3.2A THE SPACED ANTENNA DRIFT METHOD

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ABSTRACT

The spaced antenna drift method is a simple and relatively inexpensive method for determination of atmospheric wind velocities using radars. The technique has been extensively tested in the mesosphere at high and medium frequencies, and found to give reliable results. Recently, the method has also been applied to VHF observations of the troposphere and stratosphere, and results appear to be reliable. This paper discusses briefly the principle of the method, and investigates both its strengths and weaknesses. Some discussions concerning criticisms of the technique are also given, and it is concluded that while these criticisms may be of some concern at times, appropriate care can ensure that the method is at least as viable as any other method of remote wind measurement. At times, the technique has definite advantages.

INTRODUCTION TO THE METHOD

The spaced antenna drift method was earlier applied to measurements of electron drift in the ionospheric E and F regions, and later to measurements of neutral winds in the ionospheric D region. For D-region work, the method has been denoted by "PRD" ("partial reflection D1 drifts" e.g., BRIGGS, 1977). Since its introduction to tropospheric and stratospheric measurements at VHF (e.g. ROTTGER and VINCENT, 1978), it had become known as the "SAD" ("spaced antenna drift") method (ROTTGER, 1981a). Following the Estes Park VHF conference of May, 1982, the notation "SA" was adopted ("spaced antenna"). In this paper, the latter notation will be adopted, although this is still not universally accepted.

The spaced antenna method of wind measurement began with MITRA (1949), who used a very simple approach involving measurements of time delays at three antennae. This technique was subsequently improved by a variety of workers, including BRIGGS et al. (1950), PHILLIPS and SPENCER (1955), FOOKS (1965), FEDOR (1967) and BROWN and CHAPMAN (1972). BRIGGS (1968a) presented a formal review of the method. However, possibly the best review of the method to date is one due to BRIGGS (1977b). That review is recommended to any reader who is seriously interested in understanding the spaced antenna method. Because the mathematical and conceptual details of the technique are so well covered in that article, they will not be repeated here in any great detail. Nor will a history of the method be presented; BRIGGS (1977b) presented a short history. Rather, the first objective of this paper will be to describe the basic principle of the technique, free of any mathematics. Having presented this general overview. a more extensive discussion of the shortcomings and strengths of the method will be given.

APPARENT VELOCITY

The principle of the SA method is very simple, and is illustrated in Figure 1. Pulses of radio waves are transmitted into the atmosphere, and are partially backscattered or reflected. These scattered signals form diffraction patterns on the ground, and these diffraction patterns move at twice the speed of the scattering irregularities. The factor 2 arises because the transmitter is effectively a point source (e.g., FELGATE, 1970). The scale of these

diffraction patterns depends on the polar diagrams of the transmitting and receiving aerials, and the backscattering polar diagrams of the scatterers. The narrower the polar diagrams, the larger the scale of these diffraction patterns. The SA method measures the speed of these diffraction patterns across the ground, and this therefore gives the velocity of the scattering irregularities, after division by a factor of 2.

Figure 1 is based on an experiment conducted at Townsville in Australia to study the ionospheric D region. The experiment was designed and operated by Dr. R. A. Vincent of the Dept. of Physics, University of Adelaide, Australia. It represents perhaps the most compact and simplest form of the SA experiment. The radio waves (1.94 MHz) were transmitted from the square in the centre of Figure 1. The small black rectangle inside this square represents the transmitter and receiving building, and the four lines leading from it represent transmission lines to four half-wave dipoles, which form the outer square. Three simple crossed dipoles (A, B and C) were used for reception. The contours in the diagram represent part of the diffraction pattern amplitude (in the general case this is complex (amplitude and phase)) and the large arrow "2W" represents the diffraction pattern's velocity. As it moves, the diffraction pattern will cause temporal variations at the aerials A, B and C, and these temporal variations will be similar, but will be displaced in time (see the illustrative amplitude variations as a function of time in the bottom left hand corner of Figure 1). In the simplest case, the axis of the diffraction pattern can be taken to be perpendicular to the velocity vector 2W, and the time displacements of the signals A, B and C can readily be used to determine the velocity 2W. The same formalism also applies if the contours of the diffraction pattern are, on average, circular. Determination of the "wind velocity" under either of these assumptions leads to a quantity known as the "apparent velocity". This method was first proposed by MITRA (1949).

FULL CORRELATION ANALYSIS

Sometimes the axis of the diffraction pattern may not be perpendicular to the velocity vector, as illustrated in Figure 1. Further, the pattern may change quasi-randomly as it moves. These effects produce errors in the apparent velocity when compared to the real velocity. To remove these effects, the method of data reduction known as "full correlation analysis" (FCA) was developed. With this method, it is not only possible to more properly determine the real velocity, but it is also possible to indicate the scales of the diffraction patterns, the orientations of these patterns, and to indicate the degree of random fading. The velocity deduced by this method is termed the "true velocity". A fundamental function necessary for the application of FCA is the temporal and spatial autocorrelation function, defined by

$$\rho(\xi,\eta,\tau) = \frac{<f^*(x,y,t)f(x+\xi,y+\eta,t+\tau)>}{<|f(x,y,t)|^2>} \tag{1}$$

where x and y are orthogonal co-ordinates on the ground (e.g., East and North), t is time, ξ is the displacement in the x direction, η the displacement in the y direction, t is the time, τ is time lag, f(x,y,t) is the (possibly complex) amplitude of the diffraction pattern (after removal of the mean) and <> denotes averaging over (in principle) all x, all y, and all t; f* is the complex conjugate of f.

In practice it is unrealistic to exactly determine $\rho(\xi,\eta,\tau)$, since it requires measurements of f(x,y,t) at all points (x,y) on the ground. Nevertheless, if some very reasonable assumptions concerning the form of ρ are made (see BRIGGS, 1977b for the details of these assumptions), the $\rho(\xi,\eta,\tau)$ can be fairly accurately estimated from determinations of the temporal autocorrelations
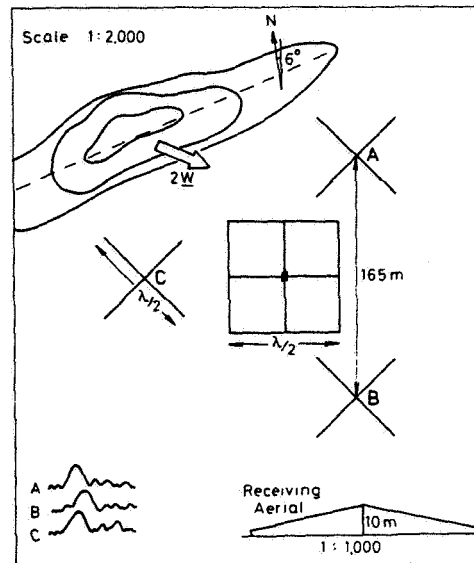
Figure 1. The principle of the spaced antenna method.

and cross correlations of 3 or more aerials. BRIGGS (1977b) described how this could be done.

Having determined an approximation to the function , it is a relatively simple matter to deduce the so-called "true velocity", as well as the variety of other parameters described earlier (BRIGGS, 1977b). These "other parameters" can provide useful information concerning the nature of the scatterers (e.g., STUBBS, 1977), but in this paper we will concentrate primarily on the "true velocity".

However, it is instructive to briefly mention the significance of one of these extra parameters. Since the backscattered signal varies as a function of time, it is of course possible to form the autocorrelation function of the signal, and thence to find the time lag for this function to fall to 0.5. This time lag will be denoted by $\tau_{0.5}$, and is sometimes called the "fading time". But FCA allows the experimentor to carry this one step further, and determine the fading time which would have been observed if the radar had been moving at the same mean speed as the scattering irregularities. Let us call this parameter $T_{0.5}$. Then BRIGGS (1980) has shown that if the scatter is due to isotropic turbulence, the Root Mean Square (RMS) vertical velocity of the turbulence scatterers, v_{RMS} say, (more generally, v_{RMS} is the RMS velocity of any chosen component) is related to $T_{0.5}$ by the relation

$$v_{RMS} = \lambda\sqrt{2\ln 2}/(4\pi T_{0.5}) \tag{2}$$

(This formula is valid if complex data are used to estimate $T_{0.5}$.)

MANSON and MEEK (1980) and MANSON et al. (1981) have extended this formula to relate v_{RMS} to the turbulent energy dissipation rate (ϵ), and the Brunt-Vaisala frequency (ω_B). A relation of the form

$$\epsilon = K v_{RMS}^2 \omega_B \tag{3}$$

where K is a constant (of the order of 0.3-0.5) was obtained (also see HOCKING,

1983a). Thus in principle it is possible to obtain ε from Full Correlation Analysis. However, a word of warning should be sounded here. The equation (3) assumes that the RMS motions associated with horizontal and vertical directions are the same within the effective radar beam. (The effective radar beam includes consideration of the backscattering polar diagram of the scatterers.) Unfortunately, this may not be the case. The vertical motions are those associated with the Buoyancy scale of the turbulence, whilst the horizontal motions are those associated with scales of the order of the width of the effective radar beam at the height of scatter. This latter scale is often of the order of several kilometres, and the motions associated with such scales may be either two-dimensional turbulence, or gravity waves. This point was not considered either by BRIGGS (1980) or MANSON and MEEK (1980). Thus equation (3) is not really applicable for SA measurements of v_{RMS}, and it is necessary to distinguish between horizontal and vertical motions. This point has been emphasized by HOCKING (1983a). (Also see WRIGHT and PITTEWAY (1978)). Thus it is not really possible to estimate ε by SA measurements. Equations (2) and (3) can be used to place upper limits on ε, but it is not possible to estimate, from simple SA measurements, just how much (3) overestimates the true value of ε. A more elaborate procedure, such as that described by HOCKING (1983a,b) is necessary to properly estimate ε, and is only possible with a large array of antenna capable of forming a narrow beam.

From now on, this paper will concentrate on estimates of wind velocities derived from the SA method. As has been seen, the principle of the method is quite simple. With modern computers, the application of the method is relatively easy, and can even be efficient with small on-site minicomputers (e.g., MEEK, 1980).

ACCEPTANCE CRITERIA

Because the SA method requires estimation of the function $\rho(\xi,\eta,\tau)$ (equation (1)) from a few simple cross-correlation functions, it is important to take care that the fitted function ρ is reasonable. Therefore proper application of the FCA method requires that certain acceptance criteria are obeyed. These acceptance criteria (also called rejection criteria) are quite stringent, and must always be applied. Failure to apply these criteria can allow many erroneous wind speed estimates to be accepted, and this can bias the results and perhaps even give the appearance that the SA method is unreliable. The rejection criteria used at Adelaide, Australia, by the University of Adelaide Physics Dept., are listed below (e.g., BALL, 1981). A data sample is rejected if

(1) The receiver was saturated for a significant time during the data record;

(2) The digitized signal levels are only of the order of a few digitial units (weak signal);

(3) The mean autocorrelation function has not fallen below 0.5 after about 20 time lags (slow fading);

(4) Any cross-correlation maxima are less than 0.2;

(5) Any cross- or auto-correlation functions are oscillatory in nature over the first 20 time lags;

(6) The polynomial fit to the cross-correlation functions breaks down, preventing determination of certain crucial time delays;

(7) The sum of the three time delays of the peaks of the cross correlations between aerial pairs AB, BC and CA is greater than 0.2 times the sum of

the moduli of these time delays (MEEK et al. 1979);

(8) The "true" and "apparent" velocities are very different;

(9) The quantity "V_c^2" estimated in FCA is significantly less than 0. (In the case that V_c^2 is only slightly less than zero, the apparent velocity can be used in place of the true velocity, since this probably indicates very little random fading);

(10) The signal-to-noise ratio is small;

(11) The contours of the diffraction pattern are non-elliptical (they become hyperbolic) in form.

Despite the apparent complexity of these tests, they are not difficult to apply with a digital computer, and they do not normally result in excessive rejection rates.

POTENTIAL PROBLEMS WITH THE SA METHOD

As will be seen later, tests of the spaced antenna technique in the meso-sphere (at MF and HF) and in the troposphere and stratosphere (VHF) have almost invariably shown it to be reliable. Nevertheless, from time to time objections to the method arise, and it is a useful exercise to consider these objections in more detail. It will be suggested that while there may be situations which can in principle produce erroneous results, they do not occur commonly in the atmosphere. Furthermore, it will be shown that objections can be raised to almost any method of remote wind measurement, and in all such remote observa-tions a degree of care and selection is necessary.

BRIGGS (1980) has shown that, for the case that all scatterers in the radar volume move with the same horizontal velocity, and have zero vertical velocity, then the SA method must give identical results to the so-called Doppler method of wind measurement. If however, there are also vertical motions, these will affect the Doppler estimates of the horizontal velocity. Nevertheless, if a vertically pointing radar is also used, the effects of these vertical velocities can also be taken into account with the Doppler method.

The main difference of the SA method and the Doppler method lies in the direction of the radar beams. The SA method uses vertically directed beams, whilst the Doppler method uses beams tilted from the zenith to obtain horizontal wind velocities (plus a vertical beam to obtain vertical winds). Often, also, the SA method uses beams with wide half-widths, whilst Doppler estimates require very narrow beams. (Nevertheless, the SA method can also be applied with narrow beams.)

Most objections to the SA method are based on the assumption that there are two types of scatterers in the radar volume, and that these two types of scatterers move at different velocities. The most common assumption is that there are specular scatterers, aligned approximately horizontally, which scatter primarily from the vertical, and more isotropic scatterers. Specific mechanisms are then invoked which claim that the specular scatterers move at different velocities to the isotropic scatterers. It is then claimed that, since the SA method is more susceptible to scatter from the vertical, it will measure primarily a drift speed associated with these specular scatterers. It is most common to invoke gravity waves as the cause of these specular scatterers. Unfortunately it is never really stated clearly exactly how gravity waves cause these specular reflectors, and this point will be closely examined in this article.

Before proceeding to this examination, however, it is worth pointing out that gravity waves could also produce isotropic scatterers moving with the wave. For example, HODGES (1967) has shown that under certain circumstances, a gravity wave could produce turbulence during part of its cycle. If a layer of air existed which was close to statically unstable, but not quite unstable, the gravity wave temperature gradient at particular parts of the cycle may render the layer unstable. This may then cause turbulence. If the turbulence died out sufficiently quickly, then these turbulent patches would appear to move horizontally with the gravity wave, and both the SA method and the Doppler method would measure the horizontal component of the phase velocity of the gravity wave in such circumstances. Whether such a mechanism is realistic is a matter for debate; the main point is, however, that it is unfair to single out the SA method for criticism by means of specific examples without discussing similar cases for other methods of remote wind measurement.

Perhaps the most comprehensive discussions of the effects of gravity waves on the SA method can be found in HINES and RAO (1968), HINES (1972) and HINES (1976), although other authors (e.g., BROWNLIE et al., 1973) have also made contributions. However, it should be remembered that those papers primarily applied to measurements of drifts by totally reflected radio waves from the E and F ionospheric regions. In those cases, specular reflection was the main means of backscatter. Gravity waves curve the electron density isopleths, producing focusing and defocusing, and therefore fading of the radio signal at the ground. In the D region and lower atmosphere, it is not nearly so easy to make this assumption. It is necessary to carefully consider how gravity waves can influence only the specular reflectors, and also to consider the scales at which these effects occur.

To begin with, let us assume that these specular reflectors form independently of the gravity wave, by some unspecified mechanism, and are then influenced by it. Figure 2a illustrates the situation. Specular reflectors are indicated at times $t = t_1$ and t_2. In this case, it is assumed that the specular reflectors (thick lines and dots) are only separated by short distances, and cover most of the sky at the altitude under examination. In the limit, they may form continuous sheets. A gravity wave oscillation is assumed to tilt the reflectors at these two times. The specular reflectors are also blown by the mean wind, but this is taken to be zero in Figures 2a,b. Radio waves incident from transmitters TX1 and TX2 are "focused" and "defocused" respectively. Therefore as the gravity wave moves across the ground, it produces fading. An SA experiment may then measure the speed of this gravity wave. Is such an argument valid?

This situation may be applicable for total reflection from the ionospheric E or F regions at HF, because the isopleths of electron density are continuous, and reflection is total. However, for MF, HF and VHF scatter from the meso-sphere, Figure 2a is not applicable. Rather, the specular reflectors which exist there are much more temporally and spatially intermittent (e.g., HARPER and WOODMAN, 1977; HOCKING, 1979; JONES, 1982). The same is often true for VHF tropospheric and stratospheric echoes. A situation like Figure 2b is more likely, in which only a small fraction of a gravity-wave cycle contains the reflectors. In such cases, the receiver will either receive a signal (when the reflectors are appropriately orientated), or receive no signal at all. If the oscillation has a very short period the radar signal will alternate between "high" and zero in an on-off manner. This will produce oscillatory correlation functions, and the "wind measurements" will be rejected in the FCA. Objectors to the SA method who have applied this argument have failed to recognize the importance of the "acceptance criteria" of section 4. If, on the other hand, the gravity-wave period is much longer than the typical data duration used to perform an SA measurement, then the tilting of the reflectors may be too slow to have a measurable effect. Rather "roughness" on the reflector (e.g., ROTTGER,
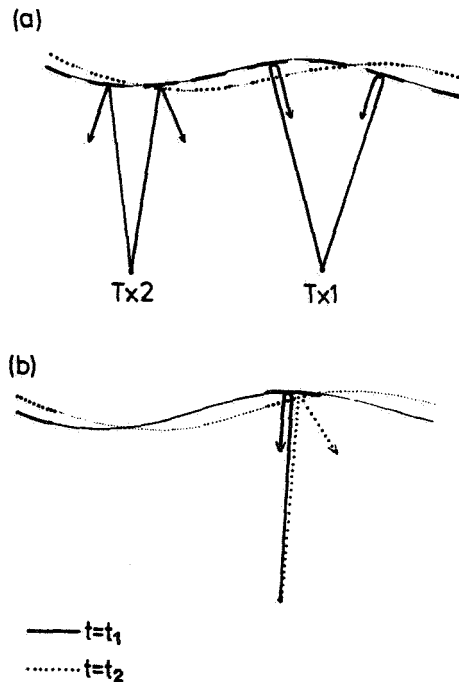
(a)

(b)

——t=t$_1$

·········t=t$_2$

Figure 2.   Illustration of gravity-wave-induced tilts to specular
reflectors, and the effects of radar backscatter.

1980 refers to "diffuse reflection") will produce most of the fading, as the
reflector moves with the wind, and the SA method will give the true wind velo-
city. When it is noted that most SA measurements use data lengths of about 1
minute or less, and that gravity waves have periods of at least 5 minutes (and
at least 10 mins in the troposphere), it becomes clear that generally the scales
of gravity waves are such as to reduce the possibility of this mechanism being a
realistic threat to the application of the SA technique.

    The point concerning the scale of the gravity waves is also pertinent to
Figure 2a. If the scale of the diffraction pattern produced is similar to that
of the gravity wave, then the gravity-wave-induced fading will be very slow. and
faster fading (which the SA method will utilize) will occur due to motions of
the more isotropic irregularities, and due to roughness on the surfaces of the
reflector. Both the scatterers and the reflectors move with the wind, so that
the SA method will measure this true wind speed. However, it can occur
(particularly when many waves are present) that the scales of the diffraction
pattern produced by gravity waves reflections can be considerably smaller than
the gravity-wave scale ("interference fading": e.g., HINES and RAO. 1968;
BROWNLIE et al., 1972), so that fast fading can at times occur due to gravity
waves. In such cases, the SA method can produce erroneous results. Neverthe-
less, for VHF and HF partial reflection work, such gravity-wave-perturbed
continuous reflectors seem rare; and when they do exist, it can also be
difficult to obtain horizontal wind speeds by Doppler methods. One of the few
catalogued tropospheric cases observed in which such stratification occurs has
been presented by GAGE et al. (1981), and the wave had a period of about 18
min. It is doubtful that any effects of the phase velocity of the gravity wave

would have shown in any SA measurements of the wind in this case.

As an extra point, if high amplitude gravity waves occur, they may tilt these specular reflectors quite markedly, in which case Doppler radars may also observe the reflectors and therefore measure a finite (erroneous) wind velocity. This point has been emhasized by ROTTGER (1981a). The SA method, with its more stringent acceptance criteria, is more likely to reject the measurement. ROTTGER (1981a) also pointed out that such large amplitude waves are most likely to occur in the region of critical level interaction, in which case the phase velocity of the wave equals the mean wind anyway. But to be fair the above case may be rare and in most instances of critical level interaction, both the SA and Doppler methods will measure a wind equal to the sum of the mean wind and the wind due to the gravity wave, which is of course the desired value.

It therefore seems fair to suggest that this attempted criticism of the SA method is not, in reality, applicable, except perhaps in rare circumstances. In such circumstances, these erroneous measurements should stand out from the rest of the data, thereby enabling them to be rejected. Such rejection procedures are quite common, and would not be unique to the SA method. For example. LARSEN et al. (1982) using Doppler recorded winds, talk of rejection of questionable data.

The second way in which we could imagine gravity waves to influence the specular reflectors is that the gravity waves actually produce the reflectors, rather than simply acting on already existing reflectors. In this way the gravity wave actually carries the reflectors with it.

As mentioned earlier, this is not hard to envisage for total reflection from the E and F region. The gravity wave curves the contours of constant electron density in the region where the absolute refractive index approaches zero (i.e., the height of reflection), thereby produce focusing and defocusing. However, this scheme cannot be applied for partial reflection. For partial reflection, the refractive index gradient is the important quantity, rather than the absolute refractive index. Any change of refractive index must occur within less than about one quarter of the radar wavelength -- changes which occur more slowly are very very inefficient reflectors (e.g., ATLAS, 1964; HOCKING and VINCENT, 1982). Therefore we need only look at the case that the gravity wave wavelength is of the order of the radar wavelength. The most likely mechanism is that reflection occurs from the wavefronts of the gravity wave. For example HINES (1960) has proposed that at 60-70 km, gravity waves with vertical wavelengths of a hundred metres or so can explain observed HF and MF specular reflection from this height range. The gravity wave must have a wavelength perpendicular to its wavefronts equal to one-half of the radar wavelength. Such a process, however, would give strongest scatter from the off-vertical.

As an example, consider wavelengths of 3 m at $\simeq$ 10 km altitude. Could these exist, and produce the observed VHF specular scatter? HINES (1960, equation 49) showed that the smallest vertical wavelength which would not be dissipated by viscosity is

$$\lambda_z(\text{min}) \simeq 2\pi\sqrt{\eta T}, \tag{4}$$

where T is the wave period (sec) and η is the kinematic viscosity. Above 10 km, $\eta \leq 3\times10^{-5}$ m^2 s^{-1}. We require $\lambda_z(\text{min}) \leq 3$ m, so T $\leq$ 100 min; at 18 km, T $\leq$ 40 min. Yet, as seen from HINES (1960, Figure 9), this means that all such wave fronts must be tilted at angles of $\geq$ 2°-3° from the horizontal at 10 km altitude. At 18 km altitude, the tilt must be $\geq$6°. At 65 km, 3 m waves cannot exist, and even 75 m waves (capable of specular reflection at 150 m radio wavelength) must have tilts of greater than 10°. This effect of preferred scatter from off-zenith angles has never been observed, yet if it existed would be quite

obvious. It therefore seems unlikely that gravity waves cause specular reflections directly. Further, even if equation (4) is in error and gravity waves can cause specular reflections, the waves must be at least of very long peroid, in order to have near-horizontal wavefronts. As discussed earlier, long period oscillations do not have a substantial effect on the recorded signal when time durations of less than a minute are considered; the specular signal would just produce a constant offset. (At times, however, interference fading could be important.) Thus any fading of the signal during each data collection period would be due to other irregularities blown by the wind, and the SA method would still measure the proper wind speed.

It should also be noted that if the situation did occur in which two different types of scatterers moved at different velocities, and the two types of scatter contributed approximately equal power, and both had velocities significantly different from zero, then two peaks would often occur in the cross-correlation functions. This would also mean that the data sample would be rejected.

It therefore appears that in most cases, gravity waves do not bias SA measurements of wind velocities, and this point will be re-emphasized later by means of experimental data. However, the SA method does suffer from one weakness which must be mentioned, and this is the so-called "triangle size effect". In principle, the "true velocity" found from the SA method should be independent of the spacing of the aerials used to measure the wind, provided that the spacing is less than the typical diffraction pattern scale. However, it has been found that the "true velocity" often increases with receiver separation, tending to a limit for large separations. The same effect is observed for the "apparent velocity". The limiting values at larger separations appear to be the correct values. This effect has never been satisfactorily explained (BRIGGS, 1977b), although several proposals have been made. Nevertheless, the effect is not a major one, and appropriate choice of the aerial spacings results in reliable estimates of the wind velocity.

ADVANTAGES OF THE SA METHOD

In the previous section, objections to the SA method were examined. It would be unfair to consider only objections to that method, however. Therefore let us consider some weaknesses of another method, namely the Doppler method. In this technique, tilted beams are used to measure radial Doppler shifts, and these are then converted to horizontal velocities. To do this, the vertical velocity must be known, and this can be obtained using a vertically pointing radar. However, it has to be assumed that the vertical velocity above the radar equals that at the scattering region for the tilted beam, and this may not always be so. Furthermore, if the radio-wave scatterers are anisotropic, with horizontal dimensions greater than their vertical dimensions, then the scatterers will also backscatter anisotropically. Radio waves will be returned more effectively from zenith angles closer to the vertical. If a radar beam is tilted at an angle θ_0, the received backscattered radiation intensity will not be greatest at $\theta = \theta_0$, but a smaller angle, θ_1. Thus the measured radial velocity of the scatterers will be that for scatterers at a zenith angle θ_1, and this is less than the radial velocity of scatterers at θ_0. When this radial velocity is converted to a horizontal velocity under the assumption that scatter was strongest from θ_0, the resultant value will be an underdestimate. This has been emphasized by ROTTGER (1981a).

It is true that if the polar diagram of the scatterers is known, θ_1 can be estimated, and therefore the true horizontal wind can be obtained. At present, however, such corrections are not normally applied with the Doppler method, and would be difficult to apply if the properties of the scatterers were continually changing.

Another problem can arise for the Doppler method, and this occurs when
there are significant horizontal fluctuations of the wind velocity. This is
illustrated in Figure 3. Doppler velocities from the region 'a' will produce a
spectrum indicated by 'A' in Figure 3, and the range of velocities from region
'b' produce the spectrum 'B'. Likewise from 'c' we get the spectrum 'C'. The
width of each "subspectrum" A, B and C depends on the RMS horizontal velocity of
the scatterers, and the mean tilt angle for the regions a, b and c. Thus
"sub-spectra" produced by scatter from larger tilt angles have a broader range
of frequencies, reducing the peak power in their spectra. The result is that,
when these "sub-spectra" are summed to produce the full spectrum, there is a
bias towards low frequency components, and so the frequency offset of the peak
of the spectrum is less than would have been obtained in the case of a constant
mean wind with no horizontal fluctuations. This situation has been numerically
modelled by HOCKING (1983a), who showed that if a radar with a beam half-power
half-width of 4.5° is used, and if the RMS horizontal fluctuating velocity is
similar to the mean wind speed in magnitude, then an underestimate in the wind
velocity of ≈20% results. This is true even for isotropic backscatter.

The main point of these examples is not to downgrade the Doppler method,
but rather to emphasize that all methods of remote wind measurements suffer from
some form of weakness. It is important not to become too prejudiced against any
method on the basis of a few speculations.

There are weaknesses and advantages of most radar methods. For example, as
emphasized earlier, measurements of small scale turbulence are best done by
Doppler methods (HOCKING, 1983a,b). Also, there are fewer acceptance tests
necessary when the Doppler method is used. On the other hand, the SA method
does not underestimate the wind velocity when scatter is anisotropic. In fact
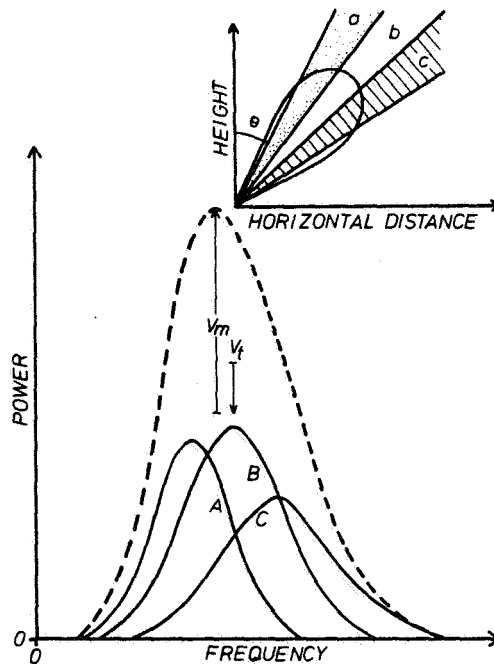

Figure 3. Distortion of radar spectra due to horizontal fluctuating
motions of the scatterers.

one of the major advantages of the SA method is that it can utilize specular reflections in regions where scatter from the off-vertical is hidden by noise. For example, Figure 4 illustrates this effect. Figure 4a shows a Doppler spectrum recorded with the vertically pointing SOUSY radar beam, from a height of 25.2 km. Figures 4b and 4c show the spectra recorded with beams pointing at 7° off-zenith in the North and East directions, respectively. In Figures 4b and c the signal is hidden in the noise, and Doppler estimates of the wind velocity are not possible. However, there is plenty of signal at vertical incidence, which the SA method could utilize to obtain wind estimates. Further, as pointed out by ROTTGER (1981a) fading is slower with vertical beams, so more coherent integration can be applied with the SA method.

The SA method can also give a measure of the polar diagram of the scatterers, by virtue of its determination of the pattern scale. (In the case of gravity-wave oscillations in extended reflectors, interference fading can produce scales at the ground considerably smaller than the gravity-wave scale (see earlier). Care is necessary in such circumstances, but normally for VHF and HF partial reflections this should not be very common.) The Doppler method, in a fixed beam mode, cannot measure the polar diagram, but it can by using beam-swinging techniques.

The SA method can also apply the Doppler technique to determine vertical velocities. ROTTGER (1981a,b) has also emphasized that the SA method can be used to determine mean angles of arrival of the scattered radiation, and therefore to determine if any of the "vertical velocity" measured could be due to contamination from horizontal motions. For wide beams, this is probably most feasible over time scales of tens of minutes, since some averaging is necessary. Possibly narrow beams, such typically as those used by Doppler radars, may be better tools for estimation of short-term vertical velocity variations. Of course, the SA method can also be applied using narrow transmitter beams, and determination of angle of arrival is then an added bonus.

One of the greatest advantages of the SA method is its cheapness and simplicity. It only requires a transmitter array, and three small receiving arrays. Because of the small size, it also has advantages in regions where space for aerials is limited.

Another advantage of the SA method is that it measures wind speeds immediately above the observing array. The Doppler method measures the vertical wind overhead, but measures horizontal winds at points some distance from the overhead point. Further, the two orthogonal horizontal wind components are measured at different points in space. Thus when the three wind components are used to determine a total wind vector, it must be assumed that the wind field is homogeneous over a large area of sky.

Thus both the Doppler and SA methods have advantages and disadvantages, and the method finally adopted in any circumstances must depend largely on the requirements of the user.

EXPERIMENTAL TESTS OF THE SA METHOD

The best way to test the SA method is, of course, by comparison with other methods. Extensive tests of the method have been carried out, and all suggest that the SA method is a reliable means of estimation of wind velocity in the mesosphere (at MF and HF) and in the troposphere and stratosphere (at VHF).

FRASER and KOCHANSKI (1970) and GREGORY and REES (1971) initially showed that SA measurements at MF and HF in the D region produced reliable winds. STUBBS and VINCENT (1973) and STUBBS (1973) then showed that the SA method agreed well with meteor measurements of winds at 80-100 km altitude. Further

(a) VERTICAL BEAM
Power Density
Frequency Hz.
-3.   3.

SOUSY RADAR
17 OCT. 1981   1300 HR.
25.2 KM.

(b) NORTH BEAM
7°
Power Density
Frequency Hz.
-3.   3.

(c) EAST BEAM
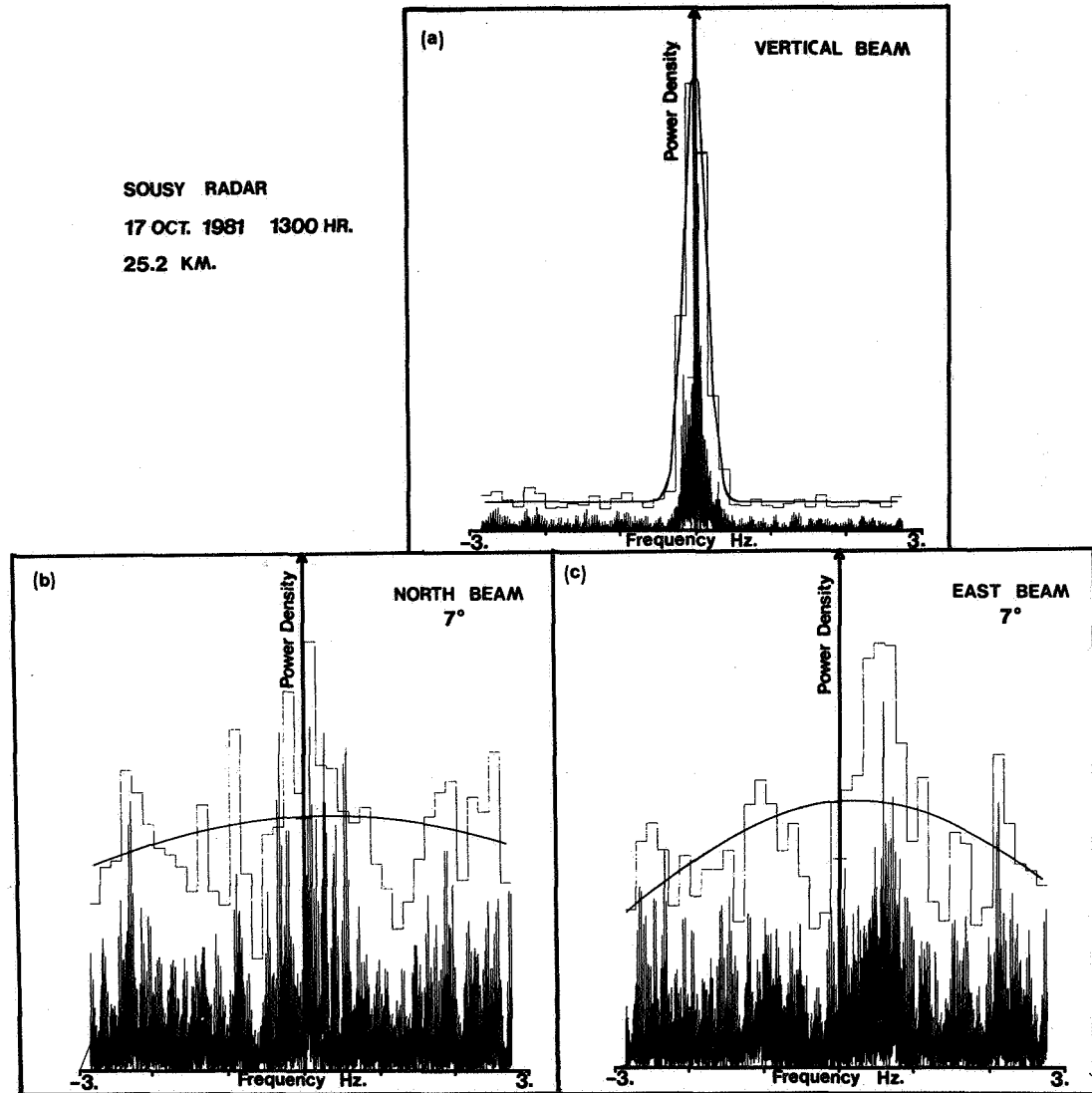7°
Power Density
Frequency Hz.
-3.   3.

Figure 4. An example in which specular VHF backscatter is very strong
(graph a) but off-vertical backscatter (b,c) is hidden in the noise.
The "spikey" plots are the raw spectra — the "histograms" are these
spectra after averaging in frequency blocks. The smooth curves
represent a best fit Gaussian plus offset.

comparisons with meteor measurements by WRIGHT et al. (1976) also showed good
agreement. VINCENT et al. (1976) compared the SA method to measurements of D-
region winds made by rocket techniques, and again good agreement was obtained.
BRIGGS (1977a) presented further comparisons with meteor measurements. Measure-
ments of means winds at Adelaide, Australia (e.g., VINCENT and BALL, 1981) and
Saskatoon, Canada (e.g., MANSON et al., 1981) show that these means are
consistent with accepted models of mesospheric circulation.

In the troposphere and stratosphere, several sets of SA measurements have
been compared to wind measurements made by more conventional meteorological
means. The first such report was by ROTTGER and VINCENT (1978). Good agreement
was found between balloon measurements and VHF SA wind measurements. Likewise,
results presented by VINCENT and ROTTGER (1980) showed similar good agreement.
Subsequent comparisons by ROTTGER (1981a,c) and ROTTGER and CZECHOWSKY (1980)
have also given no cause to doubt the SA method. More tests are probably
necessary, but there are certainly no grounds yet on which to reject the method.

Recently, the Physics Dept. at the University of Adelaide, Australia, has
modified the Buckland Park aerial array (which is used at 1.98 MHz to observe
the ionospheric D region) to allow Doppler measurements of D-region horizontal
winds. An example of a comparison between the SA method and the Doppler method
is given in Figure 5. The Doppler beam had half-power, half-width of 4.5°, and
was tilted at 11.6° from the vertical. The comparison was prepared by I. Reid
and R. Vincent (private communication). Agreement is good; the differences can
be attributed to vertical mean motion, since the horizontal winds determined by
the Doppler method have been estimated under the assumption of zero vertical
velocity. The effect discussed in connection with Figure 3 may also be
important. HOCKING (1983b) also presented comparisons of SA and Doppler
measurements, and again agreement was favourable.

The very fact that regular oscillations in winds are observed with the SA
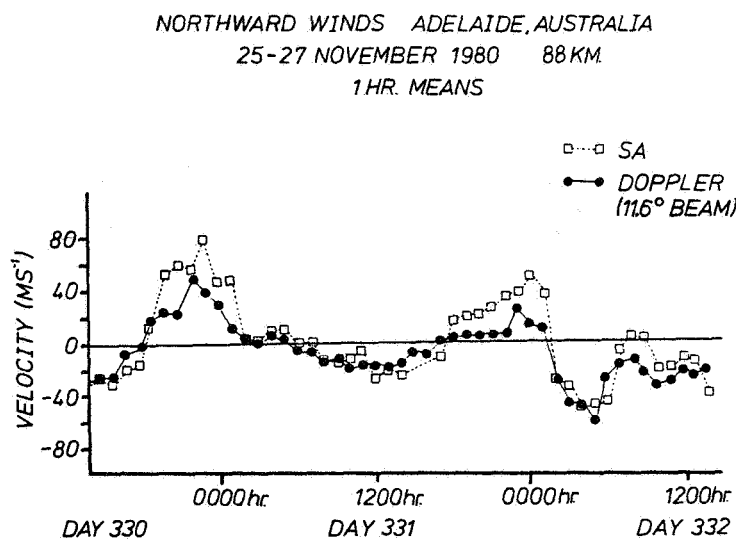method in the D region, and that these have a cutoff at periods less than the

Figure 5. A comparison of wind measurements by the spaced antenna
and Doppler methods, using an HF radar (REID and VINCENT, private
communication).

Brunt-Vaisala frequency (e.g., VINCENT and BALL, 1977; MANSON et al., 1981) further suggests that the SA method does measure gravity-wave winds, and not the phase velocity of the gravity wave.

DISCUSSION AND CONCLUSION

Evidence has been presented that the SA method is a reliable means of measuring neutral wind velocities in the mesosphere (at least at medium and high frequencies) and in the troposphere and stratosphere (at VHF). Some specific objections to the SA method has been considered, and it was concluded that the scales of gravity waves in the atmosphere, and the intermittency in space and time of specular reflectors, ensure that the SA method is generally quite viable when data lengths of less than 1 min are used, at least for the atmospheric regions and radio frequencies considered. (These arguments do not apply when total reflection and extremely short period waves ($\leq$ 3 min) are involved.) Further, the correct use of acceptance (rejection) tests in the SA method is emphasized. These tests must be applied in any SA measurements.

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