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AN INVESTIGATION OF VERTICAL WINDS OBTAINED FROM VERTICALLY POINTING AND TILTED BEAMS OF A FIVE-BEAM 915-MHz WIND PROFILER

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1.0 INTRODUCTION

The Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Program has operated a 915-MHz radar wind profiler coupled with a Radio Acoustic Sounding System (RASS) since November 1992 at its Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) central facility in north central Oklahoma. The system is designed to provide continuous wind profiles from near the surface (100 m) to 5 km or more and virtual temperature profiles from near the surface to 1.5 km. During normal operation (see Table 1), the system uses four tilted beams (two each in the north-south and east-west vertical planes) and a single vertical beam to determine mean wind and virtual temperature profiles every hour.

The average vertical velocity should normally be close to zero, in the absence of strong topographic forcing or prolonged convective activity. However, the statistics of vertical motion are especially useful in the measurement of atmospheric turbulence. Realistic evaluations of vertical velocity (w) statistics often require a sample rate larger than that available from normal profiler operations at the CART site. However, the existence of four tilted beams (rather than the minimum of two required for horizontal wind measurements) allows additional measurements of the vertical component of motion with pairs of beams tilted in opposed directions and thus can provide better vertical velocity statistics as well as direct measurements of momentum flux.

In this paper we illustrate and compare different methods for calculating w and several statistical variables from profiler data. The results are compared with those derived when the profiler is operated in a vertical-only mode under similar conditions.

2.0 DATA ANALYSIS TECHNIQUES

In normal operation of this profiler consecutive samples are taken along each of the five beams (approximately 33 s each). The sequence is repeated at a higer power (longer pulse length) before the cycle begins again. The total cycle time of roughly 5.5 min results in nine samples from each of the ten beam-power combinations (five directions and two power settings) during each 50-min averaging period. (10 min of each hour is reserved for RASS operation.) Switching between low- and high-power modes maximizes the height range (at high power), yet allows sampling as near the surface as possible (at low power). Although the range gates and beam directions are redundant, high- and low-power measurements along the same beam may not be equivalent, because the signal-to-noise ratios can be significantly different between high- and low-power modes.

Table 1.
Usual operating parameters for the 915-MHz profiler.

Parameter	Low Power	High Power
Wavelength (m)	0.29	0.29
No. of beams	5	3
Peak power (W)	500	3.9
Pulse length (ns)	700	2800
Tilted beams (deg)	14	14
Min height (km)	0.14	0.33
Max height (km)	3.0	5.5
Range gate (m)	105	105
Spect ave. time (s)	33	33
Ave time temp. (min)	10	NA
Ave Time Wind (min)	50	50
No. of spectral points	64	64
Transmit order	VSNEW	VSNEW

For each of the vertical beam possibilities (V_l or V_h for low or high power,

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respectively) used, nine samples of w at each range gate can be obtained during each hour. We can double the number of samples by using data from both power levels. By adding the tilted radial components of motion (N, S, E, W for north, south, east, and west radial components, respectively) at both power levels we can obtain a total of 54 samples of the vertical component of motion resulting from six different combinations (two vertical and four tilted beams) during the 50-min averaging period. That is, at either power level,

$$w_{v,p} = (N_p + S_p) / (2\cos(\theta)), \qquad (1)$$

$$w_{u,p} = (E_p + W_p) / (2\cos(\theta)), \qquad (2)$$

where θ is the tilt of the beams from vertical, and the subscript p (=l or h) indicates power level.

It is tempting to use the resultant time series w_c (w_l, $w_{v,l}$, $w_{u,ll}$, w_h, $w_{v,h}$, $w_{u,h}$,)to investigate the turbulence structure of the lower troposphere. However, there are several problems with the use of such a time series:

1. The calculation of w from (1) or (2) results from samples separated both spatially (by $2 \cdot z \cdot \tan(\theta)$, where z is the height) and temporally (33 s in the present example). This separation should result in overestimates of the variance, as detailed by Kristensen and Gaynor (1986), in reference to horizontal velocity variances in sodars.
2. The time between samples from the combined time series is not constant. Because samples 2, 3, 5, and 6 are derived from multiple beams, the time separation between the six values will be 49.5, 66, 49.5, 49.5, 66, and 49.5 s for this system. Spectra will probably be affected (see below) by this artifact, as will correlations with other variables sampled at regular intervals.
3. The assumption of horizontal homogeneity is now required for calculations using w because of equations (1) and (2). However, this assumption is already implicit in the calculations of the horizontal components of motion.

A potentially powerful tool provided by the multiple tilted beams in common vertical planes is the ability, at least in theory, to estimate the vertical transfer of horizontal momentum through calculation of the covariance between the horizontal and vertical motion. The formulations of Kropfli (1986, equations 10b and 10c) are for scanning radars. However, it is straightforward to limit the scanning case to tilted beams along the four ordinal directions:

$$\mathrm{cov}(vw_{v,p}) = \frac{\left[VAR(N_p) - VAR(S_p)\right]}{[2\sin(2\theta)]} \qquad (3)$$

$$\mathrm{cov}(uw_{v,p}) = \frac{\left[VAR(E_p) - VAR(W_p)\right]}{[2\sin(2\theta)]} \qquad (4)$$

where *VAR()* indicates the variance and *cov()* indicates the covariance. We can also calculate the covariances directly by using the so-called eddy correlation formulation:

$$\mathrm{cov}(vw_p) = \overline{w_p'(N_p - S_p)'}, \qquad (5)$$

$$\mathrm{cov}(uw_p) = \overline{w_p'(E_p - W_p)'}. \qquad (6)$$

Here primed quantities are differences from the mean. We note that if (5) and (6) are calculated with the correlation of $w'u'$ and $w'v'$ using (1) and (2) for values of w, the result is identical to that for (3) and (4). The problems enumerated above also apply to this approach and are exacerbated by the fact that we are now calculating the products of terms with those drawbacks.

3.0 RESULTS

Data from 27 September 1994 were used in the calculations discussed above. Figure 1 shows some comparisons among the estimates

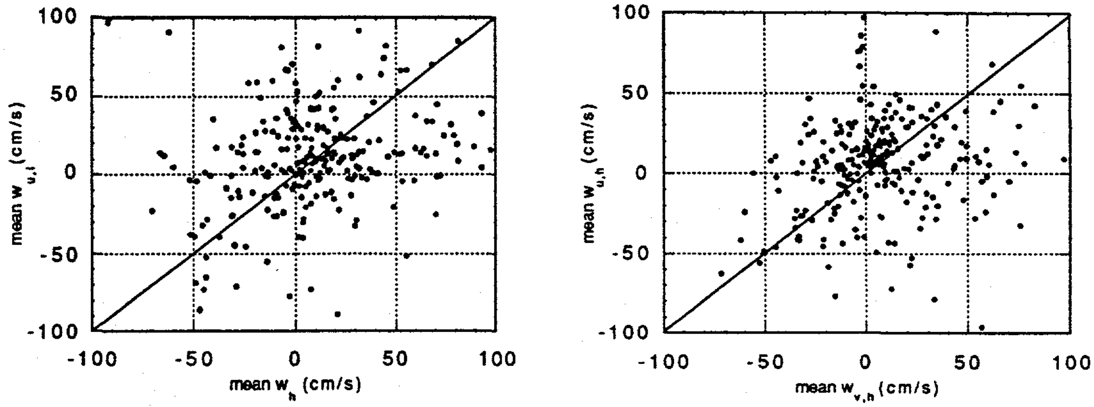

Figure 1. Comparisons of different estimates of 50-min mean vertical velocity. Solid lines indicate one-to-one correlation.

of mean w. Other possible pairs for comparison (not shown) show similar scatter. Because the measurements required for the means were not obtained at the same time a perfect correlation is not expected. Figure 2 illustrates the time-lagged correlation for w_c (all forms of w used) and for the vertical estimates alone (both low and high power). For comparison, Fig. 2 also shows the time-lagged correlation for 13 October 1994 obtained with the profiler operating in a vertical-only, low-power mode that produced a sample of w_l every 15 s. Here, the lagged correlation reaches a second maximum at

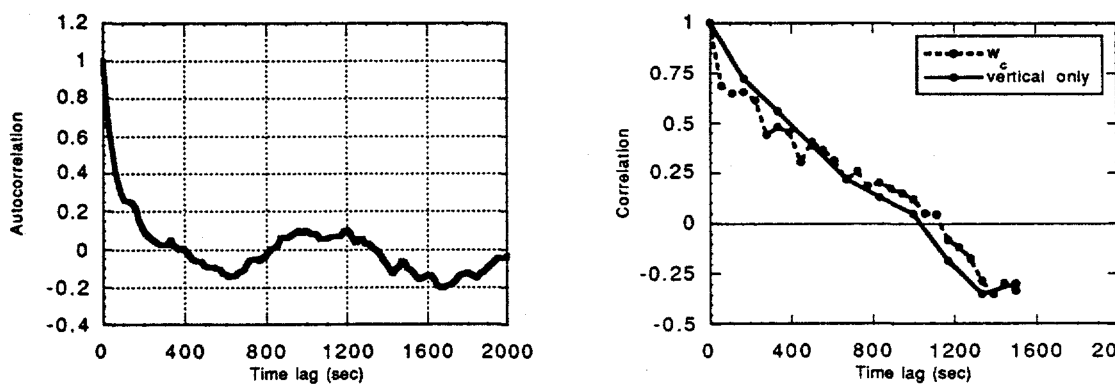

Figure 2. Time lagged autocorrelation coefficient with low-power direct vertical velocity estimates (left) sampled every 15 sec and with time series derived from tilted and vertical only beams (right) during horizontal wind profiling as discussed in the text.

about a 15-min delay, corresponding to the time period between thermal plumes passing over the profiler. The second maximum is not seen in the w_c or w_p time series, possibly because the horizontal winds were much lighter or thermal plumes were not yet well developed.

Figures 3a and 3b compare the spectra determined with the w_c and w_h time series for 27 September and the w_l time series for 13 October. The expected decrease in spectral amplitude with increasing frequency is observed with the w_l time series. The w_h time series appears to capture the

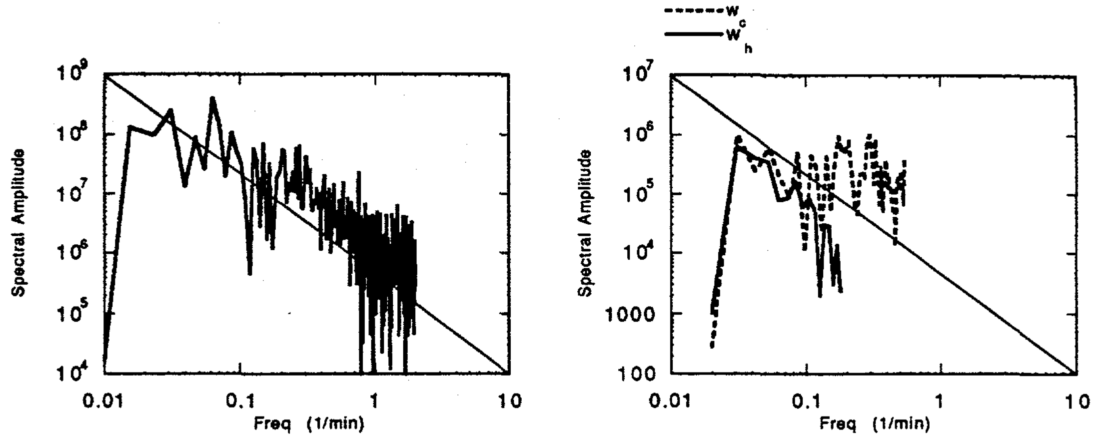

Figure 3. Vertical velocity spectra in convective conditions sampled directly at 15-s intervals (left) on 13 October 1994 and vertical velocities derived from vertical and tilted beams (right) as discussed in the text. Solid, straight lines indicate the -5/3 slope expected in atmospheric turbulence.

low-frequency input to the turbulence spectrum and the initial decrease with increasing frequency. The w_c time series, however, displays a sudden increase in spectral amplitude when the frequency exceeds the maximum available with the w_h series. This is possibly because of the variable sample time used in this series and the additional contributions to signal variance with w_u and w_v. The effect of these terms is most prevalent at higher frequencies, where these estimates fill in gaps between vertical beam-only estimates of w (w_l and w_h).

Figure 4 shows examples of profiles of *cov(uw)* and *cov(vw)* calculated with (3)-(6) in moderately convective conditions on 27 September, when signal levels were

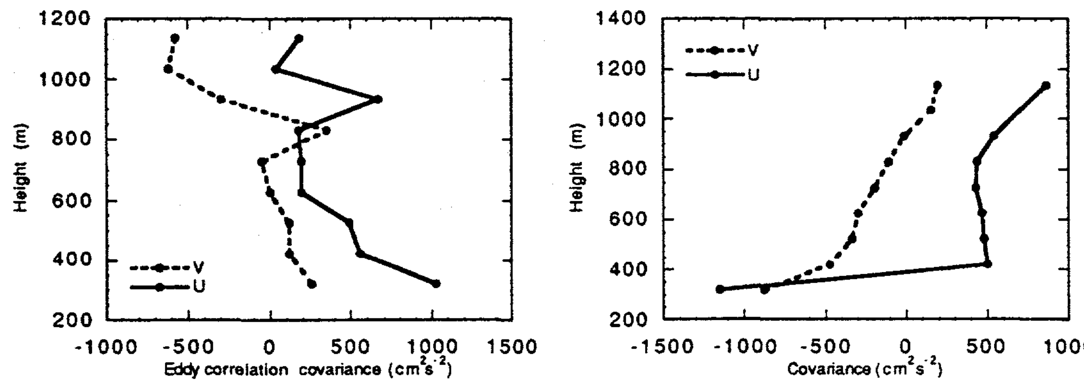

Figure 4. Profiles of the vertical transport of horizontal momentum in very light wind conditions at 0900 LST on 27 September 1994, calculated by using (2)-(3) (left) and (4)-(5) (right).

good. The magnitudes derived by the two approaches appear to be reasonable, but the data are insufficient to evaluate the validity of these methods of calculation. Figure 5 compares the two methods for all values (hourly averages) within the lowest nine range gates.

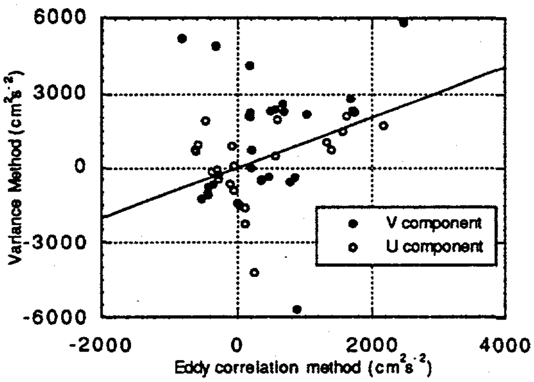

Figure 5. Comparison of estimates of vertical transport of horizontal momentum obtained with eddy correlation and variance techniques. Solid line indicates one-to-one correlation.

4.0 CONCLUSION

We have shown methods for enhanceing the time series of vertical velocities by using higher effective sample rates for five beam wind profiler data. Tentative results indicate that problems exist with the above approaches at higher frequencies because increased variance is introduced by spatial and temporal separations in the vertical velocities calculated from opposing tilted beams. Additional noise is apparently introduced by the irregular time spacing of the enhanced time series.

On the other hand, the low-frequency resolution of the enhanced time series may be improved. This should aid in the detection and resolution of coherent structures like thermal plumes as shown by Coulter and Li (1995). Better selection of beam sampling order may well eliminate the irregularity in the enhanced time series. For example, arranging for the vertical low- and high-power beams to operate sequentially and averaging their signals will yield a time series with five different estimates of *w* that are equally spaced in time.

6.0 ACKNOWLEDGEMENT

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