

3. RELATIONSHIP OF SPACED ANTENNA AND DOPPLER TECHNIQUES  
FOR VELOCITY MEASUREMENTS  
(Keynote Paper)

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INTRODUCTION

The Doppler, spaced-antenna and interferometric methods of measuring wind velocities all use the same basic information -- the Doppler shifts imposed on backscattered radio waves -- but they process it in different ways. The Doppler technique is most commonly used at VHF since the narrow radar beams are readily available. However, the spaced antenna (SA) method has been successfully used with the SOUSY and Adelaide radars. At MF/HF the spaced antenna method is widely used since the large antenna arrays (diameter  $> 1$  km) required to generate narrow beams are expensive to construct. Where such arrays of this size are available then the Doppler method has been successfully used (e.g. Adelaide and Brisbane). In principle, the factors which influence the choice of beam pointing angle, the optimum antenna spacing will be the same whether operation is at MF or VHF.

Many of the parameters which govern the efficient use of wind measuring systems have been discussed at previous MST workshops (e.g. ROTGER, 1983; STRAUCH, 1983; HOCKING, 1983; FARLEY, 1983). In the following some of the points raised by these workers and others are summarized.

SPACED ANTENNA TECHNIQUES

The SA method uses 3 or more antennas to sample the moving diffraction pattern produced by backscatter from a given range from the atmosphere. The pattern can be decomposed into Fourier components which are formed by interference between signals scattered at complementary angles to the zenith (Figure 1). The differential Doppler shifts induced by the horizontal velocity  $u$ , cause the pattern to move with velocity  $2u$  (BRIGGS, 1980).

Usually only 3 antennas are used, arranged in the form of an equilateral triangle since the symmetry is less likely to introduce a bias in determining the velocity. The auto- and cross-correlation functions of the signals are computed (Figure 2) in order to determine the pattern velocity. The three time delays of the maxima of the cross correlation functions between the three pairs of spaced antennas give the apparent velocity. This is an overestimate of the actual (true) velocity since random motions etc. will cause the pattern to change as it moves. The so-called full correction analysis (FCA) is used to correct for these changes as well as for the anisometry of the pattern. The FCA makes use of such information as the lag at which the autocorrelation function is the same as the instantaneous correlation between 2 spaced antennas.

Obviously, if the antennas are too closely spaced then the errors become large and experimentally it is found that the corrected ('true') velocity is too small. On the other hand if the spacing is too large then random changes in the pattern can dominate over the translational effects (e.g. ROYRVIK, 1983) and the correlation values are so small that the analysis breaks down. On pragmatic and experimental grounds it is found that the optimum spacing is where the average zero lag correlation is about 0.5.

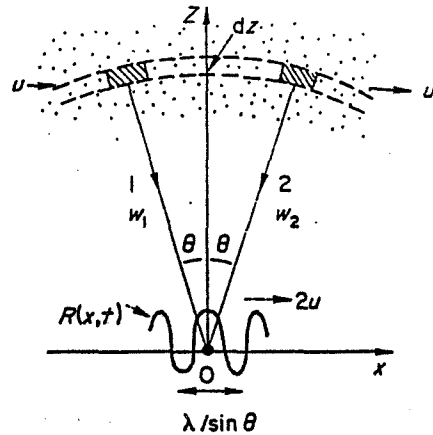


Figure 1. Two-dimensional radar situation with a uniform wind  $u$  in the  $x$  direction (after BRIGGS, 1980).

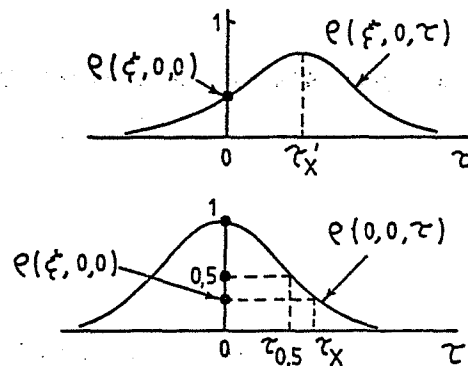


Figure 2. The cross- and autocorrelation functions of the signals from two antennas separated along the  $x$  direction by a distance  $\xi$ .

The mean pattern size and hence the distance at which the mean correlation is about 0.5 is determined by the angular distribution of the backscattered energy. In turn, this angular distribution is determined by the polar pattern of the transmitting and the receiving antennas as well as the angular distribution imposed by the nature of the scattering irregularities. It is possible to show (BRIGGS and VINCENT, 1973) that the complex spatial correlation function as a function of spacing  $\alpha$  ( in wavelengths) is

$$\rho(\alpha) = \int_0^{\infty} R(s) S(s) T(s) s^2 J_0(2\pi\alpha s) ds$$

where  $R(s)$  and  $T(s)$  are the receiver and transmitter power polar diagrams, respectively, and  $S(s)$  is the angular distribution of backscattered power; all are evaluated as a function of  $s = \sin\theta$  where  $\theta$  is zenith angle and circular symmetry is assumed.  $J_0$  is the zero order Bessel function.

At MF/HF, the antenna polar diagrams are usually broader than the irregularity angular distributions so that it is usually the latter (half power-half widths  $\sim \theta_0 \sim 2-20^\circ$ ) which determine  $\rho(\alpha)$ . It may be expected that since  $\theta_0$  varies as a function of height and time that  $\rho(\alpha)$  will also be variable but on average it is found that spacings of the order of 150-200 m ( $\alpha \sim 1-1.5\lambda$ ) are optimum for radio frequencies near 2 MHz.

At VHF the antenna polar diagrams are of the order of a few degrees in

width i.e. comparable in width to the angular spectra of the irregularities ( $\theta_0 \sim 1-5^\circ$ ). The minimum spacing may be computed for a given  $R(s)$  and  $T(s)$  by assuming isotropic scatter ( $S(s) \sim 1$ ). At Adelaide, with a transmitter beam having a half width of  $\theta_T \sim 1.6^\circ$  it is found that this minimum spacing is  $5\lambda$  (about 30 m at a frequency of 50 MHz) but in practice it is found that a mean spacing of about 50 m ( $\alpha \sim 9\lambda$ ) is optimum for the troposphere. Incidentally, this implies a mean  $\theta_0 \sim 2^\circ$ .

Despite the narrowness of the angular spectra of backscatter from the lower mesosphere at MF and from the lower atmosphere at VHF, it is found experimentally that the SA method gives reliable measurements of the wind velocity. In each case it is found that the importance of random changes in producing temporal changes in the signals are small compared with those changes caused by movement of the pattern. This may not always be true in the mesosphere when working at VHF and with narrow beam antennas. In this case the random motions may become dominant leading to a breakdown in the SA analysis (ROYRVIK, 1983).

#### DOPPLER TECHNIQUES

It is, in principle, quite straightforward to measure the vertical wind component  $w$  by using a vertically pointing beam. The horizontal wind components must, however, be estimated by projecting the radial velocity  $v_r$  measured along a beam offset at an angle  $\theta$  from the vertical, onto the horizontal plane. STRAUCH (1983) has summarized the factors which determine the optimum value of  $\theta$ .

Among those factors which favor the use of a small angle  $\theta$  are: (a) the desire to make use of the aspect sensitivity of the scatterers which gives enhanced power from near the zenith; (b) the effects of horizontal variations in the wind field are reduced; (c) the  $r^{-2}$  effect is minimized.

On the other hand if  $\theta$  is large then: (d) errors in  $v_r$  translate into smaller errors in the horizontal velocity; (e) the effects of the vertical velocity is less pronounced and (f) the influence of the aspect sensitivity on effective beam direction is less important if  $\theta$  is large.

Probably (f) is the key factor. As ROTIGER (1983) emphasizes, the effective beam pointing direction is determined by the product of the beam pattern and the angular distribution of the scatter. The effective beam zenith angle is smaller than the physical angle and the horizontal velocity component is underestimated. This can be a serious problem when using antennas with relatively broad beams ( $\theta_H > 3^\circ$ ). For example, at Adelaide with a beam angle of  $\theta_H > 4.5^\circ$  it is found that the horizontal velocity can be up to a factor of 2 too small when the physical pointing angle is  $12^\circ$ . In principle, this factor can be allowed for if  $\theta_0$  is known (e.g. WHITEHEAD et al. 1983) but this probably entails measurements of the scattered power at more than one angle and of course  $\theta_0$  will change with height and time so that only a statistical analysis can be used. Overall, Strauch recommends an angle of  $\theta = 15^\circ$  for VHF studies of the lower atmosphere. At this angle the scatter from isotropic irregularities is presumed to overcome the anisotropic scatter.

#### RADAR INTERFEROMETRY

The radar interferometer exploits the Doppler information inherent in coherent spaced antenna measurements. Cross spectral analysis of the signals received at separated antennas can be used to locate and track irregularities while Doppler sorting can be used to discriminate against multiple targets -- provided they have different radial velocities (FARLEY et al., 1981). PFISTER (1971) seems to have been the first to use this method in a study of gravity

motions in the E-region. This method seems to have merit for studying spatial variations in the wind field.

In another variation of this method, ROTTGER and VINCENT (1978) digitally 'steered' the lobes of an interferometer formed from widely spaced antennas in order to study the fine structure and horizontal tilts of refractive index irregularities. This method has significant potential for correcting for the "vertical" velocities induced by these tilted irregularities.

#### DISCUSSION

The intrinsic errors in each velocity determination by either the Doppler or SA methods are determined by such factors as the signal-to-noise ratios and the record lengths. Expressions have been derived for the rms error of a line-of-sight Doppler velocity by, for example, DOVIK et al. (1979). The precision of SA velocities has not been as rigorously determined but, provided the random changes are small the error is determined by the accuracy to which  $\tau_x$  (Figure 2) can be measured. The fractional error is independent of wind speed because the width is narrower for larger velocities (small lag) and becomes broader as the velocity becomes smaller (large lag). For either technique the velocity measurements can be improved by averaging the power spectra (Doppler) or the unnormalized cross correlation functions (SA). However, this process can only be carried out for durations which are short compared with the time for significant changes in the mean wind.

Another factor limiting the precision of horizontal wind determinations is the "noise" imposed by unresolved vertical velocities. Since the Doppler and SA methods utilize the same information, it may be expected that they will be affected in the same way by such factors as spatially and temporally varying vertical velocities. Significant short-period vertical velocities such as those encountered in the mesosphere where rms amplitudes  $\sim 1-2 \text{ ms}^{-1}$  are possible can lead to difficulties in estimating the mean zonal wind. BOWHILL (1983) estimates that averaging times of an hour are required for Doppler measurements of  $u$  but that the effects can be minimized by using tilt angles of  $10^\circ$ . ROYRVIK (1983) has shown that the differential velocities caused by vertical velocities which vary in the horizontal will be interpreted as horizontal motions by the SA method. The importance of this effect is not yet clear since the SA method is not as easy to model as the Doppler technique.

In summary, the choice of operating parameters for a given radar will be determined by compromise between a number of opposing factors. What is optimum for one height range (e.g. the lower atmosphere) may not be the most suitable for another height (e.g. the mesosphere).

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#### SUMMARY AND RECOMMENDATIONS

OPTIMUM POINTING ANGLE: There are a number of factors which determine the choice of the off-zenith pointing angle for Doppler velocity measurements. At frequencies near 50 MHz the main factor is the strong aspect sensitivity of the scattering which can cause the effective pointing direction to be smaller than the physical beam direction. There is consensus that zenith pointing angles of 10 to 15° are suitable for tropospheric, stratospheric and mesospheric studies. At these angles however, signals received through sidelobes pointing near the zenith may become significant. Such signals can be distinguished by their signature in the Doppler spectra and so their contribution should be rejected by the use of appropriate algorithms at the analysis stage.

OPTIMUM SPACINGS FOR SA MEASUREMENTS: The receiving antennas should be separated by distances comparable to the mean pattern scale (i.e., the separation where the zero-lag correlation is 0.5 on average. A MF/HF separation of about 1.0 to 1.5 $\lambda$  have proved satisfactory. At VHF, the scale will be determined in general by the use of the transmitting antenna and the angular distribution of the backscattered signals. While it is possible to calculate the spacing, the optimum spacing has to be determined experimentally. For a radar with a transmitting antenna with a 3° beam, a spacing of about 50 m has been found to be satisfactory.

RECOMMENDATION: Noting that there are some uncertainties associated with the vertical velocities measured by MST radars working in the lower VHF range where specular reflections are important and noting that for radars working at UHF such echoes are not observed, it is recommended that comparative studies of vertical velocities be made as soon as possible with co-located VHF and UHF radars and other suitable techniques such as lidar. Where practicable, interferometric techniques should be used to remove the effects of any tilts in the specularly reflecting surfaces.

RECOMMENDATION: It is noted that the aspect sensitivity at zenith angles smaller than 10 - 15° causes the effective antenna pointing direction to be closer to the zenith than the physical pointing direction. This effect will be most important for wide beams and will give errors in estimating the horizontal wind velocity. Investigations to obtain estimates of the likely errors and how they can be minimized are necessary.