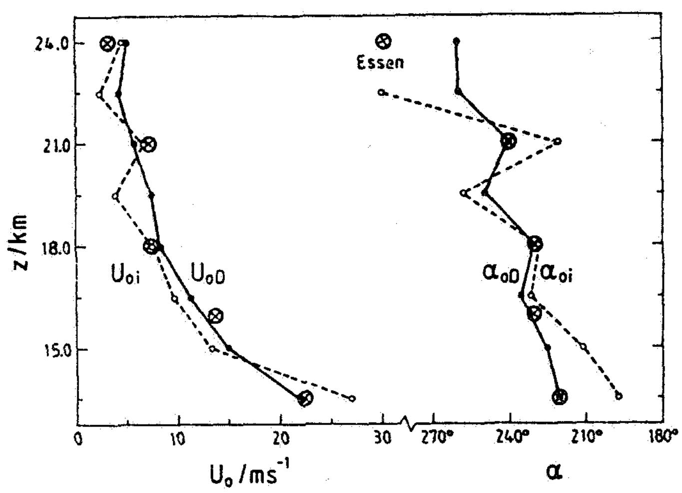

Figure 7. Average wind speed U_0 and direction α_0, deduced with the interferometer (i) and the drift method (D) using spaced antenna radar on 9 September 1980, 0540-0640 UT. Circles with crosses denote corresponding radiosonde data from Essen.

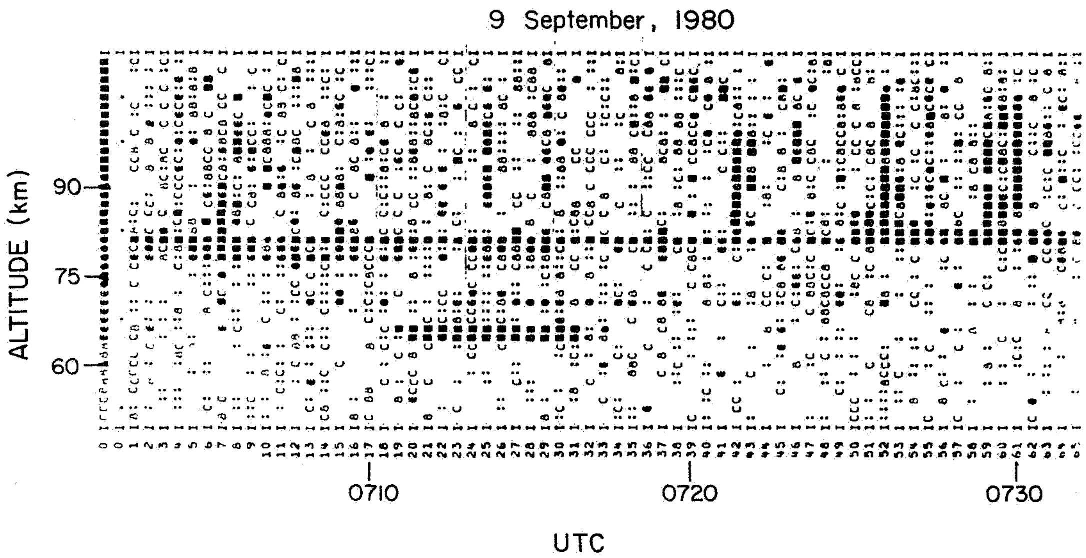

Figure 8. Height-time intensity plot of VHF radar echoes from the mesosphere.

pointing antenna, with beam width larger than the tilt angle of the structure, will measure the radial velocity

$$v_r = w \cos\psi + (u \cos\theta - v \sin\theta) \sin\psi + w^* + u^*.$$

The projections of u and v cause errors in determining w from v_r which may not be negligible. These errors and possible corrections can only be determined if one can measure u, v, θ and ψ independently of v_r. This can be achieved appropriately by spaced antenna measurements. The components u and v are deduced by the cross-correlation analysis with the spaced antenna drift method. Under realistic assumptions u and v, deduced by this method, are in a first order independent of measurements of w by means of the Doppler analysis and are not instrumentally correlated. The angles θ and ψ are computed from measure-

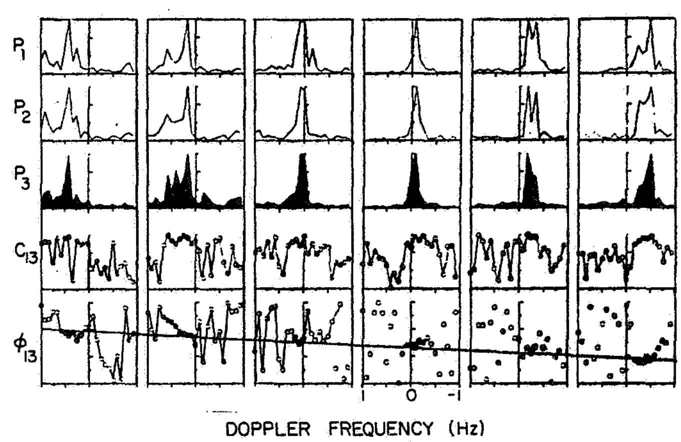

Figure 9. Power spectra P_1, P_2, P_3 of mesospheric echo, measured at three antennas, and coherence C_{13} and phase ϕ_{13} measured between antennas 1 and 3.

ments of the phases of the radar echo between different spaced antennas (measurement of the incidence angles by the interferometer method).

Let, for example, two antennas being lined up in east-west direction at a distance d. For $\theta = 0°$,

$$\sin\psi = \frac{\Delta\phi}{360°} \cdot \frac{\lambda}{d}$$

Analyses of sample data from the lower stratosphere yield, for instance, for a one-hour average typical phase differences $\Delta\phi \approx 2°$ between two antennas separated by $d = 4.5\lambda$. This yields an average tilt angle $\psi = 0.07°$. Horizontal velocities of 20 m s^{-1} then lead to $u^* = 2$ cm s^{-1}. Since typical radial velocities $v_r = 10$ cm s^{-1}, the average vertical velocity w is then determined with an error of 20%.

To measure the tilt for correction will therefore improve the determination of average vertical velocities and additionally yield a meteorological parameter, viz. the average inclination or tilt angles of reflecting structures which are related to baroclinic disturbances. To know the tilt angle will also be of eminent importance during pronounced gravity wave events, e.g., lee waves and propagating waves with wavelengths of several kilometers.

OPTIMUM POINTING ANGLES

Because of the angular dependence of the anisotropic turbulence structures an apparent beam direction is manifest at off-vertical beam pointing directions (ROTTGER, 1980). This is schematically illustrated in Figure 10. Assume the angular spectrum of the diffusively reflecting irregularities to be centered at an angle ϕ_0, which usually is the zenith direction. Let the antenna beam width be comparable to the width of the angular spectrum. The physical antenna beam pointing direction shall be off the vertical at an angle ϕ_b. The echo power results from the convolution of the angular spectrum and the antenna beam pattern. As indicated in Figure 10, this yields an apparent beam with a pointing direction ϕ_a, which is closer to the zenith than the physical pointing direction ϕ_b. It was pointed out by ROTTGER (1980) that for an average angular dependence $\delta = 1.5$ dB/degrees, a beam pointing direction $\phi_b = 7°$ and a beam width of 5°, the apparent beam direction is $\phi_a = 6°$. This gives rise to an underestimate of the horizontal wind velocity by 20%. The wind direction is not affected by this effect if the irregularity structure is isometric in the horizontal plane.

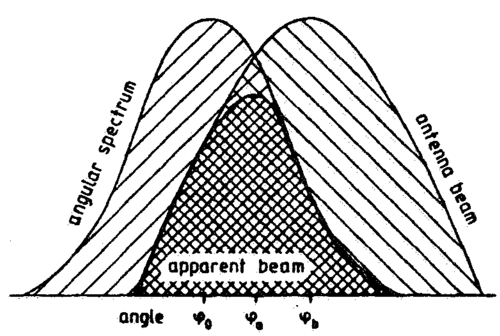

Figure 10. Formation of an apparent beam direction ϕ_a when the antenna beam points to direction ϕ_b but the angular spectrum (distribution) of the scatterer is anisotropic or the reflecting surface (seen at angle ϕ_0) is diffuse.

ROTTGER and CZECHOWSKY (1980) have presented experimental evidence for this effect. They had evaluated horizontal velocities measured at 3.5° and 7° zenith angle with a 5° wide antenna beam. An evident difference (beam at 3.5° yielded lower velocities than at 7°) was found in the height region above the tropopause where the aspect sensitivity was most substantial. Precautions, therefore, have to be taken if one deduces horizontal velocities with the Doppler beam pointing method. The magnitude of this systematic error depends on the aspect sensitivity which has to be measured to correct the velocity estimates. One also has to bear in mind the apparent beam direction when describing the effect of beam width broadening of the Doppler spectrum (turbulence fluctuations). These errors of velocity estimates have to be considered if the off-zenith beam pointing direction is comparable to the beam width. To the author's knowledge attempts have now been made to apply such corrections to wind measurements with the Doppler method.

When choosing the optimum pointing angle, one has also to bear in mind that with increasing off-zenith angle the signal-to-noise ratio substantially decreases (e.g., Figure 11), the effective aperture of the antenna and the height resolution decrease, as well as sidelobes may be close to the zenith direction yielding again contaminations from the reflected component, but the effect of apparent beam direction (due to aspect sensitivity) gets smaller and the accuracy of the horizontal velocity estimates increases.

QUESTIONS ON TIME RESOLUTION TO MEASURE LONG- AND SHORT-PERIOD VARIATIONS

Any kind of spectrum or correlation function measurements has to take into account ensemble averaging in order to obtain statistically significant estimates. The error of any estimate decreases with the square root of numbers of samples, and one therefore would be inclined to average over very long time periods. However, the averaging period depends obviously on the stationarity and the time scales of processes of interest. The shortest time scale, MST-VHF radars can resolve, is given by typical time scales of the variations at the Bragg wavelength λ' of the refractive index to which these radars are sensitive. These times are typically of the order of seconds. To obtain acceptable statistics, averaging over some ten seconds must be done. Further averaging has to take into account the geophysical effects of interest, and one may decide to average over 1-2 min in order to still resolve short-period gravity waves, to average over several hours to smooth the gravity wave oscillations and obtain semi-diurnal and diurnal tidal variations. The synoptic-scale

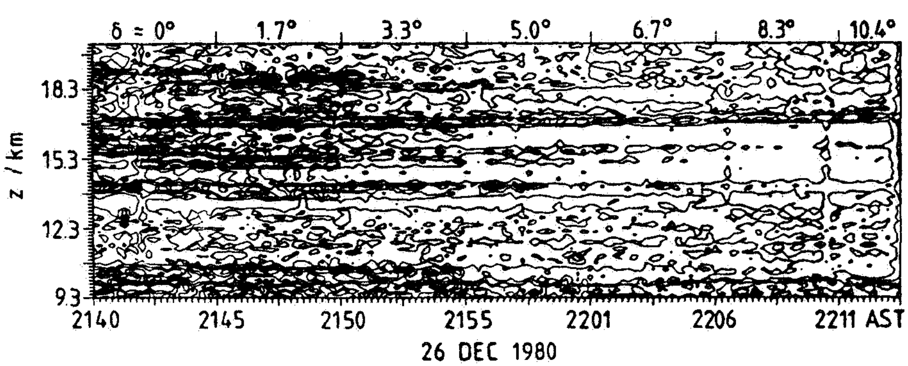

Figure 11. Contour plot of signal strength observed with 1.7° beam width and different zenith angles δ, which indicate the considerable decrease of signal with increasing δ. Observations were with the 46.8-MHz radar at the Arecibo Observatory, contour steps are 2 dB.

disturbances and planetary waves have periods of several days and averaging over 12-24 h will be suitable. However, because of the relative persistency of some of these processes, sampling during a short period at suitable time intervals often is sufficient.

As a general rule for deducing velocities from radar data, one may start with quality assessment of the autocorrelation functions and power spectra to apply an optimum fitting procedure and discard bad data. The next step would be to display short time series of velocities deduced for periods of one minute to get ideas on gravity wave oscillations and only later apply longer-term averaging.

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REPORT AND RECOMMENDATIONS

The essential subtopics of this session were reviewed in several working papers which follow; four main subtopics (a) - (d) were discussed in detail.

(a) The meteorological requirements for the determination of vertical velocities connected with all different scales of motions was elucidated by K. S. Gage (this volume, p. 215). It was found that MST radars are most suitable tools to measure the vertical velocities. However, intensified investigations on the accuracy to be expected from MST radar measurements have to be continued. It is recommended that special emphasis shall be given to the following items:

(1) Investigations shall be carried out to determine if the turbulence structures observed with MST radars are locked into the large-scale motions, which means that they would be extended along the isentropic surfaces.

(2) Can MST radars measure the inclination of isentropic surfaces, and how accurately can this be done eventually?

(3) How accurately can the vertical velocity (defined as the velocity component in the topocentric z-direction) be measured, and how crucial are remaining contaminations from the horizontal wind?

(4) Following the Poker Flat routine observations of the vertical wind in the mesosphere, other MST radars should be used in the same mode to obtain information on global variations.

(b) The applications of the spaced antenna method to measure winds in the mesosphere by MF/HF radars and in the stratosphere and troposphere by VHF radars was reviewed by Hocking (this volume, p. 171), and he concluded that this method is as viable as any other method. Some discussion on its strengths and weaknesses followed; including the question of how bulk velocity estimates can be contaminated by gravity wave oscillations (Royrvik, this volume, p. 228). The Doppler method essentially was discussed in terms of the accuracy which can be obtained by different pointing directions of the antenna beams (Koscielny and Doviak, this volume, p. 192; and Strauch, this volume, p. 232). Considering the remaining uncertainties in measuring horizontal and vertical velocities it is recommended that investigations have to continue to solve the questions:

(1) How can the vertical velocity contamination due to the horizontal wind best be accounted for?

(2) How can the inaccuracy of horizontal wind measurements with the Doppler method be minimized, when horizontal shears in u, v and w exist?

Since troposphere and lower stratosphere radars are now seriously being proposed (and are starting to be tested) for widespread use in networks for wind measurements, definite experiments need to be conducted as soon as possible to determine:

(3) How the spaced antenna drifts methods and the Doppler method compare in terms of economics, accuracy etc. for troposphere and lower stratosphere wind profiling. An exhaustive study to compare both these methods must be done by including experts in both of these fields in a common program. It is also necessary to have other independent measurements, e.g., radiosondes, included.

(4) What range of wavelengths are suitable for profiling networks; in particular will VHF/UHF radars be more suitable to contribute to wind profiling than the new 10 cm Doppler weather radar (NEXRAD)?

(c) Another extended discussion took place on the application of MST radars to measure gravity wave parameters, since this topic was also of pronounced interest in session 4 on techniques to measure gravity waves and turbulence. The following recommendations were adopted:

(1) In order to measure horizontal and vertical wave velocities simultaneously in the same volume, the application of bistatic or tristatic MST radar systems should be considered.

(2) It is noticed that monostatic MST radars can be used to measure vertical and horizontal phase velocities of gravity waves, if these are fairly monochromatic (coherent). More use of both, the Doppler method (on-line beam steering) and the spaced antenna method (off-line beam steering), would be desirable to measure these gravity wave parameters.

(3) It is recommended that networks of MST radars have to be used for obtaining statistical information (climatology) on incoherent gravity waves.

(d) Radar interferometer techniques which recently were applied also to MST radars were reviewed by Farley (this volume, p. 237). It was noticed that these techniques have some potentials for investigating turbulence structures.

It is recommended that the application of the interferometer technique shall be encouraged. It is assumed, however that its application is not suitable for operational use rather than for basic scientific research.