Proceedings of ERAD 2006

Crossbeam Wind Measurements with Phased-Array Doppler Weather Radar

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1 Introduction

Electronically scanned agile beams of phased-array antennas have been used by the military for decades (Brookner, 2006), but their cost has not allowed them to be a practical option for weather radars. The advent and proliferation of wireless communication equipment, however, and the drive to miniaturize, increase performance, and decrease the cost of transmit/ receive modules, has progressed so rapidly that electronically steered beam agile array antennas can now be considered for future weather radars. Furthermore, the agility of an electronically steered beam allows the integration of multiple functions into a radar to realize cost reduction in maintenance and the number of systems required for surveillance of national airspace (OFCM, 2006). For example, multifunction phased-array radar (MPAR) could serve many if not all the existing civilian radar functions of weather and aircraft surveillance (OFCM, 2006). Furthermore, the use of beam-agile phased-array radar opens possibilities of extended measurement capabilities not possible with mechanically steered beams (e.g., measurement of crossbeam wind, tracking of non-cooperative aircraft with a monopulse function, etc). This paper examines some of the problems in obtaining cross beam wind with a monopulse phased-array weather radar.

The National Severe Storms Laboratory, with the assistance of the Lockheed Martin Corp (LMC), has on loan from the U.S. Navy a monopulse phased-array antenna (Fig. 1) that has been mated with a transmitter used by the U. S. National Weather Service's network of Doppler weather radars (i.e., the WSR-88Ds), but modified for this purpose. This 10-cm wavelength radar, called the National Weather Radar Testbed (NWRT), is the first to support testing of research and development ideas for weather observations with phased-array radars, and is available to students and faculty of any University for research and education. The NWRT has one face of the four-faced antenna used in the AN/SPY1-A radar of the Aegis system. Each face has a beam that can be electronically steered in azimuth and elevation from pulse to pulse to rapidly cover a 90^o sector in azimuth and elevation—the single faced array of the NWRT is mounted on a turn-table that provides full hemispherical coverage.

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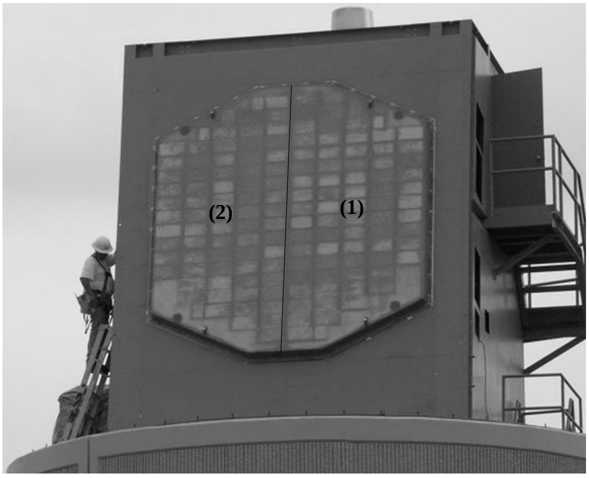

Fig. 1 The NWRT antenna before the installation of an enclosing radome. Marked are the left (1) and right (2) halves of this array.

2 Application of monopulse radar to SAI

Crossbeam wind measurements typically use the cross- and auto-correlation functions (i.e., $C_{12}(\tau)$ and $C_{11}(\tau)$, $C_{22}(\tau)$) of weather signals from pairs of spaced receiving antennas that form a spaced antenna interferometer (SAI). That is, the left and right halves of the NWRT array could be used to measure the crossbeam wind component parallel to the baseline connecting the phase centers of the two spaced antennas (e.g. the azimuth SAI, Fig. 1). But signals from each half of the array are not available on the NWRT because they are combined into sum and difference signals using waveguide power combiners and hybrid tees to form a phase-comparison monopulse radar. Nevertheless, the sum and difference weather signals, $s(t)$ and $d(t)$, can be processed to derive $C_{12}(\tau)$, $C_{11}(\tau)$, $C_{22}(\tau)$. Although the NWRT is a monopulse radar, useful meteorological information cannot be obtained from a single pulse; Doppler velocity requires at least a pair of pulses and then many independent samples pairs of the statistically varying weather signal are required to obtain accurate wind measurement. Thus, the monopulse PAR can be used simultaneously to track aircraft and perform the functions of SAI, and common Doppler weather radar observations.

Assume $v_1(t)$ and $v_2(t)$ are the weather signals from the left and right sides of the array. These signals are combined by the monopulse antenna to form the sum $s(t) = v_1(t) + v_2(t)$ and azimuth difference $d(t) = v_1(t) - v_2(t)$ weather signals; these signals will be processed to obtain weather information (e.g., azimuth cross beam wind, etc.). The auto-correlation function of the sum signal is defined as $C_{SS}(\tau) \equiv \langle s(t+\tau)s^*(t) \rangle$ with similar expressions for the auto-correlation of $d(t)$ and the cross-correlation function of $s(t)$ and $d(t)$ where "*" indicates a complex conjugate operation and brackets denote ensemble averages. Assuming that the scattering media across the beam is statistically stationary and homogeneous,

$$C_{SS}(\tau) = C_{11}(\tau) + C_{22}(\tau) + C_{21}(\tau) + C_{12}(\tau). \quad (1)$$

By forming the correlation functions $C_{SS}(\tau)$, $C_{DD}(\tau)$, $C_{SD}(\tau)$, and $C_{DS}(\tau)$, we have a system of equations from which we can solve for the auto- and cross-correlation functions $C_{11}(\tau)$, $C_{22}(\tau)$, $C_{12}(\tau)$; these functions are typically used (e.g. Cohn et al., 1997) to calculate the crossbeam wind from SAI data. For example, it can be shown,

$$4C_{12}(\tau) = C_{SS}(\tau) - C_{DD}(\tau) - C_{SD}(\tau) + C_{DS}(\tau) \quad (2a)$$
$$4C_{11}(\tau) = C_{SS}(\tau) + C_{DD}(\tau) + C_{SD}(\tau) + C_{DS}(\tau) \quad (2b)$$

At this point any of the many available algorithms (e.g., Doviak et al., 2004) can be used to obtain the azimuthal component of the crossbeam wind. If signals from the left and right sides of the array are matched $C_{11}(\tau) = C_{22}(\tau)$, and it can be shown that $C_{SD}(\tau) + C_{DS}(\tau) = 0$. The sum and difference patterns shown in Fig. 2 suggests that the gains of the left and right half arrays are well matched; note that the magnitude of the difference pattern is plotted, but the difference pattern is an odd function about zero.

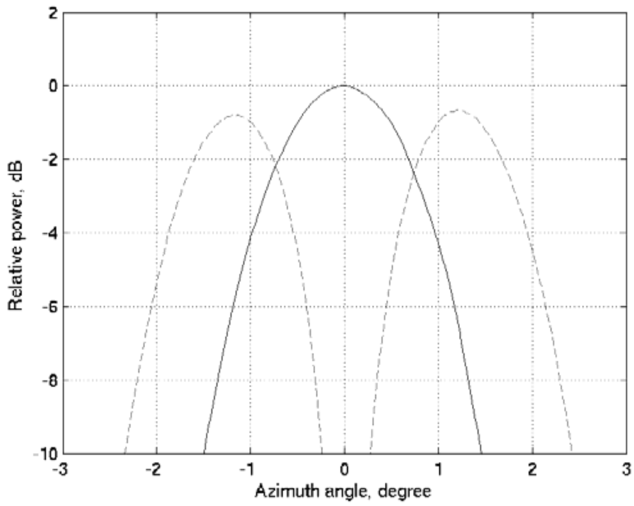

Fig. 2 The sum and difference reception patterns for the NWRT

3 Application to weather radar

Practically all SAIs are used to vertically profile the crossbeam (i.e., horizontal) wind, under the assumptions of statistically homogeneous stochastic Bragg scatter, isotropic turbulence, and spatially and temporally uniform mean wind. Recently Zhang and Doviak (2006) have extended SAI formulation to weather radars wherein auto- and cross-correlation functions are based on wave scattering by randomly distributed particles, turbulence is anisotropic, antenna apertures are not circularly symmetric, and the mean wind has shear. They show weather radar interferometry cannot separate crossbeam wind from crossbeam shear of the mean wind component parallel to the beam axis. That is, the SAI measures an apparent crossbeam wind, a combination of the crossbeam wind and crossbeam shear. Furthermore, because beamwidths are small, it can be shown that SAI measures, approximately, the mean angular shears of the radial wind, a measurement that can be made using Doppler Beam Swinging (DBS) methods (e.g., the VVP method; Waldteufel and Corbin, 1979). Angular shears are defined as the radial velocity change per differential arc length (e.g., $r_0 \sin\theta_0 d\varphi$). But with the SAI method, angular shear is measured within the beam, not so for the DBS methods.

Finally, shear and turbulence within V_6 can be separated using the SAI. Turbulence can be estimated from the width of the Doppler spectrum using single aperture Doppler weather radars such as WSR-88D. Such estimation is neither accurate nor reliable because beam broadening (i.e., radial velocity shear associated with uniform wind across the beam) and shear bias turbulence estimates. Melnikov et al., (2003) show that layers of unusually large spectrum widths (e.g., larger than 8 m s^{-1}), suggestive of turbulence hazardous to safe flight (Lee, 1977), are seen in stratiform precipitation. But these large widths are principally due to shear, and are not necessarily hazardous to safe flight. The fact that SAI separates within-beam shear from turbulence suggests that improved measurements of turbulence can be made using weather radar interferometry.

4 Application to the NWRT

For preliminary tests, the NWRT monopulse radar has had the azimuth difference channel activated so that the azimuth component of the crossbeam wind can be measured. For this configuration the cross-correlation coefficient of signals from the left and right sides of the array can be obtained from Eq. (13) of Zhang and Doviak (2006); that is:

$$c_{12} = \exp\begin{bmatrix} -j2kv_{0x'}\tau - 2k^2(\sigma_R^2 s_{x'}^2 + \sigma_{tx'}^2)\tau^2 - \\ k^2\sigma_{e\theta}^2 {v_{az'}}^2\tau^2 - k^2\sigma_{e\phi}^2\{v_{ay'}\tau - \frac{\Delta y'_{12}}{2}\}^2 \end{bmatrix} \quad (3)$$

where $v_{az'} \equiv (r_0 s_{z'} + v_{0z'})$; $v_{ay'} \equiv (r_0 s_{z'} + v_{0y'})$ are apparent crossbeam wind components; ($v_{0x'}, v_{0y'}, v_{0z'}$) is the mean wind at the center of V_6 at range r_0, the primes indicate a tilted Cartesian coordinate system in which $v_{0x'}$ is parallel to the beam axis with $v_{0y'}, v_{0z'}$ parallel to the azimuth and elevation directions; $s_{x'}, s_{y'}, s_{z'}$ are the shears of $v_{x'}$; σ_R is range resolution; $\sigma_{tx'}$ is the rms intensity of the x' component of turbulence (for narrow beams, crossbeam components typically can be ignored, especially if turbulence is isotropic); $k = 2\pi/\lambda$ where λ is the radar wavelength; τ is time lag; $\sigma_{e\theta}^2, \sigma_{e\phi}^2$ are the beamwidths (the second central moments of the radiation pattern) along the elevation and azimuthal directions, and $\Delta y'$ is the separation of the phase centers of the left and right halves of the NWRT antenna.

This equation can be reduced to the simplified Gaussian form

$$c_{12}(\tau) = \exp\left[-j2kv_{0x'}\tau - \eta - \frac{(\tau - \tau_p)^2}{2\tau_c^2}\right] \quad (4)$$

by matching like terms in powers of τ , where

$$\tau_c = \frac{\lambda}{4\pi}\left\{\sigma_{tx'}^2 + \sigma_R^2 s_{x'}^2 + \sigma_{e\theta}^2 v_{az'}^2 + \sigma_{e\phi}^2 v_{ay'}^2\right\}^{-1/2},$$

$\tau_p = k^2\sigma_{e\phi}^2 v_{ay'}\Delta y_{12}^2\tau_c^2$, and

$$\eta = \frac{k^2\sigma_{e\phi}^2\Delta y_{12}'^2}{4} - \frac{\tau_p^2}{2\tau_c^2}$$

Often there are advantages to calculate crossbeam wind using the cross spectrum defined as

$$s_{12}(v) = \frac{2}{\lambda}\int c_{12}(\tau)\exp[+j2kv\tau]d\tau$$

Performing the integration we obtain

$$s_{12}(v) = \frac{2\sqrt{2\pi}\tau_c}{\lambda}\exp\begin{bmatrix} -\eta + j2k(v - v_{0x'})\tau_p - \\ 2k^2(v - v_{0x'})^2\tau_c^2 \end{bmatrix} \quad (5)$$

In this form, the apparent crossbeam wind component $v_{ay'}$ is obtained from the slope of the phase term; the value of phase at $v = 0$ measures the along-beam velocity $v_{0x'}$.

5 Estimation of apparent wind

The apparent baseline wind $v_{ay'}$ can be calculated from the cross-correlation function using a cross-correlation ratio (CCR) method (Zhang et al., 2003), analogous to pulse pair processing, or the Full Correlation Analysis (FCA) method (Briggs, 1984). In the CCR method, the logarithm of the cross-correlation magnitudes at equal positive and negative lags leads to the relatively simple expression

$$L_\phi(\tau) = \ln\frac{|c_{12}(\tau)|}{|c_{12}(-\tau)|} = 2k^2\sigma_{e\phi}^2\Delta y'_{12}v_{ay'}\tau \quad (6)$$

Thus, the apparent baseline wind $v_{ay'}$ is

$$v_{ay'} = \frac{L_\phi(\tau)}{2k^2\sigma_{e\phi}^2\Delta y'_{12}\tau}. \quad (7)$$

Because baseline shear combines with baseline wind, the accuracies of measuring $v_{ay'}$ can be directly derived from theoretical error analyses developed for baseline wind measurements in absence of shear (e.g., Zhang et al., 2004; Doviak et al., 2004). Fig. 3 shows standard deviation of $v_{ay'}$ as a function of r_0 and $\sigma_{tx'}$. The error increase with range is due to $s_{z'}$. Compared to measurements of the along-beam wind component using Doppler measurements, baseline wind measurement requires much longer dwell times. For example, if the turbulence $\sigma_{tx'} = 0.5$ m s^{-1}, about 5 seconds of data collection time is required to achieve a measurement accuracy of 2.0 *m s*$^{-1}$ using the NWRT at near ranges.

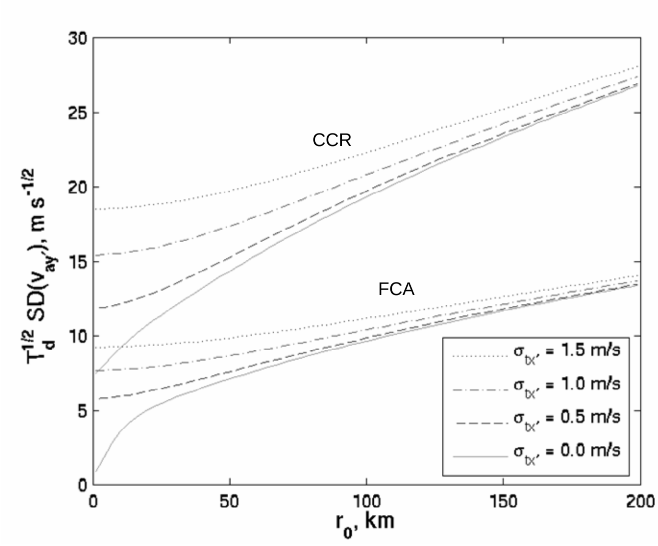

Fig. 3 Normalized standard deviation of estimates $\hat{v}_{ay'} = r_0\hat{s}_{y'} + \hat{v}_{0y'}$ versus r_0 for various levels of $\sigma_{tx'}$ and NWRT parameters: λ = 0.0938 m, $\Delta y'_{12}$ = 1.46 m, $\sigma_{\phi T}$ = 0.65°, $\sigma_{\phi R}$ = 1.30°. Meteorological parameters are: $v_{ay'}$ = 20 m s^{-1}, $v_{0x'}$ = 0, $v_{0z'}$ = 5 m s^{-1}, $s_{x'} = 0$, $s_{z'} = 0.002$ s^{-1}.

6 Conclusions

It is shown that monopulse phased-array weather radar should be capable of measuring radial wind and apparent crossbeam wind, as well as tracking aircraft. Although crossbeam wind cannot be separated from shear, the SAI can separate turbulence from shear within the beam, suggesting that more accurate measurements of turbulence. It is suggested that using weather radar interferometry, simultaneous measurements of apparent crossbeam and along beam winds might provide additional observational constraints on numerically derived wind fields.

Acknowledgements: Many thanks go to the NSSL engineers and technicians (J. Carter, C. Curtis, R. Wahkinney, M. Benner, and R. Adams) for helping to make monopulse pattern measurements, and to M. Campbell of LMC for help in activating the monopulse feature on the NWRT. This work was partially supported by NOAA/NSSL under the cooperative agreement NA17RJ1227.

References

Briggs, B. H., 1984: The analysis of spaced sensor data by correlation techniques, *MAP Handbook*, **13**, edited by R. A. Vincent, 166-186. (Available from SCOSTEP Secretariat, University of Illinois, Urbana, Ill.).

Brookner, E., 2006: Phased arrays and radars-past, present and future. *Microwave Journal*, **49**(1), 24-46

Cohn, S. A., C. L. Holloway, S. P. Oncley, R. J. Doviak, and R. J. Lataitis, 1997: Validation of a UHF spaced antenna wind profiler for high-resolution boundary layer observations. *Radio Science*, **32**(3), 1279-1296.

Doviak, R. J., G. Zhang, S. A. Cohn, and W.O.J. Brown, 2004: Comparison of spaced-antenna baseline wind estimators: Theoretical and simulated results. *Radio Sci.* **39**, doi10.1029/2003RS002931, 1-21.

Holloway, C. L., R. J. Doviak, S. A. Cohn, R. J. Lataitis, and J. S. Van Baelen, 1997: Cross correlations and cross spectra for spaced antenna wind profilers, 2. Algorithms to estimate wind and turbulence. *Radio Sci.*, **32**(3), 967-982.

Melnikov, V. M., R. J. Doviak, and M. Fang, 2003: Radar observations of turbulence and wind shear. *31st Conference on Radar Meteorology*, Seattle, Wash., Amer. Meteor. Soc.

Lee, J. T., 1977: Applications of Doppler radar to turbulence measurements which affect aircraft, Final Rept. No.FAA-RD-77-145. FAA Syst. Res. Dev. Serv., Washington, D. C.

OFCM, 2006: Report on federal research and development needs and priorities for phased array radar, Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM), 8455 Colesville Rd., Suite 1500, Silver Spring, MD 20910.

Waldteufel, P. and H. Corbin, 1979: On the analysis of single Doppler data. *J. Appl. Meteorol.*, **18**, 532-542.

Zhang, G., R. J. Doviak, J. Vivekanandan, W. O. J. Brown and S. A. Cohn, 2003: Cross-correlation ratio method to estimate cross-beam wind and comparison with a full correlation analysis. *Radio Sci.* **38**(3), 17-1 to 17-14.

Zhang, G., R. J. Doviak, J. Vivekanandan, W. O. J. Brown and S. A. Cohn, 2004: Performance of correlation estimators for spaced-antenna wind measurements in the presence of noise. *Radio Sci.* **39**, doi:10.1029/2003RS003022, 1-16.

Zhang, G. and R. J. Doviak, 2006: Weather Radar Interferometry to measure crossbeam wind, shear and turbulence: theory and formulation, submitted to *Jo. Oceanic and Atmos. Tech.*, March 2006.