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The effect of thin scattering layers on the determination of wind by Doppler radars

Peter Thomas May, Shoichiro Fukao, Toshitaka Tsuda, Toru Sato, and Susumu Kato

Radio Atmospheric Science Center, Kyoto University, Japan

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It has recently been suggested that the observed tendency for intense turbulence to occur in thin layers in the atmosphere introduces an error in horizontal wind measurements with MST radars, even in the absence of wind shear. This effect, called the finite range volume effect, is a consequence of the tilted pulse volume when using the Doppler technique. A model is shown which illustrates that this effect may be very important in MST radar measurements when wide antenna beam widths are used. These model results are supported by observations performed with the MU radar in Japan, where wind measurements with different beam widths have been performed. The impact of these measurements on MST radar design and possible methods to minimize the error are discussed.

INTRODUCTION

Recent work by *Fukao et al.* [this issue *a*, *b*] has shown that the presence of thin scattering layers in the atmosphere may cause a quasi-systematic error in the determination of horizontal wind vectors by the MST (mesosphere-stratosphere-troposphere) Doppler radar or wind profiler technique. This error arises because only a fraction of the radar pulse volume is filled by these layers and in the case of tilted radar beams the effective center of the scattering region within the pulse volume may be centered at some angle other than the mean tilt angle of the antenna beam. This phenomenom has been named the "finite range volume effect" (Figure 1) and is independent of the aspect sensitivity of the scatterers. The theory of this error shows that in the region of the thin layer an apparent vertical shear of the horizontal wind, which can be of a very large magnitude, is produced. An accompanying wind shear with the opposite sign will also be found in the region of weak scatter in the range gates next to the one producing the strong echo. Thus an artificial vertical structure of the wind field with a vertical scale of the order of four times the pulse length can be generated. In addition to this effect, it is well known that the layers of the high reflectivity may cause errors in the determination of the wind where there is a large wind shear [e.g., *Sato and Fukao*, 1982]. This is because the observed mean Doppler velocity will be an appropriate estimate for the height of the layer and not the height of the center of the range gate.

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Convincing observational evidence for the reality of the finite range volume effect has also been shown [see *Fukao et al.*, this issue *a*, Figure 4], but it is not clear from these studies how important the effect will be for routine observations and how much consideration should be given to this effect in the design of MST radars. In order to answer these questions a simple model has been developed in which the magnitude of this effect can be observed for various radar parameters, such as polar diagram half-width, tilt angle and range resolution. Both cases with and without the wind shear within the pulse volume will be discussed, with examples of various "wind" profiles. It will be shown that these effects are an important consideration and can lead to significant errors in routine wind observations for many of the currently operating MST radar systems.

The model makes explicit predictions concerning the severity of this effect as a function of antenna beam width and pulse length. In order to test these results, observations have been performed using the MU radar system. This radar is an advanced MST radar system with an active phased array of yagi antennas (see *Fukao et al.* [1985*a*, *b*] for a comprehensive description of this radar). With this radar it is simple to transmit and receive the signal with various combinations of antennas and antenna beam tilt angles, and in particular, combinations which give a two-way 3-dB antenna polar diagram beam width,

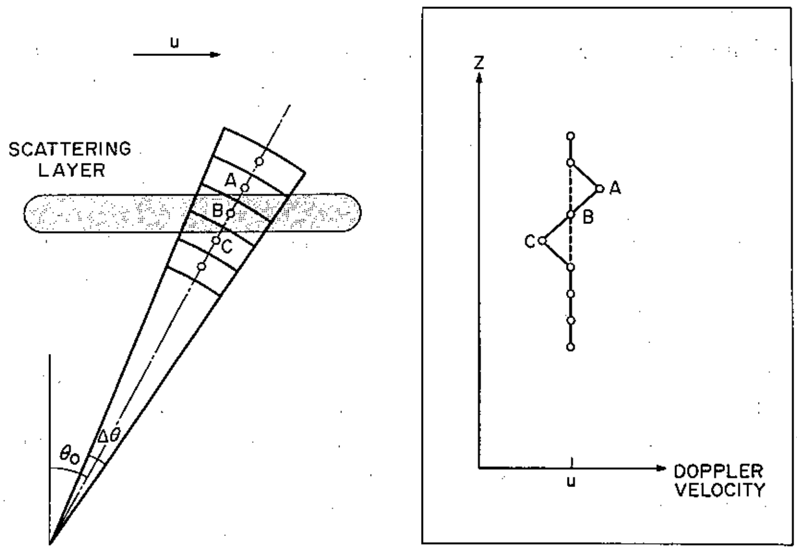

Fig. 1. A geometric representation of the finite range volume effect [after *Fukao et al.*, this issue *a*].

$\Delta\theta$, of 2.6, 3.6, and 5.1° are possible for a tilt angle, θ_0, of 10°, and which have been used for an experiment to verify the importance of the effect for real MST radar observations.

For the purposes of the discussion, only one component of the wind will be considered, and a positive wind shear will be one where the magnitude of the wind component is increasing with altitude. The wind component normal to the radar beam will affect the spectral width of the measured signal but not the mean Doppler shift, which is the main subject of the paper.

FINITE RANGE VOLUME EFFECT

Turbulence in the troposphere and stratosphere has been observed to occur in layers of the order of 50 m thick and to have a much larger horizontal extent (see, for example, *Röttger and Schmidt* [1979], *Woodman* [1980], and *Crane* [1980]). In the troposphere layers with an increased humidity contribution to the refractive index may also produce enhanced scatter. The observed layering of the scattering regions, together with the finite beam width and the effect of wind shear on the spectral width of the returned signal has been discussed [*Hocking*, 1983], but the effect of these factors on the mean Doppler shift of the signal has not been fully investigated, although some studies on the effect of a pulse volume being filled by a nonuniform distribution of scatterers have been performed [*Atlas et al.*, 1969]. *Fukao et al.* [this issue *b*] considered the importance of the layering in some observational results and numerical simulations and found that the errors induced into wind profile estimates could be important. If there is an intense scattering layer located at an altitude such that it intersects the pulse volume only in one corner (e.g., Figure 1, volume A), then the measured line-of-sight wind velocity is the projection of the horizontal wind component at that height, $U(z)$, along the angle $(\theta_0 + \Delta\theta/2)$. This leads to an erroneously large wind estimate for that particular range. Similarly, the wind estimate for volume C will be biased toward a lower value than the volume "average" wind velocity. Thus there will be an apparent positive wind shear produced in the data, even if the wind is uniform with height. *Fukao et al.* [this issue *a*, *b*] discuss this error on a more quantitative basis and show that the magnitude of this artificial wind shear can be very large and may lead to significant errors in the data. For examples of the typical artificial structure in the wind profiles which is produced by this effect, see Figures 5*a*–5*c*. Note also that the worst possible case is not affected by the thickness of a layer in this simple model, since a given pulse volume may still intersect the layer in just one corner. However, for thicker layers or longer pulses the effects described above may only be important in isolated range gates and not show the wavelike structure. In addition the use of longer pulses will reduce the probability of a layer intersecting the pulse volume on the "edges," thereby reducing the chance of the effect being important in a given measurement.

If there exists a real wind shear with height, the situation becomes more complex, as then there are errors produced by the wind shear as well as by the finite range volume effect. For example, the wind estimate will not only be biased by the received signal being returned from some angle different from the antenna beam tilt angle, but the measured Doppler shift will be for the horizontal wind at the altitude of the scattering layer, and not the height of the center of the pulse volume. This produces a distorted wind profile, but these "wind shear" errors do not produce the kind of structure which is generated by the finite range volume effect. Simple geometric considerations show that the wind shear effect will tend to decrease the importance of the finite range volume effect if the true wind is increasing with height, but will make the situation even worse if the true wind shear is negative as then the errors will have the same sign. The magnitude of these effects will be affected by such parameters as the beam width and beam tilt angle, and the frequency of occurrence will depend on the height resolution of the radar compared with the "average" distance between scattering layers.

It has been observed that these intense, thin scattering layers may exist for considerable periods in the atmosphere [e.g., *Yamanaka and Tanaka*, 1984]. While the cause of this persistence is clearly beyond the scope of this discussion, it is worth noting that the errors induced by the effects described above will therefore also be persistent and will, in this sense, constitute a systematic bias in the observed wind field. This persistence makes it very important to have some quantitative measure of the errors likely to occur in the wind measurement. For statistical comparisons with balloon measurements this effect will increase the rms discrepancy between the wind determinations, and the persistence of the layers over many records means that averaging several radar records decreases the errors only slightly.

A SIMPLE MODEL

In order to examine the importance of these effects for wind observations with MST radars, a simple model has been constructed. This model uses a variety of wind profiles such as a uniform wind (no shear with height), sinusoidal profile and a sinusoid plus a linear trend between the altitudes of 5–15 km. The heights of the scattering layers are produced from a population of random numbers with a uniform distribution. The density of the random numbers gives some average distance between layers. In order to simulate layers of finite thickness, every layer produced from the original population has an additional five layers above and below the central layer, with the overall layer thickness being defined by the height difference between the top and bottom layers of the eleven. The 11 "sublayers" are a reasonable approximation to a real scattering layer and are sufficient for the simulations to be realistic.

The beam width referred to in the remainder of the paper is the two way full width at half maximum power of the polar diagram. Two polar diagram/pulse shape functions will be used in the following discussion, the first simple case is for illustrating the possible errors due to the effect of the layers and allowing some simple quantitative estimates and a second more sophisticated model for comparisons with real experiments. The Doppler shift of the returned signal is found by calculating

$$u(r_0) = \frac{\int_{r_1}^{r_2} \int_{\theta_1}^{\theta_2} P(r - r_0)T(\theta)R(z)U(z)\, d\theta\, dr}{\int_{r_1}^{r_2} \int_{\theta_1}^{\theta_2} P(r - r_0)T(\theta)R(z)\, d\theta\, dr}$$

where r_0 is the center of a given range gate, r and θ are the range and angle from the zenith, respectively, and z is the altitude for a given r and θ. The range-weighting function, $P(r - r_0)$, is dependent on the pulse shape (and receiver response in a real experiment), and $T(\theta)$ is the polar diagram weighting function. $U(z)$ is the horizontal velocity for an altitude z. $R(z)$ is the reflectivity weighting, which is unity within a layer and zero outside. The region bounded by r_1, r_2, θ_1 and θ_2 is where $P(r - r_0)$ and $T(\theta)$ have significant values. This discussion assumes that the vertical velocity is zero, although similar arguments apply to this contribution to the line-of-sight Doppler shifts as for the horizontal wind.

The first sets of simulations are for an antenna polar diagram with a uniform illumination between two angles ($\theta_0 \pm \Delta\theta/2$), so that the polar diagram weighting is 1 within the beam and zero outside. While this seems to be a crude approximation to an actual polar diagram, it is reasonable for qualitative purposes. For example, the signal from angles between θ_0 and $\theta_0 + \Delta\theta/2$ will be overestimated, but this is partially compensated by the zero contribution from angles outside of the "beam," which in a real radar will be significant. Therefore we expect that the "rectangular" polar diagram with a beam width of $\Delta\theta$ will give a reasonable approximation to the half-power beam width in a real experiment. The Doppler shift of the radar signal is found by summing the contributions of the scatter appropriate to the layer by stepping across the layer in increments of 1 m when the scattering layer is within a given range gate. The pulse shape is assumed to be rectangular, with a range-weighting function which is unity within the pulse and zero outside, which is unlike any realistic weighting function but is still suitable for illustration by similar arguments to the above and allows the worst case situations to be calculated easily. Therefore the pulse volume is bounded by the range corresponding to the beginning and end of the pulse and by the beam width, with a rectangular polar diagram.

Both cases where the wind is uniform with height within a given pulse volume and the more realistic case where wind shear within the pulse is allowed (i.e., the horizontal wind is calculated for the layer height and not the height of the center of the pulse) are considered. All the relevant parameters such as beam width, pulse length, height distribution of layers and the layer thickness can be varied independently. The model also allows an adjustable "volume scatter" component with no bias and which was set to a very small value for the simulations of this simple case. This model will be used to illustrate the importance of the effects of the layering.

The second set of simulation parameters includes a Gaussian-shaped polar diagram and pulse shape, so that the weighting functions are Gaussian. The summations are performed only for values where the individual weighting functions have values greater than 0.0001. These weighting functions make the model more realistic in the sense that real polar diagrams can be reasonably approximated by a Gaussian and the range weighting function which is the convolution of (Gaussian shaped) radar pulse and receiver pulse response function (which is also Gaussian). This form for the pulse shape is commonly used. For the purposes of discussion the term pulse length will refer to the half-power full width of the range weighting function in the cases of Gaussian range-weighting functions and the beamwidth is the two-way half-power full widths of the two-way polar diagram. This version of the model will be used for comparisons with the actual radar experiments.

SIMULATIONS 1: NO WIND SHEAR WITH HEIGHT

In order to demonstrate the importance of the finite range volume effect and to illustrate that its existence does not depend on real wind shear, a series of simulations were performed for a wind profile which has no height variation. The beam width of the polar diagram and the tilt angle were varied. For this simulation any background "volume scatter" is very small. The layer thickness has been chosen to be 50 m and the average distance between layers has been chosen as 300 m. This value is representative of the values quoted in the above references and allows a suitable number of layers to be inspected in the simulations. Again, changing the average distance does not change the results rapidly until there are, on the average, more than one layer within the pulse volume.

The calculations of *Fukao et al.* [this issue *b*] suggest that for such a simple situation the errors in horizontal wind measurements should have a magnitude which is approximately proportional to the beam width. The dependence of the error on tilt angle is proportional to the cotangent of the tilt angle. For the worst case the errors should have a magnitude of

$$\text{error} = \frac{\sin(\theta_0 \pm \Delta\theta/2) - \sin(\theta_0)}{\sin(\theta_0)} \times 100\%$$

and the absolute error is proportional to the wind speed. The results of ten simulations for each of a range of tilt angles and beam widths are plotted on Figures 2*a*–2*c*. These simulations reveal that the "typical" error introduced by the finite range volume effect is of the order of one-half of the worst case error, but the errors are distributed almost uniformly from zero to the worst case. This distribution arises, since there is an insignificant background scatter, and the probability of a layer intersecting the pulse at any point is uniform. There is a "spike" in the error distribution at zero error because of the number of height ranges where there is no layer or where the layer intersects the entire width of the pulse. It is also observed that the magnitude of the errors follow the expectations for the dependence on beam width and tilt angle very well over a wide range of tilts and beam widths.

The main point of this section is to stress that this effect is a consequence of the observed layering of the regions of strong turbulence with layer thicknesses which are often much smaller than the pulse length

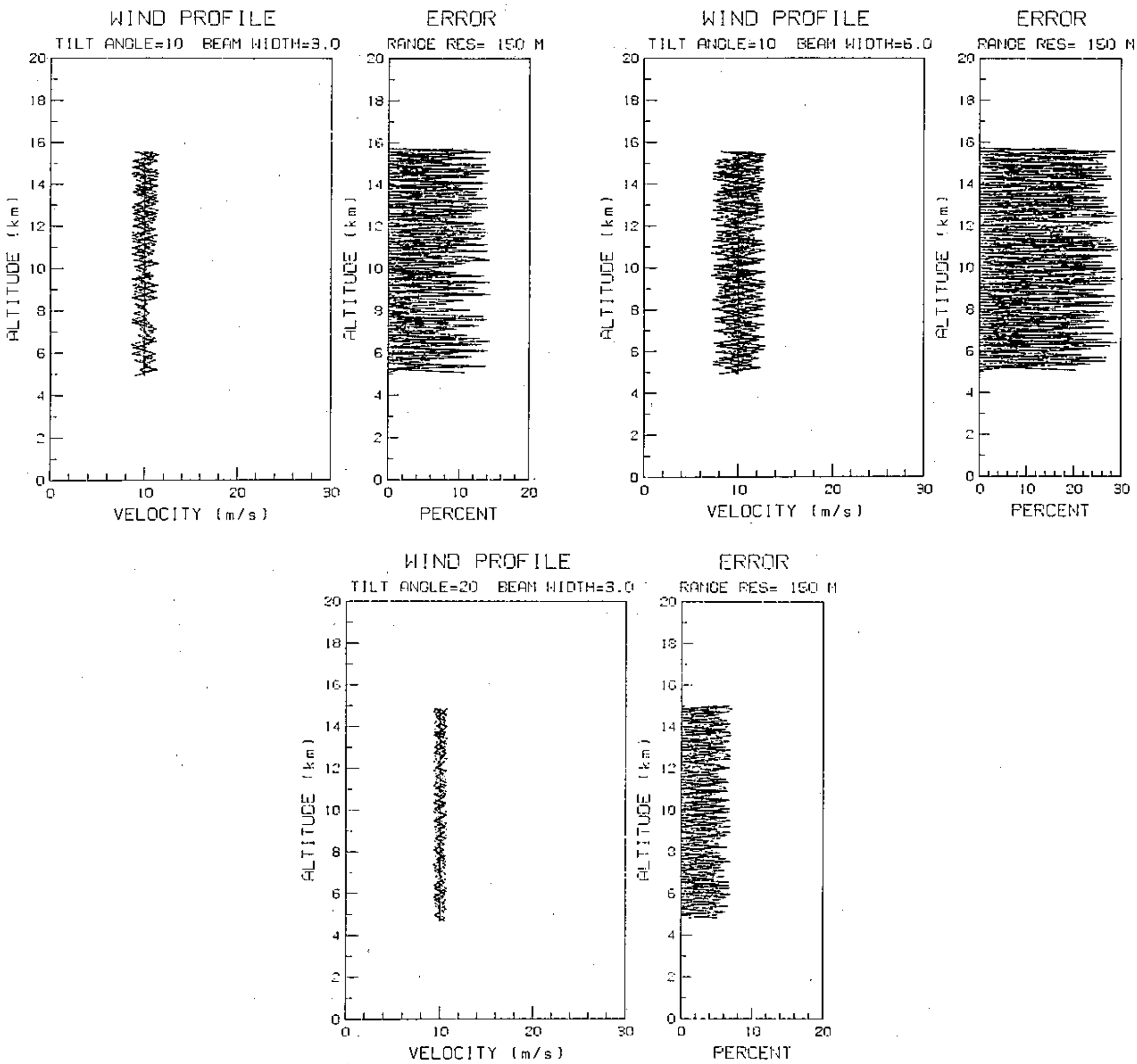

Fig. 2. The model results for a uniform wind profile for radars with a beam width of 3° and tilt angles of 10° and 20° as well as a case for a tilt angle of 10° and a beam width of 6°. The results of 10 simulations are superimposed. The model uses a "rectangular" polar diagram and range-weighting function.

and to demonstrate that for this simple case the errors show the expected functional dependence on the beam width and tilt angle.

SIMULATIONS 2: WIND SHEAR EFFECT

In the real atmosphere the wind field is rarely devoid of wind shear. When most of the power is scattered from a narrow layer an error due to wind shear is produced, because the line-of-sight Doppler shift will be proportional to the wind at the height of the layer, rather than the center of the pulse volume. The maximum size of this error is obviously proportional to the magnitude of the wind shear rather than the wind speed, as is the case for the finite range volume effect. The maximum wind shear error will be proportional to the pulse length where there is only one layer within the pulse volume and also will be roughly proportional to the beam width and tilt angle as increasing these also increase the height range of a given pulse volume. Again, we note that the wind shear error and the finite range volume

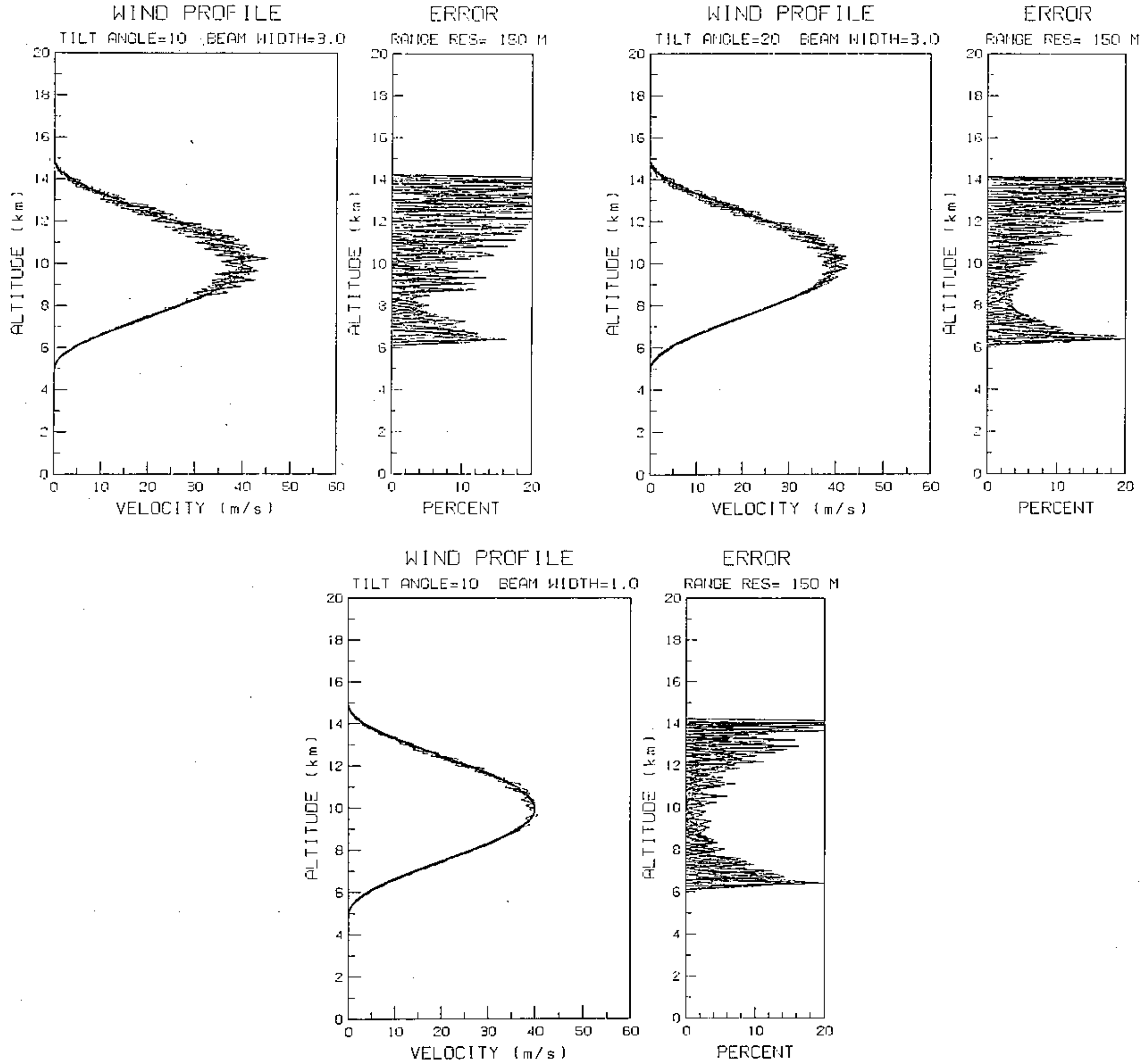

Fig. 3. Model results for sinusoidal wind profiles, so that an error due to wind shear is produced. The simulations are for a 3° beam width with tilt angles of 10° and 20° along with a 1° beam width and a 10° tilt angle. The percentage error is plotted only for wind speeds greater than 5 ms^{-1}. Note in the simulations with the wider beam width how the errors due to the finite range volume effect and wind shear partially cancel when the wind shear is positive and reinforce when the shear is negative. With the narrow beam width it is seen that the wind shear errors dominate the finite range volume effect.

effect partially cancel each other when the real wind shear is positive and reinforce when the wind shear is negative.

Figures 3*a*–3*c* shows the results of ten simulations for three combinations of beam widths and tilt angles. Note that since the wind shear errors may be significant even for small mean wind speeds the percentage error defined above may become very large in the low wind speed region. This is responsible for the large effects, even for narrow beam widths, for samples at low wind velocities. For wind speeds of more than 10 ms^{-1} the finite range volume effect is dominant, and it is only for wind speeds of less than about 5 ms^{-1} and strong wind shear that the shear error is the larger for observations with 150-m range resolution for beam widths of around 4° (see Table

TABLE 1. Worst Case Errors

Parameter	Value	
Beam width	4°	
Tilt angle	10°	
Pulse length	150 m	
Range	10 km	
Wind shear	15 ms^{-1}/km	
Wind speed	5 ms^{-1}	40 ms^{-1}
Worst case		
FRV effect error	1.0 ms^{-1}	7.8 ms^{-1}
Wind shear error	2.0 ms^{-1}	2.0 ms^{-1}

1). The combined effect of the wind shear error and the finite range volume effect is well illustrated in Figures 3*a*–3*b*. The errors produced for a very narrow beam width (Figure 3*c*) are dominated by the wind shear error, so that for beam widths of the order of 1° the finite range volume effect is unimportant, as was also found by *Fukao et al.* [this issue *a*, *b*].

RADAR OBSERVATIONS WITH THREE BEAM WIDTHS

The most drastic errors due to the finite range volume effect occur when wide antenna beam widths are used. This may be of particular importance for a number of recently built ST radars which are using comparatively wide beam widths (of the order of 4°–5° half-power beam widths). In order to test the predictions of the model the MU radar, located at Shigaraki, Japan, has been used. This radar is a modular array, that is, the large array (103-m diameter, with a two-way half-power beam width of 2.6°) is made up of 25 smaller subarrays. The system has been designed so that any combination of subarrays can be used for transmission and reception. Thus experiments can easily be performed with a variety of beam widths. The antennas may be phased to produce any desired direction within 30° of the zenith and the beam direction may be changed in one interpulse period (usually 400 μs).

When the whole array is used the MU radar has a peak power of 1 MW. For the experiments reported here a 16 bit coded pulse was used with a bit length of 1 μs, to give a range resolution of 150 m. Ranges between 5.01 and 24.21 km were sampled. The experiment consisted of three soundings of the wind profile, with just an eastward pointing beam, for each of three antenna two-way 3-dB beam widths of 2.6, 3.6 and 5.1° with a tilt angle of 10° on October 31, 1986. The wider beam widths were achieved with groups of 13 and 7 antenna subarrays, respectively. As well as producing a wider beam, the peak power is reduced as each antenna has a separate transceiver under μprocessor control. It is assumed for simplicity that the vertical motions will not be important, so that the line-of-sight Doppler shift is considered to be proportional to the projection of the eastward wind component along the center of the antenna beam. While it is possible to swing the antenna beam in each interpulse period, this was not done here in order to maximize the signal level for the wide antenna beams, and thereby improve the reliability of the individual soundings. The whole system is governed by a radar controller and a VAX 11/750 minicomputer is used for on-line analysis of the winds data. An interpulse period of 400 μs was used and data were coherently averaged over 150 pulses. Six data sets of 128 coherently averaged points were collected for each height and the power spectrum of the time series calculated by FFT. The results of the six consecutive power spectra were averaged and the Doppler shift estimated by a least squares fit of a Gaussian to the power spectrum to give a single sounding. Each of the sets of soundings for a given beam width took only about 3 min, but there was a gap of about 4 min between each data set while new instructions were sent to the transceiver modules by the radar controller to obtain the correct beam widths.

The eastward pointing direction was used in order to observe the large jet stream winds and maximize the finite range volume effect. The maximum wind speeds of about 60 ms^{-1} were observed at altitudes between 11 and 12.5 km. The strong layering of the intense echoes is seen on the power profiles in Figures 4*a*–4*c*. These strong echoes persisted at about the same height for the whole of the observing period in the stratosphere, and in the troposphere the same type of layers can be seen, but with their intensity slowly varying.

Figures 4*a*–4*c* shows one of the raw wind profiles for three beam widths and a 10° tilt angle. These profiles have fluctuations of a similar character to the small vertical scale oscillations seen in the model profiles. It is clear in these diagrams that the magnitude of the oscillations becomes very large for wide antenna beam widths. These fluctuations in the wind profiles are significantly larger than the random error in the determination of the Doppler shift. The random errors in the horizontal wind estimate (neglecting systematic effects such as wind variability

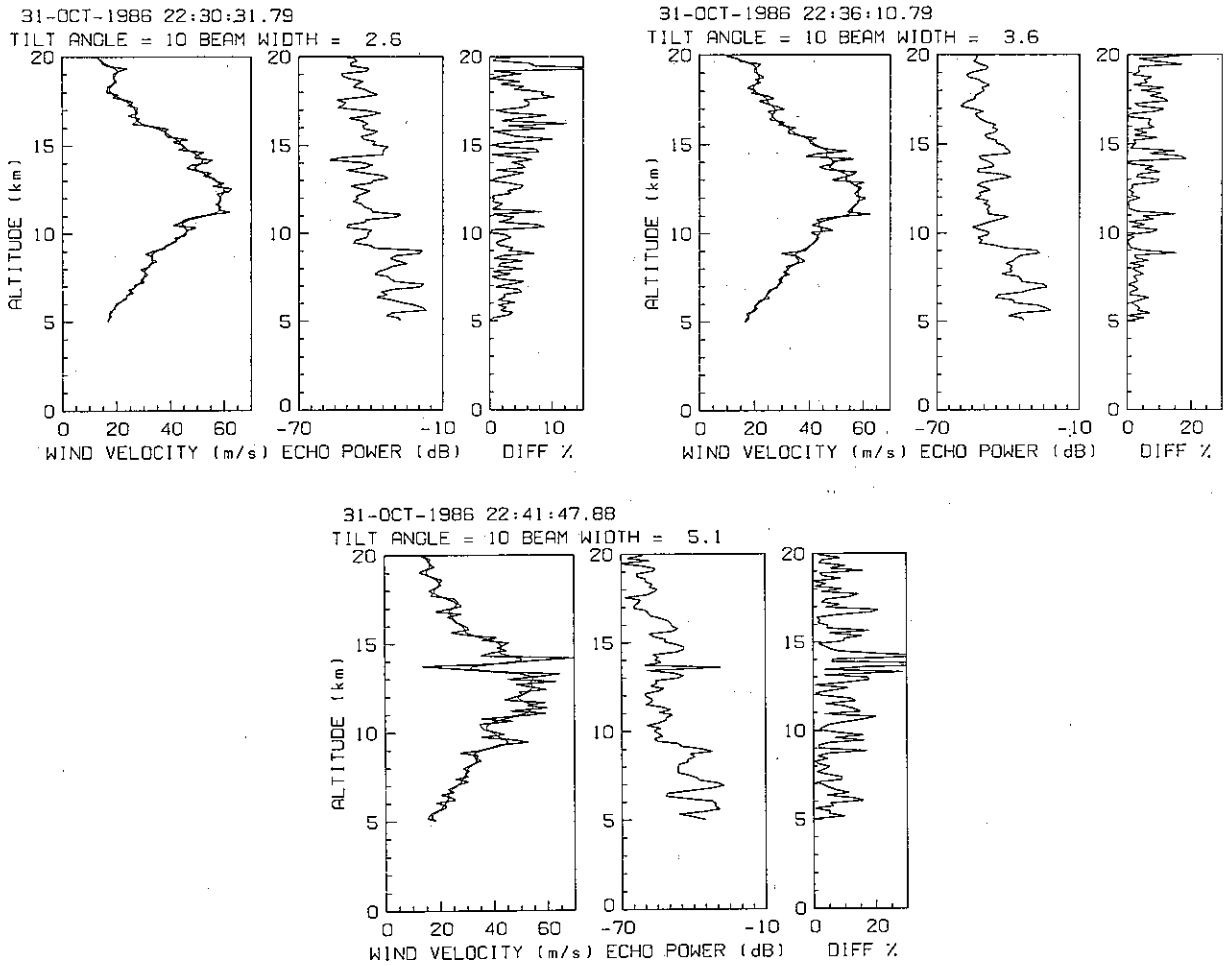

Fig. 4. MU radar observations, showing a single measured wind profile (zonal component) versus height together with a profile smoothed by two passes of a three-point running mean for various antenna beam widths (see text). The profile of echo power and the percentage difference between the measured and smoothed curves is also shown. The beam width is the two-way 3-dB beam width, and the height resolution is the range weighting function 3-dB width.

and vertical motions) for a typical spectral width of around 0.8 ms^{-1} are of the order of 1.0 and 1.5 ms^{-1} for signal-to-noise ratios (after coherent averaging) of 5 and 0 dB, respectively [e.g., *Doviak and Zrnić*, 1984], and furthermore, the three successive records the oscillations have very similar structure, even in the very fine detail, so that averaging the profiles will not improve the results. In order to obtain a reference for the magnitude of these oscillations, a smoothed curve is calculated by using two passes of a three-point running mean along the height profile, and the percentage difference between the smoothed and original (single) profile is also plotted, but it is seen on these figures that this only partially smooths the curves. The most important pieces of evidence that suggest that the fluctuations are generated mainly by the finite range volume effect are that (1) the fluctuations in the measured wind occur at about the same altitudes in all three of the wind profiles, and these altitudes correspond to peaks in the echo power profile, which eliminates the possibility that the fluctuations are random, and is supportive but not conclusive that they are generated by the finite range volume effect, (2) the fluctuations are larger when the wind shear is negative, and most importantly, (3) the magnitude of the oscillations is roughly proportional to the beam width, which strongly supports the hypothesis that these fluctuations are a result of the effect. It may be possible to explain points 1 and 2 by other mechanisms such as wave-generated shear and turbulence, but it appears that point 3 can only be explained by the finite range volume effect. The presence of strong scattering layers may imply intense wind-shears with small vertical scale, so that some of the observed fine structure is probably real, but separating this from the artificial fluctuations in the wind profile is impossible.

SIMULATIONS 3: A MORE REALISTIC MODEL

In the actual radar experiment there is a significant component of the signal from a background of turbulence that is not confined to the layer. This is typically of the order of 7–10 dB less than the backscatter from the intense layers. However, the signal component from the volume scatter is unaffected by the finite range volume effect. Therefore a background level of signal with no bias in the Doppler shift was added to the signal in the model. The power of the volume scatter is variable, but values of the ratio of volume scattered power to "layer" scatter power of approximately 0.1 was used in the simulations shown in Figures 5*a*–5*c*. This value was used because the observed enhancement of the signal power over the background signal in height ranges where there is a strongly scattering layer is of the order of 10 dB. The use of higher levels of volume scatter decreased the importance of the effect, but the finite range volume effect remains significant for wide beam widths, even if the volume scatter component is somewhat larger than the "layer" component. Also, a linear trend of wind, increasing with altitude was added to the sinusoidal wind profile in order to more closely represent the actual wind profiles observed with the radar.

It is seen in Figures 5*a*–5*c* that the errors in the simulation are qualitatively similar to the short vertical scale structure in the radar observations. Furthermore, the magnitudes of the errors are comparable to the scale of the fluctuations from the smoothed curve. In most cases the errors in the simulation are a little larger than the percentage differences in the smoothed curve and the raw curve of the radar data, and this is probably due to the fact that the smoothing of the actual data only partially removes the finite-range volume effect. It can be seen in Figure 4 that the smoothed curve still follows the raw curve to some extent. Another alternative which may give superior results is subjecting the height profiles to low-pass filtering. With a suitable filter it may be possible to smooth the profile and remove these small vertical scale fluctuations, but of course at the cost of correspondingly poorer height resolution. This sacrifice of height resolution may be necessary for radars with wide beam widths unless large tilt angles are used. In any case, it should also be noted that when wide antenna beams are used the height difference between the top and bottom "corners" of the pulse volume is significantly larger than the actual pulse length and wind shear may become important. In the case of large tilt angles the signal level may be very small due to the observed aspect sensitivity of the radar backscatter [*Rastogi and Rottger*, 1982; *Tsuda et al.*, 1986], limiting the radar operation to low altitudes.

Overall, the good agreement between the magnitude of the oscillations observed in the simulations and those observed by the radar gives strong support to the idea that a large amount of the small vertical scale oscillations observed by the radar is artificial. Furthermore, this indicates that the model is useful for assessing the importance of the finite range volume effect for real radar observations.

DISCUSSION AND SUMMARY

The presence of these errors due to the layering of the scatterers is an important consideration in the design of MST radars. It has clear bearing on the argument about whether it is better to increase the antenna size or transmitter power in order to improve the performance of a given radar system. Using larger tilt angles for the wind measurement may improve the reliability of the wind measurement, both from the point of view of decreasing the finite range volume effect and increasing the magnitude of the observed Doppler shift, thus decreasing the relative error in the wind determination. However, in practice this will be partly offset by the loss of signal level due to the aspect sensitivity of the backscatter, which is observed even for tilt angles of about 15°. Errors due to the real spatial variations of the wind field may also have to be considered if large tilt angles are used [*Strauch et al.*, 1984]. However, since the magnitude of the errors due to the finite range volume effect is proportional to the cotangent of the tilt angle for the simple model, it is expected that the errors will be approximately halved in going from a tilt angle of 10° to 20°, so that this is an alternative which may be considered, particularly for radars

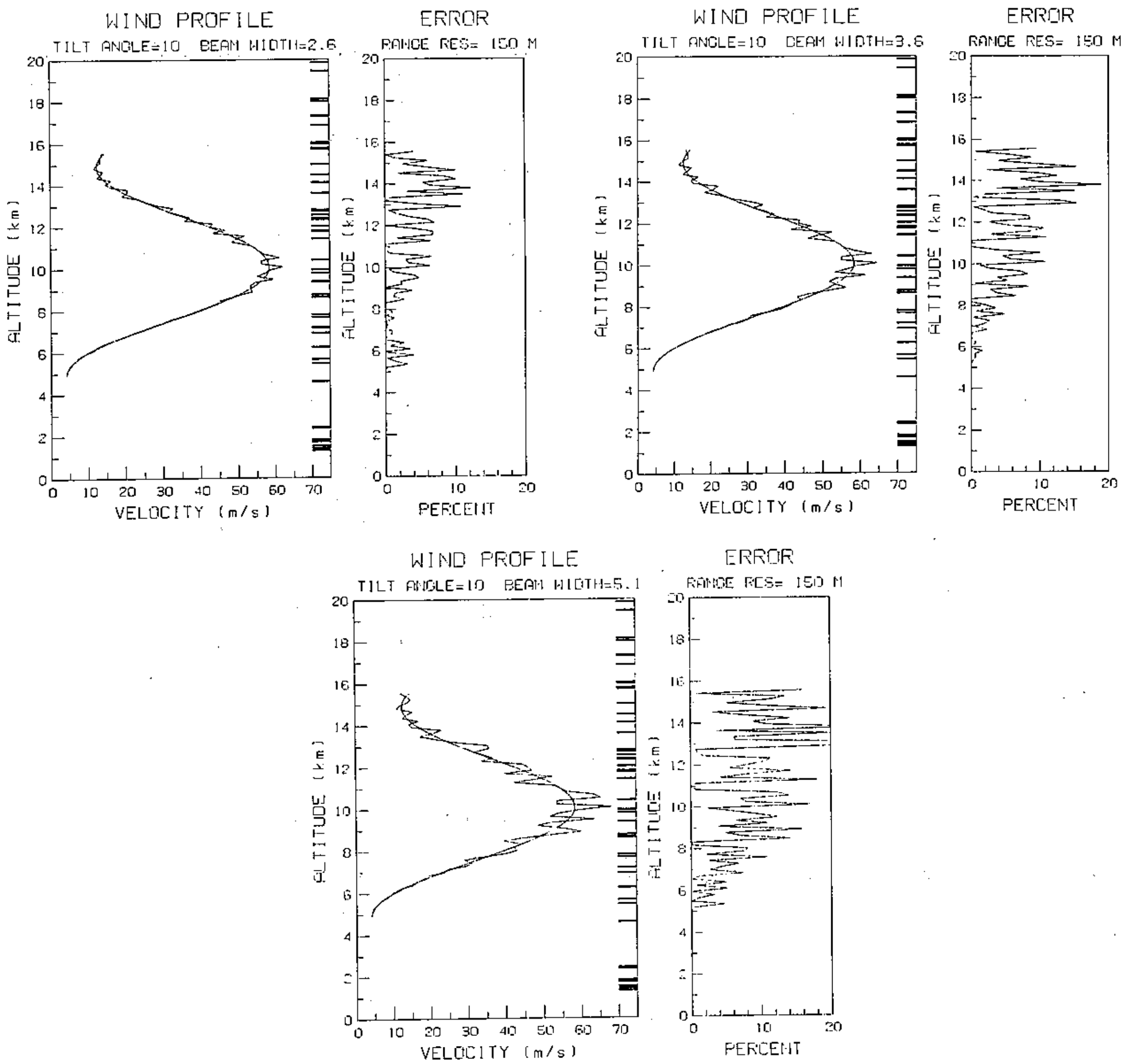

Fig. 5. Model results for a wind profile with the shape of a sine curve plus a linear trend. The beam widths are similar to those of the radar experiment, and the scatter from the layer is set to be of the order of 10 times the magnitude of the "volume" scatter component. The models used for these calculations include a Gaussian polar diagram and range-weighting function. The heights of layers are seen by the horizontal bars on the plot of the wind profile. The beam width and height resolution are defined as in Figure 4.

where it is not practical to increase the antenna size. However, this also increases the height range which the pulse volume occupies, so that the wind shear error is increased, so that for actual soundings the improvement in going to larger tilt angles is less than expected. This expectation has been realized in both experiments and simulations.

For radars with narrow beam widths (i.e., of the order of 1°) the errors due to the finite range volume effect will be less than, or of the order of, the Doppler shift measurement errors. On the other hand, the effect is most serious for radar measurements with wide beam widths, which argues strongly for the use of large arrays (Figure 6). The effects due to strongly scattering turbulent layers also apply to radars operating at UHF frequencies, but it may be easier to produce narrow beam widths with the higher frequencies.

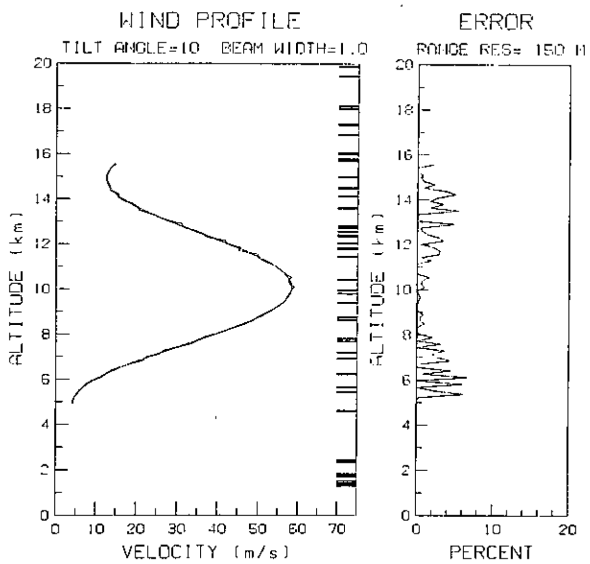

Fig. 6. Model results as in Figure 5, but for an antenna beam width of 1°. Comparing this with Figure 5 illustrates the advantage of using narrow beam widths.

Another consideration is the fine structure which the finite range volume effect applies to wind profiles. This must be considered for observations of vertical wave number spectra, of the type which are used in wave studies. The possibility of the artificial fine structure aliasing into the large vertical wave number section of the spectra must be considered, although it may only be of minor importance as the observed vertical wave number spectrum is concentrated towards small vertical wave numbers [e.g., *VanZandt*, 1982]. A major difficulty is that the presence of these layers may indicate that there is indeed small scale structure with large wind shears, but the true scale of these shears is not easily measureable because of the finite range volume effect.

There are a number of other possible ways of dealing with the errors due to the finite range volume effect. Two possibilities are the use of two (or more) beam widths or beam tilt angles and making use of the proportionality of the errors with respect to the beam width and the cotangent of the tilt angle, respectively. However, this approach has a number of difficulties. First, the proportionalities are not exact in the real case and changing the beam width and tilt angles can mean the inclusion of signal from different layers for the same range, because the effective height resolution is degraded with larger tilt angles. Second, such an approach relies on measuring the difference in the winds measured with the two widths or tilts and in this case the random statistical errors will be extremely important. For example, the magnitude of the errors due to the effect is of the order of 5–10%, and the random errors are of the order of 2–3%. Also these approaches may be very difficult on technical grounds for most MST radar systems. All these problems make this approach extremely difficult.

As already mentioned, a possible method of obtaining unbiased records is to retain the short radar pulses and therefore small vertical height steps and then use a low pass filter on the height profiles in order to remove the short vertical scale fluctuations due to the finite range volume effect. This, of course, implies a poorer height resolution, say 600 m for a 1-μs pulse (150-m sampling interval). This may be justified in an extreme case if the height resolution is much wider than the range resolution as may be the case for short pulses and wide antenna beams. An almost equivalent method may just be to use longer pulses and therefore average out both the shear effect and the finite-range volume effect. However, this requires that there be a large number of layers within the pulse volume, a requirement which will not be met unless pulses of the order of 1 km or more are used for most records and in this case errors due to wind shear may be very important [*Sato and Fukao*, 1982]. Radar measurements where the wind profile is oversampled in range, i.e., the wind is estimated for range intervals less than the range resolution, may be used to retain unbiased wind estimates with good vertical resolution as the samples at altitudes of maximum power will be unbiased, but this requires much more computing power (as the number of heights samples is increased, say fivefold), and an algorithm to obtain such unbiased estimates may be difficult to create. With a profile which is oversampled in range compared with the effective range or height resolution, it may be possible to use the profile of the power together with the known range weighting function to calculate the strength, position and thickness of the scattering layers. They by using a model it may be possible to eliminate the artificial structure in the wind profile, but all this involves deconvolutions which may be difficult and may not give unique results. Another possibility is the use of averaging the spectra of successive observations in which the range gates in successive observations are slightly staggered in altitude. This may not reduce the height resolution too much, since for wide beams the height resolution may be much poorer than the range resolution of the radar. It appears also to have the advantage of giving the most weight to the strongest signals, i.e., those ranges where the layer intersects the whole cross section of the pulse. However, this method is equivalent to using a longer pulse, which is discussed above, and will reduce the probability of the finite range volume effect being important, but the worst possible case is only slightly affected if fixed averages are used. Alternatively, only those ranges where the signal maximizes may be used, but this may limit the height resolution just as much as the range filtering method.

One fortunate circumstance is the fact that the errors due to the finite range volume effect are partially cancelled by wind shear errors when the wind is increasing with altitude. This includes most of the altitude region below the tropopause, which is of most concern for the applications of the "wind profilers" for routine operational wind observations, which often have large antenna beam widths. Model calculations with the same wind profile as considered in Figures 5 and 6 show that errors of the order of 5–10% may be expected for radars with a 5° beam width for altitudes up to about 2 km below the wind maximum. Since the finite range volume effect is proportional to the wind speed (neglecting shear), the smaller wind speeds which are generally observed in the troposphere will also decrease the magnitude of the errors.

This paper has presented some calculations and measurements which show that the observed tendency for turbulence to occur in thin layers results in significant errors in the determination of horizontal winds with MST radars using the Doppler technique, particularly when wide beam widths are used. This error should be taken into account when comparing radar measurements with other wind measurement techniques such as balloon soundings and when comparing the merits of MST radars using the Doppler and spaced antenna (SA) techniques. Since vertically pointed antennas are used in the SA technique, there will be no finite range volume effect, but errors due to wind shear and the presence of layers will be present. The results shown here indicate that the effects described above may be severe for many of the new radars with wide beam widths and that the use of radars with large antenna arrays, and therefore narrow beam widths, is to be encouraged.

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S. Fuko, S. Kato, P. T. May, T. Sato, and T. Tsuda, Radio Atmospheric Science Center, Kyoto University, Uji, Kyoto 611, Japan.