A PHASED-ARRAY RADAR FOR WEATHER RESEARCH AND EDUCATION

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INTRODUCTION

The National Severe Storms Laboratory (NSSL), through the cooperation of the Lockheed Martin Corp. (LMCO), has on loan from the U.S. Navy a passive phased-array antenna. This antenna has been mated with a modification of the transmitter used by the U.S. National Weather Service's network of Doppler radars, and a signal processor that has been developed by LMCO in cooperation with the Electrical Engineering Department of the University of Oklahoma, to form the first passive agile-beam phased-array Doppler weather radar for research and education in Radar Meteorology. This phased-array weather radar, called the National Weather Radar Testbed (NWRT), is located in Norman, Oklahoma. It will be used to test novel ideas for radar observations of weather, and will be available to students for research and education. The NWRT has one of the four AN/SPY-1A antenna apertures, but it is mounted on a turntable to allow full coverage in any selected 90^o sector. An example of a severe thunderstorm observed with the NWRT on the 30th of May, 2004 is shown in Fig.1. This image was obtained with the broad side fixed facing northwest, and the radar beam was electronically scanned in azimuth $\pm$ 45 degrees about the broadside direction. This paper reviews some of the advantages and disadvantages of the agile-beam phased-array radar (PAR) for weather observations, and suggests novel applications for the PAR.

THE NWRT CHARACTERISTICS

The antenna uses 4,096 (4,352) elemental apertures for transmitting (receiving), about four per square wavelength, uniformly placed over an approximately circular area. Other parameters of the NWRT are given in Table 1. The NWRT beamwidth is larger than that (i.e., 1^o) of radars (i.e., WSR-88D) used by the USA's National Weather Service (NWS). If PAR is to be used operationally by the NWS, a larger antenna, and one having the capability of transmitting simultaneously vertically and horizontally polarized waves, will have to be constructed. But, given the availability of the SPY1A antenna, the NWRT is perfectly suitable for research and testing of novel observational techniques.

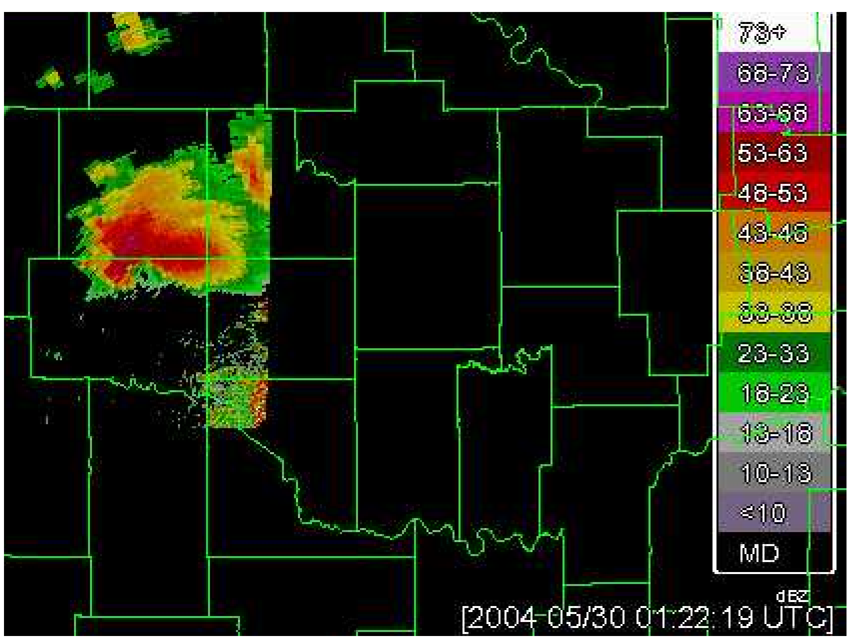

Fig. 1 A severe storm observed with the NWRT

Table 1

- Transmitting antenna diameter: $D_T \approx 3.66$ m; wavelength: $\lambda = 0.0938$ m; array face tilt $\approx 10^o$.
- Receiving beam width for SAI: θ_{1R} (SAI) $\approx 3.2^o$ (assumed); receiving aperture weighted with a Taylor distribution.
- Transmitting broadside beamwidth: $\theta_{1T} \approx 1.6^o$; transmitted power uniformly distributed across the aperture
- Transmitter power and pulse width: ≈ 500 kW peak and 1.57 μs
- Range resolution: $\sigma_r \approx 100$ m; receiver panel spacing for SAI: $\Delta x = 0.4\, D_T$ (assumed)

ADVANTAGES AND DISADVANTAGES OF AN AGILE-BEAM PHASED-ARRAY RADAR (PAR)

Doppler weather radars use mechanically steered beams and thus radar resources are inefficiently used when vast regions of the atmosphere without weather are scanned. Furthermore, Doppler weather radars only measure the radial wind component, and thus are limited in providing timely and accurate information of weather hazards. The use of PAR opens the possibility that phased array antennas and signal processing hardware can be configured in such a way that crossbeam winds can be measured as well.

Other advantages of a PAR are: 1) the resolution of a stationary beam is obtained; 2) the elevation angle of the beam can programmed to follow the blockage pattern of ground objects (i.e., buildings, mountains, etc.), so that beam blockage is a known fixed value (this allows the beam to be at its lowest elevation angle to provide the best rainfall estimates); 3) at elevation angles where ground clutter can be ignored, the agile-beam PAR allows acquisition of independent pairs of complex weather signal samples from each resolution volume, leading to a significant reduction in the time to make weather measurements; 4) more frequent measurements of meteorological hazards (e.g., tornado cyclones, hailstorms, etc.) can be obtained to improve warning accuracy, while periodically monitoring, at a lower revisit rate, the areas void of weather; 5) better ground clutter canceling (ground clutter width is determined only by the motions of the scatterers on the ground), leading to better compensation for reflectivity biases introduced by ground clutter canceling; 6) multiple applications (e.g., tracking aircraft; weather observations; vertical sounding of horizontal wind; etc.); 7) Doppler velocity bias due to coherent echoes received through sidelobes can be reduced by modulating the sidelobe phase [1]; and 8) improved turbulence measurements because spectral broadening due to antenna motion does not exist.

The principal disadvantage of the PAR is its high cost and complexity; also the beam broadens when the beam direction is displaced from broadside.. Nevertheless, advances in the miniaturization of transmit-receive modules driven by cellular technology, and the cost reduction benefit associated with the manufacture of a large number of modules, opens the potential for wider application of active beam-agile PARs than strictly for military use. Furthermore, the costs of a PAR can be offset by its lower required maintenance and potential for multi-function use.

MUTI-FUNCTION PAR

10 cm airport surveillance radars (ASRs) are used to track and guide aircraft in the vicinity of airports, and longer wavelength (e.g., 30 cm) en route surveillance radars (ARSRs) are used to detect, track and guide aircraft en route. Longer wavelengths insure that weather doesn't attenuate the signal significantly so that small aircraft at long ranges will be detected. Nevertheless, attenuation at 10 cm is not severe (i.e., about 0.02 dB/km), and thus a modest increase in power and/or Doppler processing should allow the same aircraft detection performance as obtained with the present ARSR network. PAR, with polarimetric capability, and multiple frequencies (each for a separate application if needed), could simultaneously observed weather and track aircraft. PAR could also be used to support Search and Rescue (SAR) of victims at sea by measuring surface currents that are a key parameter in SAR planning; 95% of all SAR activities are within 20 miles of the coast. Thus one PAR might serve the functions of two or more radars.

BEAM MULTIPLEXING

If weather is observed with a Doppler radar transmitting a uniform train of pulses, a larger number M_c of contiguous samples (i.e., $M_c - 1$ pairs) are required to make an acceptably accurate measurement of wind than the number M_I required if $M_I/2$ independent sample pairs are processed. Thus a PAR with beam pointing agility can multiplex the beam position so that, during the time it takes for scatterers to reshuffle to obtain a next pair of independent samples, the beam can be pointed in different directions to obtain weather signal samples in other regions. Beam multiplexing is an acceptable solution at elevation angles and directions where weather echoes are not mixed with ground clutter and weather is relatively uniform along the beam. At high SNR, the ratio M_c/M_I is

$$\frac{M_c}{M_I} = \frac{1}{4\sqrt{\pi}\sigma_{vn}}, \quad \sigma_{vn} \equiv \frac{\sigma_v}{2v_a},$$

where σ_v is the spectrum width and v_a is the unambiguous velocity. Thus for regions where spectra are relatively narrow, far fewer M_I samples are needed to obtain the requisite estimate accuracy. Recent measurements of spectrum width, σ_v, over a large variety of weather types, show median values throughout storm volumes to be mostly less than 2 m s^{-1}[2]. For 10 cm Doppler radars using a Pulse Repetition Time, PRT, at about 10^{-3} s, the ratio is 3.5; this means that a PAR can scan weather in this region 3.5 times faster. On the other hand, squall lines have extensive regions where spectrum widths are a factor of 2 to 3 times larger; thus acquisition times in this case cannot be reduced significantly. Fig. 2 compares the Standard Deviation of the radial velocity v_r estimates $SD[\hat{v}_r]$ calculated from data collected on May 2, 2005 with the NWRT. To obtain independent samples, pairs of pulses were transmitted sequentially along the azimuths A1, A8, A2, A9….A7, A14, where A8 was 7^o from A1, A9 7^o from A2, etc. This sequence was repeated 32 times so that 64 samples were collected at each of the 14 azimuths. This data collection program was interlaced with that for conventional sampling obtaining 64 contiguous samples at each of the 14 azimuths and repeated 50 times. It took 1.8 s for each mode to scan a 28^o azimuth sector. The standard deviation about a linear fit of data vs. time for 50 realizations at each resolution volume was calculated. Fig. 2 shows that if SNR is high, beam multiplexing consistently provides lower estimate variance.

PAR CROSSBEAM WIND MEASUREMENTS

Doppler weather radars only measure the radial wind component, and thus are limited in providing accurate information of damaging wind potential. The use of PAR opens the possibility that crossbeam winds can be also measured [3]. Two alternatives to measure crossbeam winds are: 1) a 3-beam Doppler Beam Swinging (DBS) technique, one used to profile winds above a radar site [4], and 2) Spaced Antenna Interferometry (SAI)[3] where the full transmitting aperture is split into two halves on reception to cross correlate signals simultaneously received. A vertical split provides measurement of the horizontal component of crossbeam wind whereas a horizontal split allows measurement of the component in the vertical plane. Although the theory [5] is based upon Bragg scatter from random perturbations of atmospheric refractive index (i.e., Stochastic Bragg Scatter), it has been deduced that the theory applies to scatter from precipitation. Fig. 3 shows a comparison of the theoretically computed SD of the crossbeam

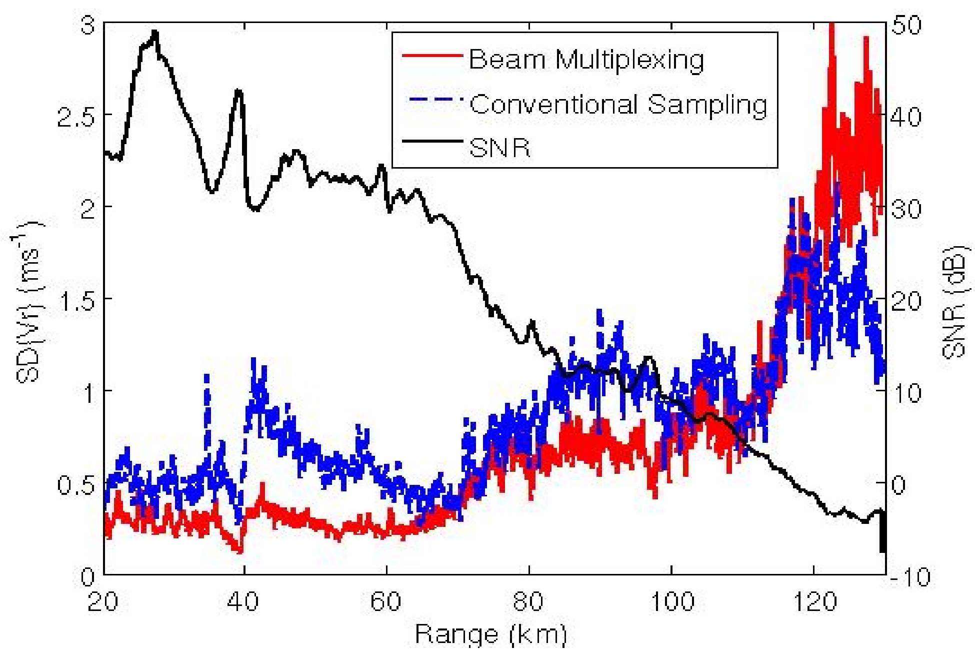

Fig. 2 Comparison of Doppler estimate accuracy along the 164.8^o azimuth at an elevation angle of 1^o.

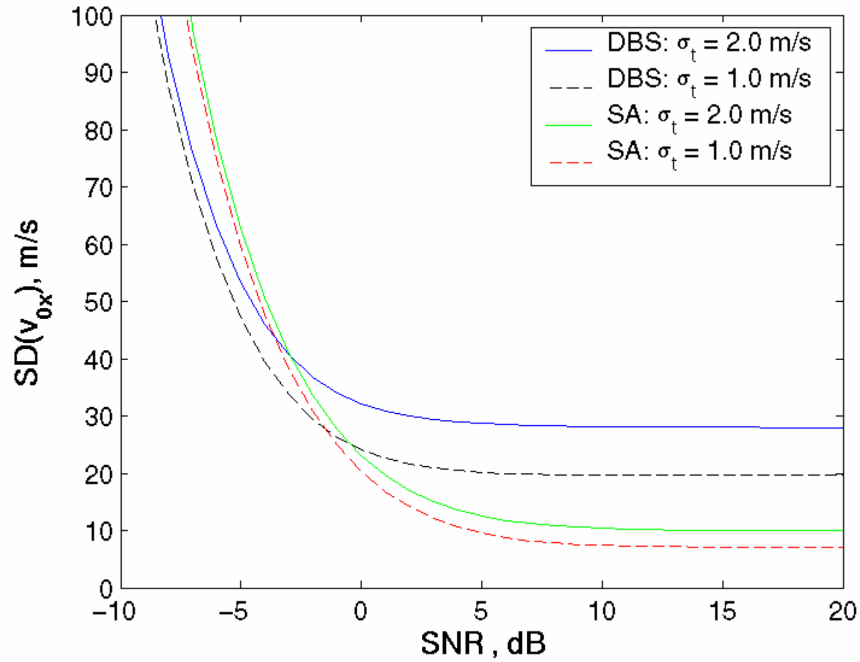

Fig. 3 Comparison of standard deviations of baseline wind, v_{0x}, estimates using DBS and SAI techniques.

wind component, SD($\hat{v}_{ox}$) plotted as a function of the Signal to Noise Ratio (SNR) for two levels of turbulence (σ_t =1 and 2 m s^{-1}), assuming the NWRT is used for both techniques, the measurement volumes are nearly matched, and data is collected over in 1 s. Parameters used for calculations are: T_s = 1 ms, $\Delta x = 0.4\ D_T$, $a_h = 2\pi\alpha\theta_{1T} / 2.36\lambda$ =1.0 m^{-1}, λ = 0.1 m, dwell time $T_d = MT_s$ = 1 s, α = 1.28 for SAI (α relates to transmitter and receiver aperture size differences); α = 1.0 and beam separation $\theta_z = 0.5^o$ for DBS. Wind components are: v_{0x} = 10 m s^{-1}, $v_{0y} = v_{0z}$ = 0 m s^{-1}. Under the stipulated conditions, the SAI outperforms the DBS at high SNR, but the converse is true at low SNR.

Although crossbeam wind cannot be estimated with the same accuracy as rapidly as the radial wind, perhaps crossbeam wind could be measured with longer dwell times at a few selected locations in regions of meteorological interest having low σ_t. Reference [2] shows median values of σ_v in tornadic storms are less than 2 m s^{-1}, and about 20% of the storm region has zero values (σ_t contributes to σ_v). Thus there should be many areas of low σ_t where useful crossbeam wind measurements could be made. Such measurements could provide the necessary constraints for sophisticated retrieval algorithms to map accurate fields of crossbeam winds over larger domains.

CONCLUSIONS

The use of phased-array radar (PAR) technology for civil applications of radar (e.g., to observe weather, to track and guide aircraft, etc.) could reap cost savings if radar can be used for multiple functions. PAR can make faster observations of weather, spend less time scanning skies void of weather, and measure crossbeam winds.

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