AGILE BEAM PHASED ARRAY RADAR FOR WEATHER OBSERVATIONS

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Capsule: Electronic beam steering enables the multi-mission phased array radar to rapidly and adaptively survey the atmosphere while detecting and tracking aircraft.

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Abstract

Weather radars with conventional antenna cannot provide desired volume scans updates at intervals of one minute or less which is essential for significant improvement in warning lead time of impending storm hazards. The agile beam Multi-Mission Phased Array Radar (MPAR) discussed herein is one potential candidate that can provide faster scanning. It also offers a unique potential for multipurpose use to not only sample weather, but support air traffic needs, and track non cooperative airplanes; thus, making it an affordable option. After introducing the basic idea behind electronic beam steering, the needs for frequent observations of convective weather are explained. Then, examined are advantages of the Phased Array Radar (PAR) for weather monitoring and improving data quality. To explore and develop weather-related applications of the PAR, a National Weather Radar Testbed (NWRT) has been established in Norman, OK. The NWRT's main purpose is to address the advanced capabilities anticipated within the next decade so that these could be projected to a possible network of future weather radars. Examples of data illustrating advantages of this advanced radar are shown, and forthcoming plans are discussed.

INTRODUCTION

Detailed precipitation and wind data in weather systems over the United States are presently derived from a network of weather surveillance radars officially designated as Weather Surveillance Radar 1988 Doppler (WSR-88D, Crum et al. 1998). Additional localized weather surveillance at major airports is provided by special radars such as the Terminal Doppler Weather Radar (TDWR, Michelson et al. 1990) and Airport Surveillance Radar (ASR, Weber and Stone 1995). When operationally introduced in the early 1990s, WSR-88D represented a quantum leap in observing capabilities over the previous non-Doppler weather radars (Doviak and Zrnic 1993). High-resolution, accurate, multi-parameter observation by WSR-88D enables detection of mesocyclones (Stumpf et al. 1998; Lee and White 1998) and tornadic vortex signatures (TVS, Brown et al. 1978, Mitchell et al. 1998), and even a limited warning of their imminence. Upon deployment of the WSR-88D, the average tornado warning lead time increased abruptly from ~7 to 10 min and stands currently at ~13 min. Overall estimates are that the WSR-88D network reduced tornado-related deaths by 45% and injuries by 40% (Sutter and Simmons 2005).

The desirability and feasibility of adding polarimetric capability to WSR-88D has been well established (Zrnic and Ryzhkov 1999; Zrnic et al. 2001) and it is expected to be incorporated into the existing network starting in 2009. This would further enhance the accuracy and versatility of WSR-88D data products while providing additional information about precipitation types.

Although NOAA’s WSR-88D network is continuously improving, it is approaching its 20-year engineering design life span. The NEXRAD product improvement investments and sustaining engineering modifications have significantly extended the service life of the WSR-88D, with current NEXRAD Program estimates projecting no significant supportability issues through at least 2020. Options for successor technology include: upgrades and refurbishments to further extend the service; replacement of all or parts of the WSR-88Ds with conventional radar systems; replacement with agile beam phased array radar; and augmentation or replacement with short wavelength radar networks (Brotzge et al. 2006).

In spite of their impressive performance, present Doppler weather radars have limitations. Their mechanical scanning arrangement enforces a sequential beam sweep through the designated cycle and precludes (because of beam smearing) update of volume scans at rates faster than about every four minutes. Further, it is not feasible to adaptively sample the atmosphere at specific locations, thus hindering intensive observations of regions with potential for severe weather. To achieve the goals of the National Weather Service for improvements in warnings and forecasts (NOAA 2005 – Strategic Plan), advanced concepts in atmospheric remote sensing must be explored.

Phased Array Radar (PAR) with agile electronic beam steering is a prime candidate for superior observation of the atmosphere. A network of such radars is recommended for consideration by the National Academies Committee on Weather Radar Technology beyond NEXRAD (National Academies 2002) and justified in the report by the Joint Action Group from the Office of Federal Coordinator for Meteorological Services (2006). That report strongly endorses multi-function (herein referred to as multi-mission) phased array radar (MPAR) for sampling weather, controlling air traffic, and tracking non-cooperative airplanes (Weber et al. 2006). The concept of multi-mission fast scanning radar has been explored from the aviation perspective and the reader is referred to the Federal Aviation Administration (FAA) document "Terminal Area Surveillance System" (TASS 1997) containing many articles on the subject. Herein we are concerned with applications of the PAR technology to observations of weather. Thus the acronym PAR refers to the phased array radar technology in general; MPAR is a possible future multi-mission phased array radar specifically tailored for monitoring weather, serving aviation needs, and tracking of non cooperative objects (see the companion article by Weber et al. 2007 that also presents a futuristic design of such radar transmitting simultaneously three beams each at a different frequency); NWRT (National Weather Radar Testbed) introduced in later sections is the proof of concept PAR in Norman, OK.

AGILE BEAM PHASED ARRAY RADAR

The fundamental difference between agile beam PAR and conventional radars that use a rotating parabolic antenna is in formation and steering of the beam. The parabolic antenna surface shapes and directs the beam, while the continuous physical rotation of the reflector around a vertical axis sweeps the beam through a volume of space surrounding the radar (Fig. 1). The reflector is tilted to change the angle of the beam's center from the horizontal. In contrast the PAR beam is formed and directed electronically by superimposing outputs from an array of radiators. This is achieved by controlling the phase and the on-off timing (pulsing) of the electromagnetic field generated by each radiator relative to the phases and pulses of the other radiators in the array. However, steering the beam by more than $\pm 45^{o}$ from the axis (normal) of a planar array is avoided to limit the effect of beam broadening that is inversely proportional to the cosine of the angle between beam direction and the axis normal to the array. Further, at large off axis angles radiating (grating) lobes appear that compete with the main lobe. Therefore more than one radiating panel is required for complete 360^o probing in azimuth. The PAR in Fig. 1 has four panels.

Each panel of the PAR has thousands (ten thousand to achieve a 1 deg broadside beam width at a 10 cm wavelength) of solid state modules containing transmit-receive (T/R) elements. Each element transmits a small portion of the total beam energy and receives a portion of the backscattered energy. Electronically controlled attenuators, phase shifters, switches, filters, analog-to-digital converters (ADCs), and digital processors are the fundamental components underlying advances in PAR design and applications. New generations of these electronic components have enabled rapid and accurate formation and steering of the radar beams. This beam-steering capability in turn permits multiple radar functions to be performed with the same radar unit. The function-specific beams of a multi-mission PAR can be interlaced in time or even generated simultaneously (Weber et al. 2007).

PAR technology has been used operationally by the U.S. military since the 1970s. Principal applications are for simultaneous tracking of multiple targets coming from many directions. Extensive technical capability was developed and other applications such as for aviation weather, begun to be explored (Katz and Nespor 1993).

Conventional surveillance weather radars have a mechanical control of beam position, and dwell a relatively long time (~ 50 ms) to obtain a sufficient number of independent echo samples for accurate estimates of Doppler spectral moments. Thus, the volume update times are dictated by two limitations: 1) the inertia of the mechanically steered antenna, and 2) the correlation time of weather signals. In contrast, phased array Doppler radars, with specially designed waveforms and/or processing of signals, offer the prospect of routinely sampling the atmosphere with volume scan rates an order of magnitude faster than the fastest (4 min) operational scan mode of the WSR-88D Doppler radars.

Transmission and processing of wideband signals (modulated signals in Fig. 1) can be done on either conventional radar or PAR. Advantages of such signals are two. One applies to transmitters that have more stringent limitations on peak power than on pulse duration as are radars with solid state transmission modules; the article by Weber et al. (2007) suggests compressing the received wide band long pulses for achieving desired range resolution and increasing signal to noise ratio (SNR). The other advantage is to radically decrease the dwell time for generating estimates by processing wide band signals. Integration of estimates over the duration of the short pulse provides reduction of variance equal to the product of pulse duration with its bandwidth. This we discus next and demonstrate that the full advantage of wideband signals *for rapid volume update* can only be achieved with the PAR. Suppose that two pulses separated by 1 ms are transmitted in the same direction. Further, the pulses are 1 μs long and have wide bandwidth, say 20 MHz, suitable for pulse compression (Bucci et al. 1997). Upon reception each pulse is compressed to 50 ns so that there are 20 compressed returns (sub-pulses) in the 1 μs interval. Then, from a pair of sub-pulse returns it is possible to obtain an estimate of the Doppler velocity and average twenty of these in range to reduce the variance of the estimate. If the antenna beamwidth is 1°, it follows that coverage of the contiguous 360^o could be achieved at a rate of 500^o s^{-1}. With the PAR, the two returns from the two pulses would come from the same resolution volume; then the beam would switch to a new position. With the conventional radar the beam would move by 0.5^o between each measurement thus the returns would come from overlapping but displaced (by 0.5^o in azimuth) resolution volumes and would suffer from decorrelation blues. That is, the displacement would cause a 30% drop in correlation (assuming a Gaussian antenna pattern with one degree beamwidth, Doviak and Zrnic 1993, p 517) between two consecutive samples. Consequently, the effective SNR at such high rotation rate would be less than 0.7/0.3 (i.e., 3.8 dB) regardless of its true value. Moreover, at a 10 cm wavelength this decorrelation would register as a huge spectrum width of 6.7 m s^{-1} overwhelming the other contributors (e.g., turbulence, shear) to this variable.

NEEDS FOR FREQUENT OBSERVATIONS

Agile beam PAR offers benefits to both research and operations. Frequent volumetric data provided with the PAR are needed for observations of short-lived phenomena, retrieval of winds, initialization/assimilation into storm scale numerical weather prediction models, and other applications.

Observation of short-lived hazardous phenomena

The PAR is well suited for repetitive rapid observations of hazardous weather phenomena. High temporal resolution data in real-time offers immediate and tangible societal benefits through improved hazard-warning (e.g., microburst and mesocyclone detection), nowcasting, and guidance for aviation operations. For example, Wolfson and Meuse (1993) compare low elevation volume scans at 3 min intervals with rapid scans at

1 min intervals. They demonstrated that, on the average, lead-times for microburst detection increased from about 2.2 min (at 3 min updates) to 5.2 min (at 1 min updates).

Additionally, rapid high-resolution measurements can potentially aid in the formulation and verification of theories of tornadogenesis. Observations of the Dimmitt, Texas tornado of 2 June 1995 (Rasmussen et al. 2000), with an airborne Doppler radar revealed that the time scale for tornadogenesis was exceedingly small; the average tangential velocity in the vortex at 700 m radius and 3 km AGL increased from 7.5 m s^{-1} to 20.3 m s^{-1} in a period of 78 s. This rapid evolution, which might typify tornadogenesis, is impossible to observe with conventional scanning radars. To fully detect the process of tornadogenesis, scan times of roughly 20−30 s are required in a relatively small volume crucial for spawning the tornado; the shape and size of that volume are crucial in tornado genesis process but to this day remain an enigma.

Retrieval of winds

Carbone and Carpenter (1983) and Carbone et al. (1985) discussed the need for rapid scan Doppler radar to sample the high temporal variability of convective elements; these have large amounts of kinetic energy on spatial scales of 1−2 kilometers and 1−3 minutes (Knight and Squires, 1982; Battan 1980; Carbone et al. 1990). Therefore, to properly capture these energy-containing structures, it is desirable to know the wind-speed in at least two-dimensions and (especially) vertical velocity at less than one-min intervals.

A number of techniques have been developed to retrieve the complete wind vector field using reflectivity and/or radial velocity data from a single Doppler radar (Sun and Crook 1994, Shapiro et al. 1995 and 2003, Xu et al. 1994a,b, 1995, Laroche and

Zawadzki 1995, Qiu and Xu 1996). In conventional thermodynamic retrievals (Gal-Chen 1978, Hane and Scott 1978) the accuracy of the retrieved perturbation pressure (and subsequently the temperature) depends on how well the time variation of the local velocity field can be determined. Crook's (1994) numerical experiments indicate substantial reduction in errors if temporal sampling of these fields is faster. Most importantly, many of the retrievals either make explicit or implicit use of *temporal constraints*, for example, velocity stationarity, Taylor's frozen turbulence hypothesis, or temporally constant forcing − *constraints whose validity degrade with time*. Recent retrieval experiments with cold front data gathered by the Doppler-on-Wheels (DOW) research radars (Shapiro et al. 2003) have focused on the role of temporal resolution. Dual-Doppler analyses were used to verify the cross-beam (azimuthal) velocity component obtained from the retrieval algorithm. Fig. 2 shows a dramatic reduction in RMS error of the tangential (cross-beam) wind if the volume scan time decreases from four min (characterizing the fastest operational WSR-88D scan rates) down to one min (the shortest time to cover a volume of 150^{o} in azimuth and about 9^{o} in elevation in that DOW field deployment).

Initialization of cloud and meso-scale numerical prediction models

A further application of frequent 3-D radar data is in the initialization and assimilation of storm and meso-scale numerical weather prediction models. Assimilation of clear air boundary layer data in cases where sea breeze fronts, inland fronts or boundaries from pre-existing convection are present may improve the timing and location of convective initiation, a key problem in the numerical prediction of severe weather. In addition, assimilation of radar data and derived fields when convective weather is present can potentially reduce the pervasive "spin-up" problem in numerical weather prediction, that is, reduce the time for model physics to generate convective elements within nonconvective background fields. A landmark study in this direction involved the simulation of the 20 May 1977 Del City, OK tornadic storm by Lin et al (1993). In that study, initial forecast fields were prepared with dual-Doppler analyzed winds and an associated thermodynamic retrieval. Discrepancies developed between the observed and simulated storm that were attributed to low update rate. More recently, Xue et al. (2006) used simulated thunderstorm data (Del City supercell sounding) and an Ensemble square-root Kalman Filter assimilation procedure to test the impact of volume scan rate and data coverage on the quality of analyses and forecasts. It was found that assimilating volumetric data from a single virtual radar at 1 min intervals provided significantly better analyses and forecasts than assimilations with less frequent updates (2.5 min or 5 min).

Lightning channels

It is known that, at the 10-cm wavelength, the lightning plasma acts as a very good conductor for 10s to 100s of milliseconds (Williams et al. 1989). During this time, continuous current flows through the channel causing strong reflections of electromagnetic waves. But because the channel branches over large volumes, so far it has not been feasible to map its three-dimensional structure in the fields of Doppler spectral moments. With the PAR it should be possible to cover a sector in azimuth and elevation of 8 by 15 deg in about 100 ms. By working backward in time, the precise map of the lightning channel could reveal the location of regions with highest values of electric field where lightning initiates. This could also help determine potential for lightning in developing convection and the influence of electrical fields on the evolution of hydrometeors.

ADVANTAGES OF THE PAR FOR WEATHER OBSERVATIONS

The myriad advantages of the agile beam and wide bandwidth PAR are summarized herein and illustrated in Fig. 3.

Fast adaptive scanning

PAR beam agility permits fast adaptive scanning and signal processing to match the weather situation. Thus the PAR can vary its focus and emphasis over different parts of the scan volume, e.g., dwelling longer on regions of a storm where tornadoes are likely to form, to collect enough samples for spectral analysis (Zrnic and Doviak 1975), while scanning benign sectors faster (Fig. 3). It can also frequently revisit critical regions to track the rapid evolution of severe and hazardous phenomena, including tornadoes. Frequent measurements of meteorological hazards (e.g., tornadoes, mesocyclones, hailstorms) can lead to better warnings and predictions of the trends in these phenomena.

The elevation angle of the beam can be programmed to follow the true horizon, say the blockage pattern of ground objects (i.e., buildings, trees, etc. see Fig. 3). This allows compensation of the spectral moments and polarimetric variables for beam blockage effects (Smith and Doviak 1984). Further, the beam positioned at its lowest elevation angle provides the best estimates of rainfall at the ground. By avoiding known ground clutter, minimum energy is wasted in regions of blocked beam.

Absence of beam smearing

PARs provide high (intrinsic) angular resolution of the beam because there is no smearing due to antenna rotation. This mitigates the effects of ground clutter, and also improves the data quality of spectral moments that in turn leads to better estimates of winds from one or two Doppler radars. The ground clutter spectrum width is determined only by the motions of the scatterers on the ground and therefore is smaller than what a rotating antenna would measure. This permits more effective ground clutter canceling and better compensation of biases (caused by clutter filtering) in the polarimetric variables and spectrum widths of weather signals. Better recovery of overlaid second trip signals is possible because the ground clutter spectrum occupies a smaller portion of the unambiguous velocity interval.

Because beam smearing is not a factor, the spectrum width estimates of weather signals would have one less bias. Typical rotation rates produce a 1.5 times larger effective beam width. If wind shear is constant across the beam and it is the only spectrum broadening mechanism then radar with such rotating antenna would measure 1.5 times larger spectrum width than radar with a stationary antenna (Doviak and Zrnic 1993). In case that turbulence is the only contributor and its outer scale is large compared to the transverse dimension of the beam the increase in measured spectrum width would be $(1.5)^{1/3}$ times (Doviak and Zrnic 1993). Similarly in a polarimetric PAR the correlation coefficient between the copolar and cross-polar signals would be less affected by gradients of differential phase across the beam. For example take again the 1.5 times increase in effective beam width, a 60^{o} change in differential phase over one degree in azimuth (such large gradients have been documented by Ryzhkov 2007), and an intrinsic cross correlation coefficient $\rho_{hv} = 1$ (upper value for drizzle). Under these conditions radar with a stationary beam width of 1^o would measure a ρ_{hv} of 0.95 (Ryzhkov 1007, eq 38) which indicates precipitation other than hail. The same radar with a rotating antenna would measure a ρ_{hv} of 0.89 which is outside precipitation range (except for large hail). Note that the larger bias causes the classification of hydrometeor schemes more confusion and it is also much harder to estimate and eliminate. Moreover, absence of beam smearing reduces the standard errors in estimates of Doppler velocity and polarimetric variables.

Retrieval of transverse winds

It may be possible to measure transverse (to the beam) winds using the spaced antenna approach. In it the antenna is illuminating a volume and reception is made at two or more sub arrays of the antenna. The backscattering volume produces a diffraction pattern that, due to transverse winds, drifts over the sub arrays. Cross correlation of the signals from two sub arrays has a maximum at a time lag inversely proportional to the transverse velocity of the scatterers. The technique has been applied to wind profiling radars and is being suggested for phased array weather radars (Zhang and Doviak 2006). Further, it has potential to separate the transverse wind and shear contribution from the turbulent contribution to the cross correlation function.

Weather surveillance, vertical profiling of horizontal winds, and tracking of objects

Beam multiplexing allows interspersing a wind profiling mode of operation with regular long-range surveillance. For a fraction of a second the beam can illuminate the atmosphere a few km above the radar, then return to surveillance mode for several minutes and alternate between these two modes. Doppler spectra from many of such observations can be combined to obtain winds from altitudes where signals are detectable.

It is also possible, while probing a precipitation event, to interweave a sequence of beam positions so that weather characteristics along the path of objects such as aircraft or balloons can be simultaneously obtained with radar and in-situ instruments. This capability would facilitate comparisons of in situ aircraft observations with radar measurements sorely needed for microphysical and electrification studies.
Moreover, the PAR can track weather balloons and estimate environmental winds (Zrnic et al. 1988) while making observations of weather phenomena.

Improved measurements of rainfall and retrieval of refractivity

An ongoing challenge in radar hydrology is the reduction of temporal sampling errors in accumulated rainfall maps, especially when maps of high spatial resolution are desired, as in urban areas (Fabry et al. 1994; Anagnostou and Krajewski 1999). Rapid scanning can reduce temporal sampling errors in quantitative precipitation estimates, leading to improved runoff estimation, flash flood forecasting, and river-stage forecasts.

Returns of the ground contain information for retrieving the fields of the refractive index (Fabry 2004). The phase change of the returns over time is proportional to the cumulative change in the refractive index, caused mainly by change in humidity, along the beam path. For a mechanically steered antenna it is impractical to repetitively direct the beam at exactly the same locations. Slight offsets from nominal positions occur; hence one resorts to analyzing returns from multiple pulses. In contrast, because the PAR can direct the beam at exactly same location and keep it stationary (Cheong et al. 2007), it suffices to examine returns from a single pulse per beam direction. Thus, errors in humidity retrieval are reduced with concomitant savings in data storage and computations.

Reduced maintenance and improved availability

Whereas the WSR-88D consistently achieves a superb service availability of 99.5%, two significant points of failure in traditional radar systems are the transmitter and the mechanism for pointing the antenna. The WSR-88D Radar Data Acquisition system (transmitter, receiver, signal processor, and antenna system) accounts for the majority of radar outages (for the RDA mean time between failures (MTBF) is 1275 hours and mean time to repair is 6.7 hours). In the PAR, transmitter modules are numerous and integrated within the active phase array transmit/receive (T/R) elements. The "usable" MTBF of individual devices is generally 10^6 hours. In case of failure of some T/R modules there is gradual degradation of performance compared to the total loss that occurs if the standard transmitter breaks down. The MTBF of individual devices gets statistically averaged across the many independently operating radiators in the phased array, for which typically 10% can randomly fail before any significant degradation is experienced in the radar performance. Electronic pointing of the antenna eliminates the electromechanical pointing system; thus there is no downtime due to failures in gears, motors, and servo systems.

NATIONAL WEATHER RADAR TESTBED

To test the expected advantages, asses the utility, explore the uses of phased array technology, and to lay a foundation for application of weather radar beyond the current WSR-88D, a National Weather Radar Testbed (NWRT) was established in Norman, OK

(Forsyth et al. 2005). This NWRT was developed by a government/university/industry team consisting of the National Oceanic and Atmospheric Administration's National Severe Storms Laboratory (NSSL), the Tri-Agencies' (Department of Commerce, Defense & Transportation) Radar Operations Center (ROC), the United States Navy's Office of Naval Research, Lockheed Martin Corporation, the University of Oklahoma's Electrical and Computer Engineering Department and School of Meteorology, the Oklahoma State Regents for Higher Education, the Federal Aviation Administration's William J. Hughes Technical Center and Basic Commerce and Industries, Inc..

The NWRT uses a converted Navy SPY-1A phased array antenna, a modified WSR-88D transmitter and a custom designed controller/processor system. The antenna is comprised of 4,352 elements that steer the beam normally up to $\pm 45^o$ in azimuth from the array axis. The antenna is tilted 10 degrees in elevation allowing for zenith scans, although with a wider beamwidth (at zenith the beamwidth is 8.6^o) and the center of the array is located 40 feet above ground level. The antenna is mounted on a pedestal capable of rotating the antenna at 18^o s^{-1}. A 90^o sector can be scanned in azimuth without moving the pedestal. Elevation scans are accomplished using electronic scanning. Other pertinent characteristics of the NWRT are

a) Transmitting antenna diameter: $\approx$ 3.66 m ($\approx$ circular aperture),

b) Wavelength: $\lambda = 0.0938$ m,

c) Transmitting beamwidth: $\approx 1.5^o$, (2.1^o at 45^o from beam center and no taper of power is applied across the array on transmission),

d) Receiving beam width: $\approx 1.66^o$, (larger than beam width on transmission due to a taper for reducing side lobes),

e) Transmitter power and pulse width: ≈ 750 kW peak and 1.57 μs or 4.71 μs.

f) Sensitivity: reflectivity of 5.9 dBZ at 50 km produces a SNR=0 dB.

This PAR supports oversampling in range by a factor of 10 (i.e, samples in range can be spaced at intervals equal one tenth of the pulse length), it can record time series data, and is controlled remotely.

Next we present examples of the unique weather-observing capability of the instrument.

Beam multiplexing

The agile beam phased array system can maximize efficient use of radar resources by employing a visionary scheme proposed by Smith et al. (1974). First, the PAR transmits two consecutive pulses in the same direction so that an estimate of autocorrelation and power can be obtained. Then, while the scatterers in the resolution volumes are reshuffling into an independent configuration, the PAR can switch its beam to another direction. From there a second pair of samples is obtained to estimate spectral moments; then the beam continues to other directions and returns to the original direction after the signal is no longer correlated (many ms later).

An experiment was conducted to demonstrate and verify beam multiplexing (BMX) on 2 May 2005. A 28^{o} sector in azimuth was scanned using two scanning strategies. First is the BMX with two 14^{o} contiguous sectors. In each sector, the PAR is beam multiplexed over beam positions as demonstrated in Fig. 5 until 32 pairs of returns are accumulated from each beam position (and from each range locations). Because the PRT is 1 ms the acquisition time in this BMX mode is 1.792 s. The other scanning strategy is a step scan, which was devised to probe the same 28^{o} sector with 28 discrete beam positions; data from 64 pulses were collected before steering the beam to the next azimuth location one degree apart. Therefore, the scan is similar to the conventional scan with a mechanically rotating antenna; except no spectral broadening produced by antenna motion (Doviak and Zrnic 1993) occurs. To make a comparison, data acquisition time of BMX is set to be same as the time of step scan. Apparent in Fig. 6 are the much smoother features in the velocity and reflectivity fields obtained with BMX; the pulse pairs (averaged in this mode) are uncorrelated with each other whereas in the step scan mode correlation between pairs is high. Quantitative evaluation of these data (Yu et al. 2006) reveals that at SNR > 10 dB reduction of variance is between a factor of 2 and 4. Therefore, a proportionate increase in the speed of volume coverage is possible with the BMX technique.

Tornadic storm

On 29 May 2004 at 20:48 CDT, a tornadic storm developing close to the NWRT provided a good opportunity for collecting data. The reflectivity field exhibited a classical hook echo and the Doppler velocity field contained well defined couplets toward and away from the radar. In Fig. 7 a sequence of images obtained by the NWRT is contrasted with two consecutive images obtained with the nearby WSR-88D. Circled are three couplets of strong shear in azimuth. At the beginning of the sequence (top in Fig. 7) the middle couplet is clearly a tornadic vortex signature (TVS), the northern one is marginally strong, whereas the southern one is a weak anticyclonic shear. On the rapidly updated data of the NWRT it is evident that the anticyclonic shear intensifies into a TVS; furthermore during these four minutes the northern shear weakens and almost dissipates. These rapid evolutionary changes are missed in scans spaced by 4 min as seen on the display of the WSR-88D data (Fig.7). The storm was subsequently tracked as it produced several tornadoes during its lifetime.

Severe hail storm

On 15 Aug 2006, a hail storm rapidly developed close to the PAR. Volume scans over a 90^{o} azimuth sector and over 42 elevation angles were collected every 28 s. A three body scattering signature (Zrnic 1987) was evident for almost 14 min indicating large hail. This signature is caused by forward scattering from a hail shaft to the ground, backscattering from the ground to the hail shaft and then forward scattering from the hail shaft to the radar. Vertical cross sections displayed in the range height indicator (RHI) format (Fig. 8) demonstrate the rapid change of storm structure aloft (Heinselman et al. 2006). The time between images is slightly less than 2 min, i.e., fields are from every fourth volume scan. Significant evolution of the storm is evident. The three body scattering signature quickly descends to the ground in concert with the rapid collapse of the core. Remarkable is the ~75 dBZ peak reflectivity factor in the core (fourth and fifth image in the sequence). Furthermore, the area of reflectivity larger than 65 dBZ (in the RHI, not shown) more than triples in 26 s. Note that with conventional scanning at about 4 to 5 min interval about every second or third image in Fig. 8 would be obtained. Such sparse density could impede timely warnings.

PLANS

The immediate and potential benefits of phased array radar technology are numerous. Still there are challenges to overcome if this technology is to realize its widest possible operational applications. Urgent studies to address pertinent PAR issues are discussed next.

With beam agility and adaptive scans, the current NWRT could achieve a five-fold increase in the speed of volume coverage. Nonetheless, to reach a ten-fold increase, advanced signal designs and processing are required. Oversampling and whitening of signals in range is a candidate for increasing the speed of volume coverage and reducing the errors of estimates (Torres and Zrnic 2003). This technique is effective at large signal to noise ratios and it will be explored. Dual frequency transmission and/or pulse compression can increase the speed of volume coverage without sacrificing signal to noise ratio. Thus, upgrades in the processing area would be the addition of a second channel and a pulse compression (Mudukutore et al. 1998, Bucci et al. 1997) scheme.

Modifications on the system are being made to enable wind measurements transverse to the beam. The technique to be evaluated is space antenna interferometry (Zhang and Doviak 2006), that requires access to the signals from the left and right side of the antenna aperture.

Ground clutter mitigation in the beam multiplex or any other mode with few sample returns needs much study as classical filter solutions are inadequate. On the NWRT, there are six receiving elements meant to suppress clutter from side lobes. The suppression principle is as follows (Le et al. 2007). Received returns in the six elements are weighted in amplitude and phase and then subtracted from the total return. With six clutter suppressing elements the weights can be adjusted to cancel clutter from six independent directions. The technique effectively removes clutter coming through side lobes but is not suited for eliminating main lobe clutter. Its capability for enhancing weather observations will be evaluated.

High priority will be given to the development of a dual polarization agile beam phased array antenna. This will start with a sub-array antenna of modest dimensions to test the concept, investigate polarimetric issues (e.g., how far off axis can the beam point without significant degradation of polarimetric measurements), and establish an economically viable solution.

Scanning strategies that adaptively adjust beam direction to the location of weather phenomena need to be developed. These will likely include periodic surveillance followed by several high resolution scans whereby regions detected by the surveillance scan would be interrogated in more detail.

Display, algorithm, and decision aid development are essential for handling the improved temporal resolution data. We anticipate much study in this area.

Close communication and interaction with experts on data assimilation and numerical models is paramount for extracting the most from this new technology. This will be an ongoing evolutionary process and will continue along the well established paths by these communities.

Multi-mission applications of the system for wind profiling, quantifying turbulence, aircraft tracking, and plume profiling (i.e., measurements of smoke plumes, volcanic ash clouds, chaff, or some other passive tracer released purposely or inadvertently into the atmosphere) will be explored. The FAA evaluated the aircraft tracking capability on the NWRT, but to fully test the multi-mission concept, a prototype must be built (Weber et al. 2007). Detection of wake vortices at takeoff or landing is another task well matched to the phased array technology that will be subject of further studies.

CONCLUSIONS

There have been many significant improvements in weather surveillance and air traffic control since radar systems were first deployed for these applications. As valuable, and even essential, as these applications have become, they are now poised for order-of-magnitude improvement in performance. The enabling technology is the agile beam PAR.

Benefits of the new PAR technology are many, and are key to providing the improvements sought by the National Weather Service for service to the nation in the 21st Century. As stated in the NOAA 2005-2011 Strategic Plan, the NOAA "Weather and Water Mission Goal" is focused on: reducing loss of life, injury, and damage to the economy; and providing better, quicker and more valuable weather and water information to support improved decisions. Some of these goals will, in part, be achieved through evolutionary improvements of the existing WSR-88D network.

There are at least two desirable features that cannot be achieved with the improved WSR-88D technology: 1) update of volume scans at intervals of one minute or less, and 2) multi-mission use to sample weather, control air traffic, and track non cooperative airplanes. The agile beam phased array technology can satisfy these two demands. Further, it can adaptively provide high resolution scans to scrutinize and anticipate small-scale dangerous phenomena, such as intense vortices or wind shears. Thus, agile adaptive scan could improve lead times of warnings. It would also provide valuable data to storm scale models perhaps enabling warnings to be issued based on forecasts in addition to those based on extrapolation of observations. Improved data quality offered by absence of beam smearing is another definitive advantage. The largest economic benefit would ensue if PAR serves multi-missions.

To explore and develop weather related applications of the PAR a National Weather Radar Testbed (NWRT) has been established in Norman, OK. The current NWRT has neither the beamwidth nor the dual polarization capability of the WSR-88D. These features are under investigation. Meanwhile the NWRT's main purpose is to address the advanced capabilities anticipated in the next decade so that these could be projected to a possible network of future PARs. Investigators from universities and government laboratories will have access to all data collected by the PAR. Moreover, the NWRT is open to experimentalists for scientific and/or educational projects. To judge the merit of proposed research, help equitably assign resources, and allocate the facility, an advisory panel of experts has been formed. Investigators wishing access to the NWRT should contact Doug Forsyth (E-mail douglas.forsyth@noaa.gov) at the National Severe Storms Laboratory.

ACKNOWLEDGEMENTS : We acknowledge the support of our various organizations in funding and helping to implement the National Weather Radar Testbed (Phased Array). The dedicated work of Bob Staples, Mark Benner, Chris Curtis, and Wayne Sabin, Jim Melody, Paul Bumgarder, Tim Hughes, and others from Lockheed Martin Corporation improved the data quality. Mike Schmidt, Richard Wahkinney, John Carter, and the Radar Operations Center's radar engineers lead by W. Urell and B. Ballard worked on adapting an existing WSR-88D transmitter for the NWRT. Allen

Zahrai, Rick Adams, David Preignitz, John Thompson, and Dan Suppes, maintained and evolved the system, while Kurt Hondl integrated the WDSS-II. Mark Campbell (Lockheed Martin Corporation) along with Bob Blasewitz and Tim Mease (Basic Commerce Industries), provided continuing support of the NWRT, and Pam Heinselman made valuable suggestions that made the paper better and provided analysis and elements for constructing Fig. 7. Three anonymous reviewers each provided focused comments that have improved this paper.

References

Anagnostou, E. N., and W. F. Krajewski, 1999: Real-time radar rainfall estimation. Part I: Algorithm formulation. *J. Atmos. and Oceanic Technol*., **16,** 189-197.

Battan, L. J., 1980: Observations of two Colorado thunderstorms by means of a zenith-pointing Doppler radar. *J. Appl. Meteor*., **19**, 580-592.

Brotzge, J., K.K. Droegemeier, and D.J. McLaughlin, 2006: Collaborative Adaptive Sensing of the Atmosphere (CASA): New radar system for improving analysis and forecasting of surface weather conditions. *J.Transport. Res. Board*, No. 1948, 145-151.

Brown, R. A., L. R. Lemon, and D. W. Burgess. 1978: Tornado Detection By Pulsed Doppler Radar. *Mon.Wea. Rev*.**, 106**, 29 - 38.

Bucci, J. N., H. S. Owen, K.A. Woodward, and C.M. Hawes, 1997: Validation of pulse compression techniques for meteorological functions. *IEEE Tr. Geosc. and Remote Sensing*, **35,** 507-523.

Carbone, R.E., B. Foote, M. Moncrieff, T. Gal-Chen, W. Cotton, M. Hjelmfelt, F. Roux, G. Heymsfield, and E. Brandes., 1990: Convective dynamics: Panel Report. Chapter 24b of Radar in Meteorology, (Ed. David Atlas). American Meteorological Society, 391-400.

Carbone R.E. and M.J. Carpenter, 1983: Rapid scan Doppler radar development considerations part I: Sampling requirements in convective storms. Preprints 21st Conference on Radar meteorology, AMS, Boston MA, 278-283.

Carbone, R.E., M.J. Carpenter, and C.D. Burghart, 1985: Doppler radar sampling limitations in convective storms. *J. Atmos. Oceanic Technol*., **2,** 357-361.

Cheong, B.L., R. D. Palmer, C. D. Curtis, T.-Y. Yu, D. S. Zrnic, D. Forsyth, 2007: Refractivity Retrieval Using the National Weather Radar Testbed: First Results and Potential for Multi-Function Observations. Submitted to *J. Atmos. and Oceanic Technol.*,

Crook, A., 1994: Numerical simulations initialized with radar-derived winds. Part I: Simulated data experiments. *Mon. Wea. Rev.,* **122**, 1189-1203.

Crum, T.D., R. E. Saffle, and J. W. Wilson, 1998: An Update on the NEXRAD Program and Future WSR-88D Support to Operations. *Weather and Forecasting*. **13,** 253–262

Doviak, R.J. and D.S. Zrnic, 1993: Doppler radar and weather observations. Dover Pub, Mineola NY p 562.

Fabry, F., A. Bellon, M. R. Duncan, and G. L. Austin, 1994: High resolution rainfall measurements by radar for very small basins: the sampling problem reexamined. *J.Hydrol.*,**161,** 415-428.

Fabry, F., 2004: Meteorological value of ground target measurements by radar. *J. Atmos. Oceanic Technol.,* **21,** 560–573.

Forsyth, D.E, J.F. Kimpel, D. S. Zrnic, R. Ferek, J.F. Heimmer, T. McNellis, J. E. Crain, A. M. Shapiro, R. J. Vogt, and W. Benner, 2006: The National Weather Radar Testbed (Phased Array). Preprints, 32nd Conference on Radar Meteorology, Albuquerque, NM, Amer. Meteor. Soc., CD-Rom, 12R.3.

Gal-Chen, T., 1978: A method for the initialization of the anelastic equations: Implications for matching models with observations. *Mon. Wea. Rev.,* **106,** 587-606.

Hane, C. E., and B.C. Scott, 1978: Temperature and pressure perturbations within convective clouds derived from detailed air motion information: Preliminary testing. *Mon. Wea. Rev*., **106,** 654-661.

Heinselman, P., D. Priegnitz, K. Manross, and R. Adams, 2006: Comparison of storm evolution characteristics: The NWRT and WSR-88D. Preprints, /23rd Conference on Severe Local Storms, St. Louis, MO, Amer. Meteor. Soc., CD-ROM, 14.1.

Interdepartmental Committee for Meteorological Services and Supporting Research, Committee for Cooperative Research (CCR) Joint Action Group for Phased Array Radar Project (JAG/PAR), 2006: Federal Resdearch and Development Needs and Priorities for Phased Array Radar. FMC-R25-2006, p 62.

Katz S.L. and J.D. Nespor, 1993: Advantages of agile beam radar for meteorological functions for hazardous weather detection. Preprints 26th International Conference on Radar meteorology, Norman, OK, AMS, Boston MA, 396-398.

Knight, C.A., and P. Squires, Eds., 1982: *Hailstorms of the Central High Plains. The National Hail Research Experiment*, Vol. 1. National Center for Atmospheric Research in Association with Colorado Associated University Press, 282 pp.

Laroche, S. and I. Zawadzki, 1995: Retrievals of horizontal winds from single-Doppler clear air data by methods of cross-correlation and variational analysis. *J. Atmos. Oceanic Technol*., **12**, 721-738.

Le, K.D., R.D. Palmer, T.Y. You, G. Zhang, S.M. Torres, and B.L. Cheong, 2007: Adaptive array processing for multi-mission phased array radar. *33rd Radar Meteorology Conference*, AMS, Cairns, Australia.

Lee R.R. and A. White, 1998: Improvement of the WSR-88D mesocyclone algorithm. *Weather and Forecasting*, **13,** 341-351.

Michelson, M., W.W. Shrader, and J.G. Wieler, 1990: Terminal Doppler Weather Radar. *Microwave Jour.* February, 139-148.

Mitchell, E.D., S.V. Vasiloff, G.J. Stumpf, A. Witt, M.D. Eilts, J.T. Johnson, and K.W. Thomas, 1998: The National Severe Storms Laboratory tornado detection algorithm. *Weather and Forecasting*, **13,** 352-366.

Mudukutore, A.S., V. Chandrasekar, and R.J. Keeler, 1998: Pulse compression for weather radars. *IEEE Tr. Geosc. and Remote Sensing*, **36,** 125-142.

National Academies, 2002: Weather Radar Technology Beyond NEXRAD. Report prepared by the National Research Council, National Academy of Science, National Academy Press.

NOAA, 2005: *New Priorities for the 21st Century – NOAA's Strategic plan, updated for FY 2006 – 2011*. Report available on NOAA's WEB site www.spo.noaa.gov, pp 22.

Qiu, C.J., and Q. Xu, 1996: Least square retrieval of microburst winds from single-Doppler radar data. *Month. Weath. Rev*. **124,** 1132-1144.

Rasmussen, E.N., S. Richardson, J. M. Straka, P. M. Markowski, and D. O. Blanchard, 2000: The Association of Significant Tornadoes with a Baroclinic Boundary on 2 June 1995. *Mon. Wea. Rev.,* **128**, 174–191.

Ryzhkov, A.V., 2007: The impact of beam broadening on the quality of radar polarimetric data. *J. Atmos. and Oceanic Technol*., **24,** 729-744.

Shapiro, A., P. Robinson, J. Wurman, and J. Gao, 2003: Single-Doppler velocity retrieval with rapid scan radar data. *J. Atmos. and Oceanic Technol*., **20,** 1758-1775.

Shapiro, A., S. Ellis, and J. Shaw, 1995: Single-Doppler velocity retrievals with Phoenix II data: clear air and microburst wind retrievals in the planetary boundary layer. *J. Atmos. Sci.,* **52**, 1265-1287.

Smith, P.L., K.R. Hardy and K.M. Glover, 1974: Applications of radar to meteorological operations and research. *Proceedings IEEE*, **62,** 724-745.

Smith, S., and R.J. Doviak, 1984: Doppler velocity bias due to beam blockage by ground targets. *Preprints 22nd Conference on Radar Meteorology*, Zurich, SW, AMS, Boston MA 534-537.

Stumpf, G.J., A. Witt, E.D. Mitchell, P. L. Spencer, J.T. Johnson, M.D. Eilts, K.W. Thomas, and D.W. Burgess, 1998: The National Severe Storms Laboratory mesocyclone detection algorithm. *Weather and Forecasting*, **13**, 304-326.

Sun, J., and N.A. Crook, 1994: Wind and thermodynamic retrieval from single-Doppler measurements of a gust front observed during Phoenix II. *Mon. Wea. Rev.,* **122**, 1075-1091.

Terminal Area Surveillance System, 1997: Document archive, CD-ROM, available form the Federal Aviation Administration.

Torres, S. M., and D. S. Zrnic, 2003: Whitening in range to improve weather radar spectral moment estimates. Part I: Formulation and simulation. *J. Atmos. Oceanic Technol*. **20,** 1443-1448.

Weber, M., J.Y.N. Cho, J.S. Flavin, J. M. Herd, W. Benner, and G. Torok, 2007: The next generation multi-mission U.S. surveillance radar network. This issue page XXXX.

Weber, M., and M. L. Stone, 1995: Low altitude wind shear detection using airport surveillance radars. *IEEE Aerosp. Electron. Syst. Mag*. **10,** 3-9.

Williams E.R., S.G. Geotis, and A.B. Bhattacharya, 1989: A radar study of the plasma and geometry of lightning. *J. Atmos. Sci*., **46,** 1173-1185.

Wolfson, M., C.A. Meuse, 1993: Quantifying airport terminal area weather surveillance requirements. Preprints, 26th International Conf. On Radar Meteorology, Norman OK, AMS Boston MA, 47-49.

Xu, Q., C.J. Qiu, and J.-X. Yu, 1994a: Adjoint-method retrievals of low-altitude wind fields from single-Doppler reflectivity measured during Phoenix-II. *J. Atmos. Oceanic Technol*., **11**, 275-288.

Xu, Q., C.J. Qiu, and J.-X. Yu, 1994b: Adjoint-method retrievals of low-altitude wind fields from single-Doppler wind data. *J. Atmos. Oceanic Technol*., **11,** 579-585.

Xue, M., M. Tong, and K. K. Droegemeier, 2006: An OSSE framework based on the ensemble square root Kalman Filter for evaluating the impact of data from radar networks on thunderstorm analysis and forecasting. *J. Atmos. Oceanic Technol*., **23,** 46-66.

Yu, T.Y., Orescanin, M.B, Christopher D. Curtis, C.D., Zrnic, D.S., and Forsyth, D.E., 2006: Beam Multiplexing Using the Phased Array Weather Radar. *J. Atmos. Oceanic Technol*., **24,** 616–626 **.**

Zhang, G. and R.J. Doviak, 2006: Weather radar interferometry to measure crossbeam wind, shear and turbulence: theory and formulation. Accepted by

Zrnic, D.S. and R.J. Doviak, 1975: Velocity spectra of vortices scanned with a pulsed-Doppler radar. *J. Appl. Meteor*. 14, 1531-1539.

Zrnic, D.S., 1987: Three-body scattering produces precipitation signatures of special diagnostic value. *Radio Sci.,* **22**, 76-86.

Zrnic, D.S., D. Sirmans, and E. Kessler, 1988: Determination of winds from balloon tracking with a Doppler weather radar. *J. Atmos. Oceanic Technol*., **5,** 442-449.

Zrnic, D.S. and A. V. Ryzhkov, 1999: Polarimetry for weather surveillance radars. *Bull. Amer. Meteor. Soc.*, **80**, 389-406.

Zrnic, D.S., A.V. Ryzhkov, J.M. Straka, Y. Liu, and J. Vivekanandan 2001: Testing a procedure for automatic classification of hydrometeor types*. J. Atmos. Oceanic Technol*., **18**, 892-913.

Figure captions

Fig.1. Basic differences between the conventional radar with a mechanically rotating antenna (left) and the agile beam PAR (right).

Fig. 2. RMS error of transverse wind as a function of time between scans Δt for a cold front data set (from Shapiro et al. 2003). Results at lowest elevation angle (1°) are indicated by solid line; dashed line indicates average over all elevation angles (1°–8.7°).

Fig. 3. Capabilities of agile beam phased array radar are shown in a panoramic view. Illustrated are a) surveillance scan through the planetary boundary layer (extending to 2 km) for mapping winds, b) surveillance scan through a cumulus “Cu” cloud, c) surveillance scan through a supercell storm, d) high resolution scan with a longer dwell time through the region in the supercell where the potential for tornado development exists, e) scan that grazes the mountain contour for “surgical-precision” avoidance of ground clutter, f) determination of propagation condition, i.e., cumulative humidity along

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Fig. 4. The NWRT: Installation of the radome over the single aperture of the AN/SPY-1A radar antenna.

Fig. 5. Schematic of beam multiplexing. Pair of pulses are transmitted sequentially at fixed angular directions a_1, a_2, ..a_{14}. Powers and autocorrelations at lag one are computed for each direction; the sequence is repeated several times; cumulative sum of intermediate values of powers and autocorrelation is obtained; after the last sequence the cumulative sums are transformed into estimates of powers and velocities (from Yu et al. 2006).

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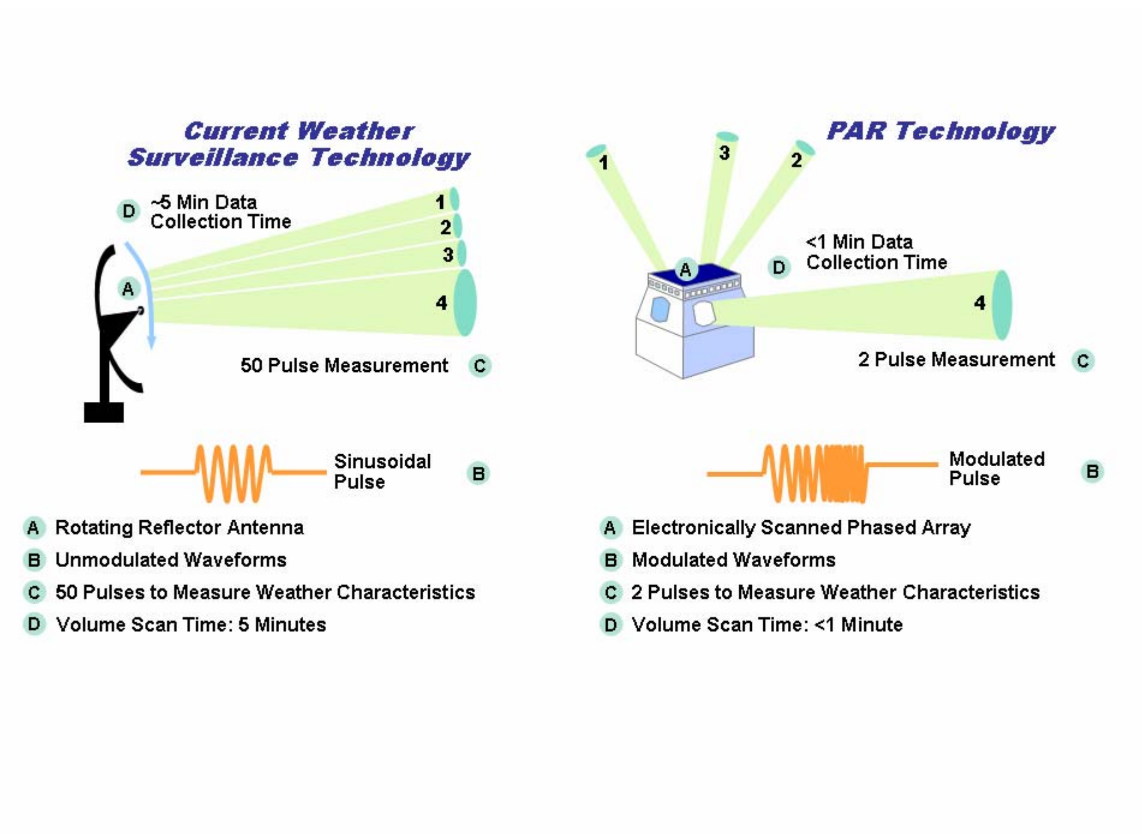

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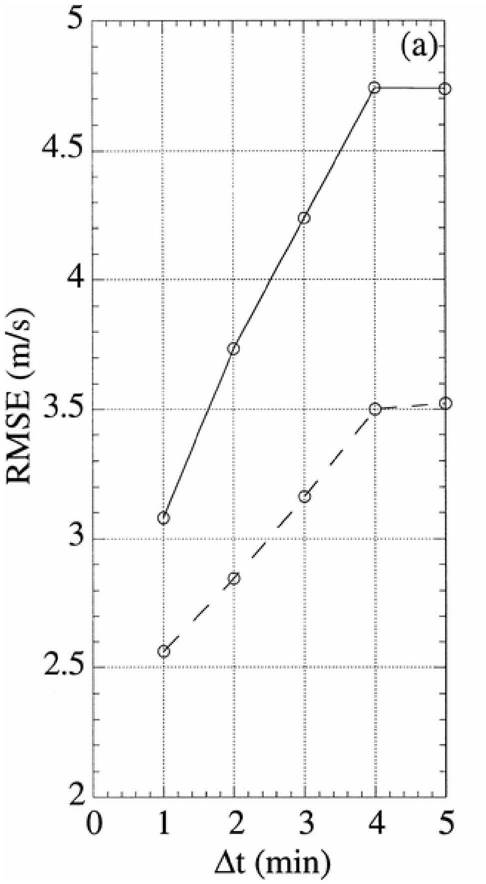

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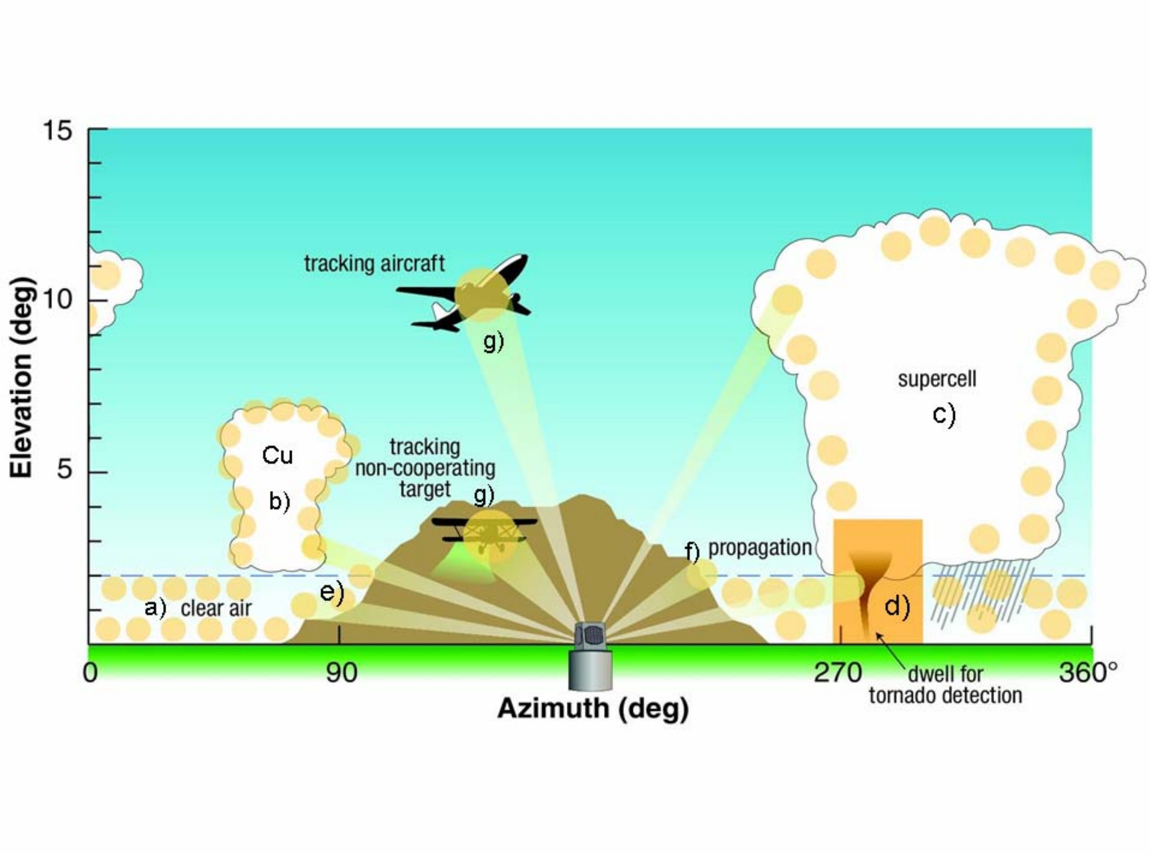

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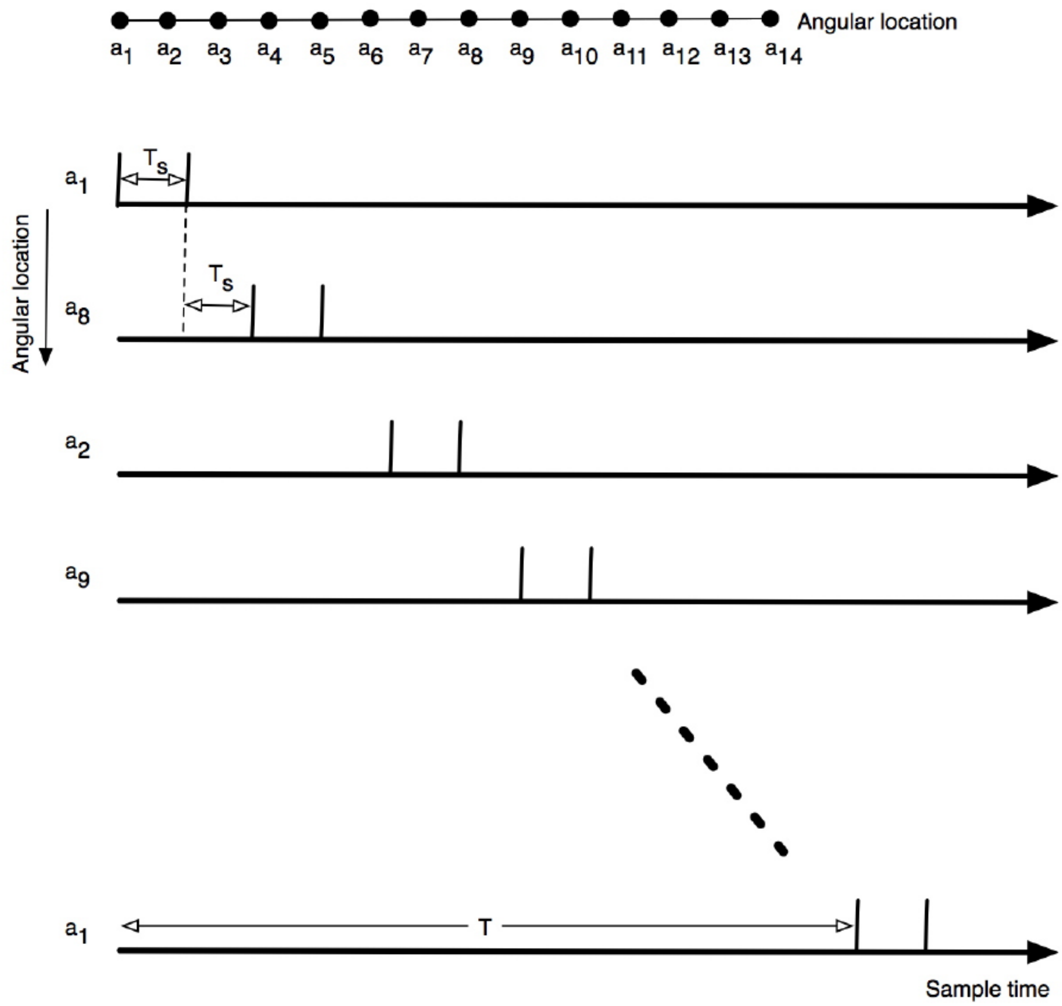

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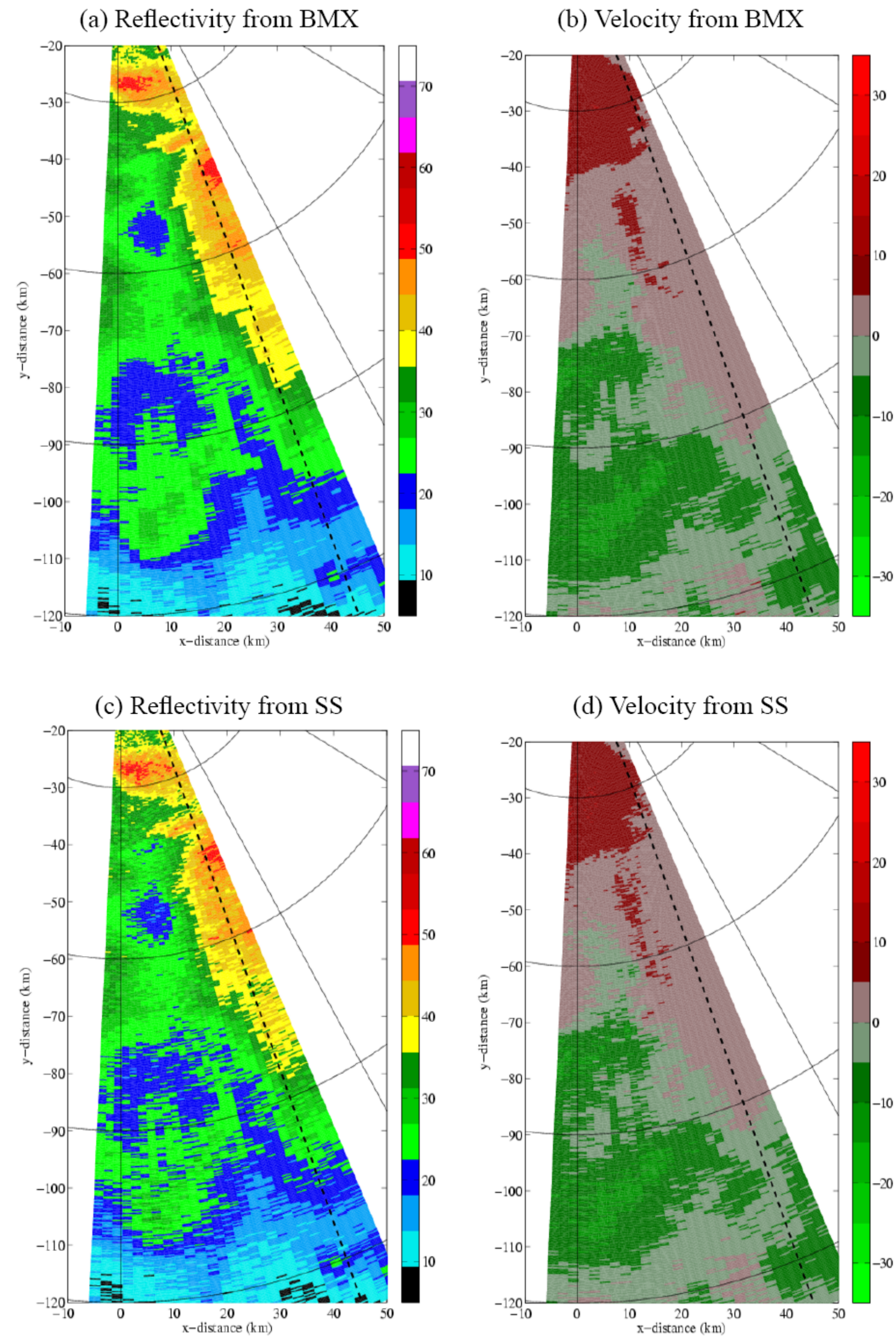

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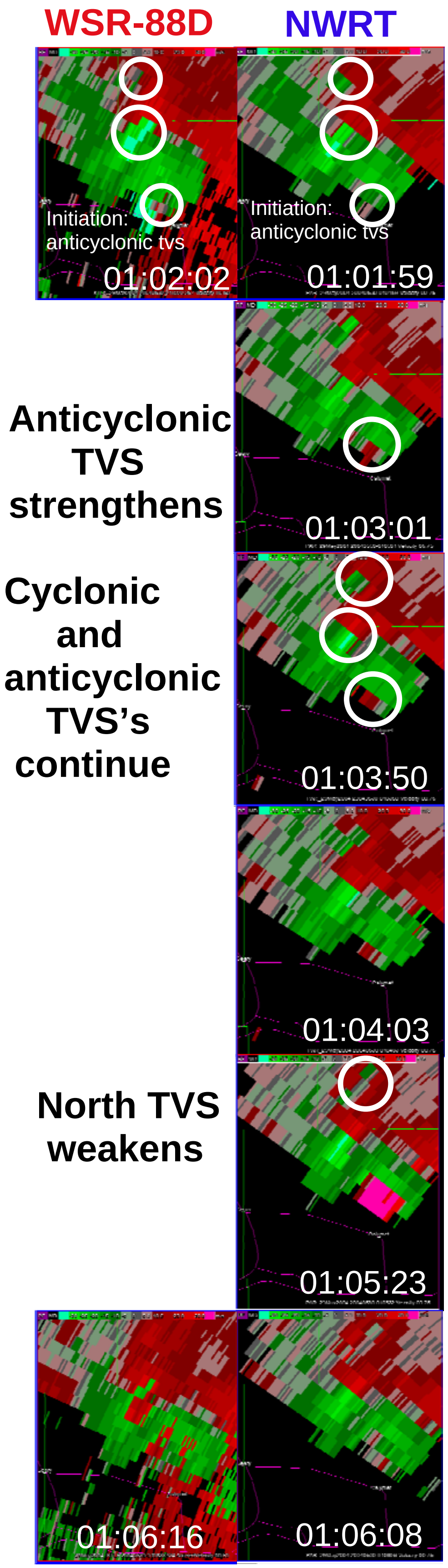

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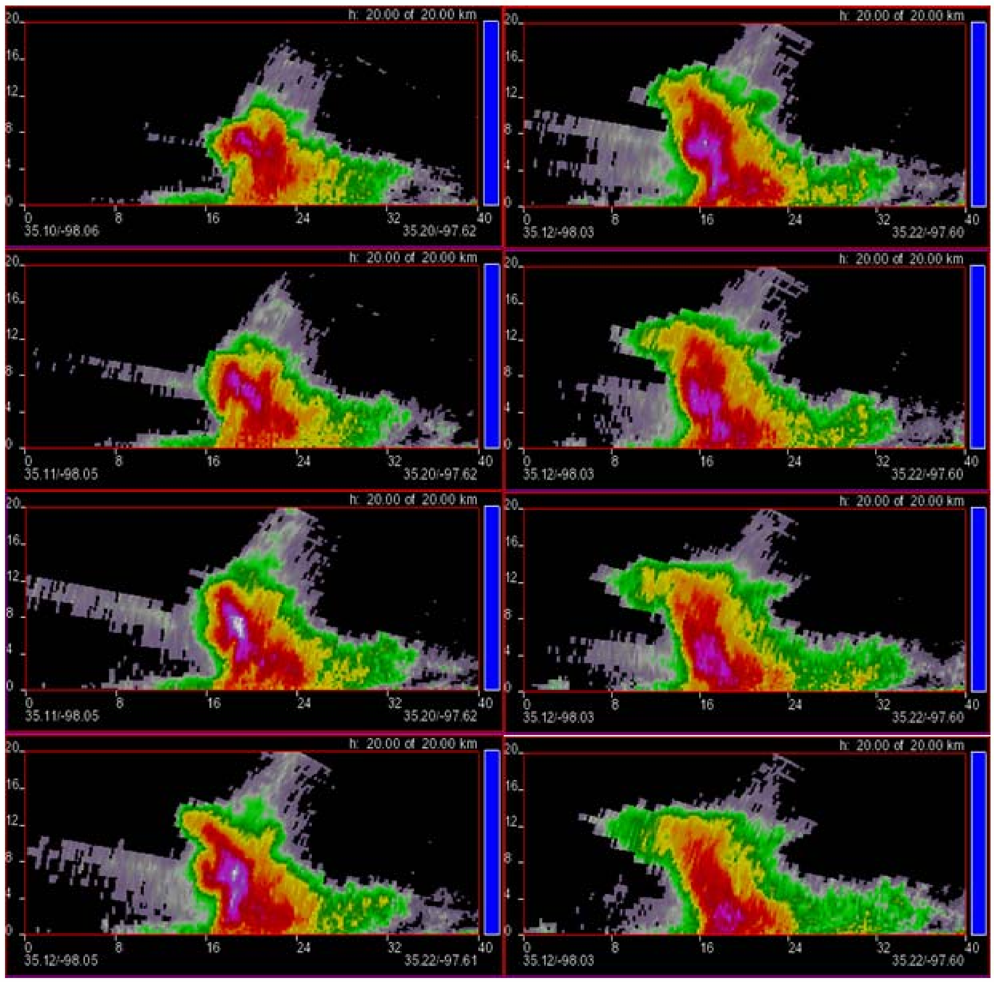

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