A Brief Overview of Weather Radar Technologies and Instrumentation

Mark Yeary, Boon L. Cheong, James M. Kurdzo, Tian-You Yu, and Robert Palmer

Weather radar technologies and instrumentation play a vital role in early warning of severe weather. For example, the annual impacts of adverse weather on the U.S. national highway system and roads are staggering: 7,400 weather–related deaths and 1.5 million weather–related crashes [1]. In addition, US$4.2 billion is lost each year as a result of air traffic delays attributed to weather. Research on high-impact weather is broadly motivated by society's need to improve the prediction of these weather events. The research approaches to accomplish this goal vary significantly with the inherent predictability of the weather system. For example, the current forecast approaches for issuing warnings of short-lived events, such as tornadoes and flash floods, are primarily based on observations with a focus on advanced Doppler radar measurements.

Research is currently often focused on engineering to develop new radar systems, research to better understand these storm systems to develop new meteorological and hydrological uses of radar measurements for prediction, and on the incorporation of radar measurements into atmospheric and hydrological prediction models through a highly mathematical process known as data assimilation. New research frontiers include moving prediction increasingly toward kilometer-scale atmospheric modeling and radar-based warn-on-forecast as opposed to warn-on-observation systems.

Weather radar, owing to operational wavelengths of approximately 3 cm to 10 cm (i.e., approximately 10 GHz to 3 GHz) is ideal for penetrating regions of precipitation while providing meaningful returns for weather phenomenon characterization. Three levels of technology, as listed below, provide a trifecta of a strong foundation through a vibrant future. Technologies that have already *emerged* are dual-polarization, multiple wavelengths, phased array radar (military, single polarization), and gap filling radars (non-adaptive).

Emerging technologies are enabling technology: solid-state pulse compression, polarimetric phased array radar, and imaging radar or *ubiquitous radar*. In the future, we expect *Digital-at-every-element* phased array radar, passive radar, cognitive radar, multi-mission networks, ultra low-cost dense networks, and spectrum sharing. Next, we look at several hardware and signal processing technology examples related to these lists.

Hardware and Signal Processing Technologies

Severe and hazardous weather such as thunderstorms, downbursts, and tornadoes can take lives in a matter of minutes. To improve detection and forecast of such phenomena using radar, one of the key factors is fast scan capability. Conventional weather radars, such as the pervasive Next Generation Radar (NEXRAD) developed in the 1980s, are severely limited by mechanical scanning with their large rotating dish. Approximately 168 of these radars are in a national network to provide the bulk of the United States' weather information. In 2009, a program was initiated to field test the feasibility of upgrading these radars with dual–polarization capability for hydrometeor classification and improved quantitative precipitation estimation. All of the NEXRADs were upgraded to dual polarization by 2013.

Under the development for weather applications, the electronically steerable beams provided by the phased array radar at the National Weather Radar Testbed (NWRT) in Norman, Oklahoma can overcome the limitations of the current NEXRAD radar [2], [3] (Fig. 1). For this reason, the phased array radar was listed by the National Research Council as a candidate technology to supersede NEXRAD. By definition, a phased array radar is one that relies on a two-dimensional array of small antennas. The apparent phase of each antenna is controllable, thus allowing the overall system to instantaneously and dynamically steer to interesting regions of weather. The National Weather Radar Testbed is the nation's first facility dedicated to phased array radar meteorology [2].

The phased array radar at the NWRT is approximately 12 ft (3.7 m) in diameter, has a peak transmitter power of 750 kW, and operates at 3.2 GHz. This radar is a spare from the U.S. Navy. When the phased array radar at the NWRT first became operational in 2004, only its sum beam was instrumented for comparison to a nearby NEXRAD. However, eight

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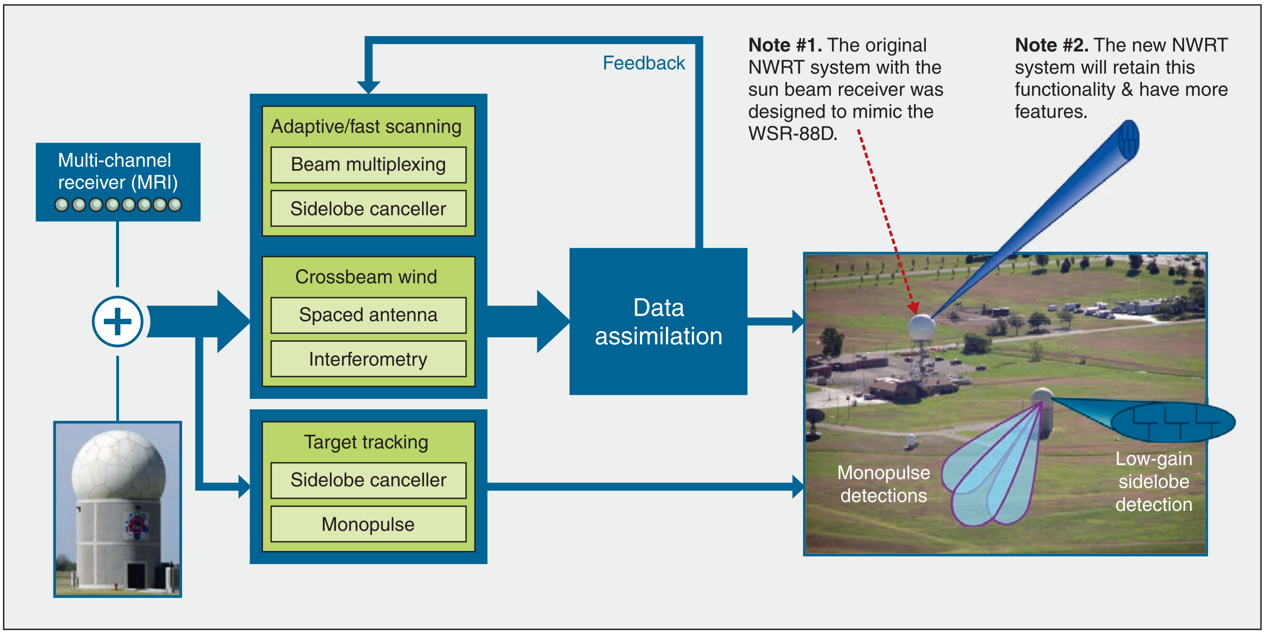

Note #1. The original NWRT system with the sun beam receiver was designed to mimic the WSR-88D.

Note #2. The new NWRT system will retain this functionality & have more features.

Fig. 1. The National Weather Radar Testbed and the multi-channel receiver yields a system that supports multi-mission capabilities. (© IEEE, M. Yeary, used with permission, [3]).

other available channels were available for instrumentation. These were: six sidelobe cancellation channels, a differential azimuth channel, and a differential elevation channel. These additional channels were later instrumented with a suite of RF down-converters and digital receiver assemblies [3]. The sidelobe cancelling channels are receive-only auxiliary channels that are separate from the main array. Six of these channels are located around the periphery of the array. These channels have been designed to have low gain and wide beam width to detect unwanted signals, e.g., clutter, interference, and non-friendly jammers. With the recent deployment of an eight-channel multi-channel receiver on the NWRT, the sum channel and sidelobe channel data can be recorded and processed to research different techniques for addressing the clutter contamination problem. The multi-channel receiver project is a collaboration between the Oklahoma University Advanced Radar Research Center (ARRC) and the National Severe Storms Laboratory.

Waveform Design for Emerging Radar Technologies

Pulse compression and other advanced waveform techniques have been used in military radar systems for decades but have been scarcely used in the weather radar community due to the distributed nature of hydrometeor targets. As defined by the IEEE 686-2008, Standard Radar Definitions [4], pulse compression is:

> *… a method for obtaining the resolution of a short pulse with the energy of a long pulse of width T by internally modulating the phase or frequency of a long pulse so as to increase its bandwidth B >> 1/T, and using a matched filter (also called a pulse compression filter) on reception to compress the pulse of width T to a width of approximately 1/B.*

Recently, however, pulse compression has begun to be exploited for use in weather radar systems. Higher resolution, both spatially and temporally, is a largely desired attribute in future weather radar platforms. By utilizing higher bandwidth, range resolutions up to an order of magnitude higher than the NEXRAD are possible. Spatial resolution on the order of tens of meters has been utilized extensively in the analysis of severe convective storms and tornadoes with research radars and could provide the ability for improved algorithm performance and data quality in future operational weather radar networks.

Temporal resolution is a critical aspect in the trends of weather radar observations, especially for severe weather that changes on the order of seconds rather than minutes. Current NEXRAD update times of greater than 4 minutes are widely regarded as insufficient for rapidly evolving convective weather. Future implementations of operational weather radars could very well utilize phased array antennas to drastically improve update rates for forecasters, but the number of individual transmit/receive elements required at a high enough power for long-range weather observations would result in high costs. Pulse compression is an ideal candidate to make future weather radar systems more affordable by utilizing low-power solid-state transmit/receive elements and transmitting a frequency modulated pulse. However, from a cost perspective, it is critical to retain as much of the additional power yielded from a long pulse as possible. Typical pulse compression waveforms often make use of heavy amplitude modulation in order to achieve low range side lobes, even with nonlinear frequency modulated designs. While this can work well for large point targets, the sensitivity of a weather radar can be improved significantly by limiting transmit and receive windowing.

Recent work by Kurdzo and his research partners has led to the design of weather radar pulse compression waveforms that have very high frequency flexibility, leading to the need for much less amplitude modulation while also achieving low sidelobe levels. This technique has been primarily demonstrated on solid-state dish antenna weather radar systems (with peak transmit powers as low as 100 W) but can be directly translated to phased array systems. When the cost considerations of lower-powered solid-state transmitters are taken into account on a phased array system, advantages in range and temporal resolution, frequency diversity, spectrum sharing, graceful degradation, and sensitivity can all be realized with careful application of pulse compression in future system designs.

Signal Processing and Algorithm Design for Emerging Radar Technologies

Research and development have been continuously performed in weather radar to enhance data quality and explore new information and application. Some of the matured technologies have been successfully transferred to operational environments. In general, the base data from polarimetric weather radar include spectral moments of reflectivity, mean radial velocity, and spectrum width, and polarimetric variables of differential reflectivity, cross-correlation coefficient, differential phase, and linear depolarization ratio. Typically, the base data are estimated from the auto and cross correlation function of signals from horizontally and vertically polarized channels at only zero temporal lag. Whitening techniques have been developed to enhance statistical performance of base data estimators using range oversampling signals. The same oversampling signals can also be used to improve the range resolution. Moreover, the polarimetric NEXRADs currently produce the super resolution data of 0.5° angular spacing and 250 m range spacing, as opposed to legacy resolution of 1.0° angular spacing and 1 km range spacing. It has been shown that tornado vortex signatures can be better characterized using super resolution data. It is also worth mentioning that characterization, identification, and mitigation of wind turbine clutter become increasingly important due to the growth of wind farms. Furthermore, abundant research has been done to enhance data quality through better calibration, attenuation correction (especially important for radar with shorter wavelengths at C- and X-bands), mitigation of range and velocity ambiguity, etc.

Spectral processing continues to be one of the important areas in meteorological radar signal processing to enhance accuracy and sensitivity of weather information. For example, it has been shown that Gaussian model adaptive processing (GMAP) for clutter filtering in the spectral domain can provide better spectral moment estimation. Spectral polarimetry was developed to combine Doppler and polarimetric measurements to reveal polarimetric variables as a function of Doppler velocity within the radar resolution volume through spectral processing. Spectral polarimetry has been used to enhance data quality especially in clutter (both stationary and non-stationary) identification and suppression, gain more information about the microphysics of precipitation, and obtain environmental parameters such as turbulence.

Weather radar can measure the refractivity field using returns from ground targets, which can be a good proxy for the near-surface humidity field. This additional information obtained by weather radar has the potential to gain understanding and to improve prediction of convective storms. Refractivity retrieval has been implemented for weather radar using various types of transmitters and wavelengths worldwide. Refractivity retrieval using a network of radars was also developed based on constrained least square approach and compressive sensing [5]. Quantitatively, given the pressure and temperature (that tends to be relatively homogeneous) over the radar coverage, humidity is expected to be estimated with reasonable accuracy. As the temperature increases, refractivity change becomes more sensitive to vapor pressure than to temperature and pressure. Vapor pressure is the dominant factor that changes the refractivity, and thus, refractivity mapping near the surface can be used as a proxy to estimate the spatial distribution of water vapor near the surface.

Another intriguing effort is to investigate the potential of measuring the transverse wind component using a spaced antenna (SA) method. Conventional Doppler radar only measures the wind component along the beam direction (radial component), while the wind vector can be retrieved by tracking reflectivity structure or via some retrieval algorithms. SA can be understood as tracking the interference pattern on the spatially separated receivers provided through a phased array system.

Spectrum Sharing

The wireless communication industry wants to operate in the weather radar band. Thus, cooperation/coordination of functions may be required. Passive radar is one solution. Adaptive phased arrays have tremendous advantages for beam agility/coordination, interference nulling, etc. Radar systems will compete with communication companies for bandwidth, especially as radars attempt to increase the bandwidth of their waveforms. These companies need more bandwidth to support a variety of emerging real-time video products. In 2011, global mobile data more than doubled for the fourth year in a row. The number of devices connected to mobile networks worldwide was approximately five billion in 2012. With regard to spectral issues, the next generation of radars will need to concentrate on: new, innovative multi-channel, adaptive filter designs for the removal of radio frequency interference; cognitive control of system function; and final product formation, i.e., images, detections, etc. As a relevant example, studies are now being completed with the multiple channels of the NWRT for radio frequency interference (RFI) mitigation. Here, it is assumed that the RFI signals are narrowband in nature. These signals may be transient and may hop within a large spectrum. As such, these types of signals are difficult to mitigate. Their non-stationary behavior suggests that analog RF filtering is

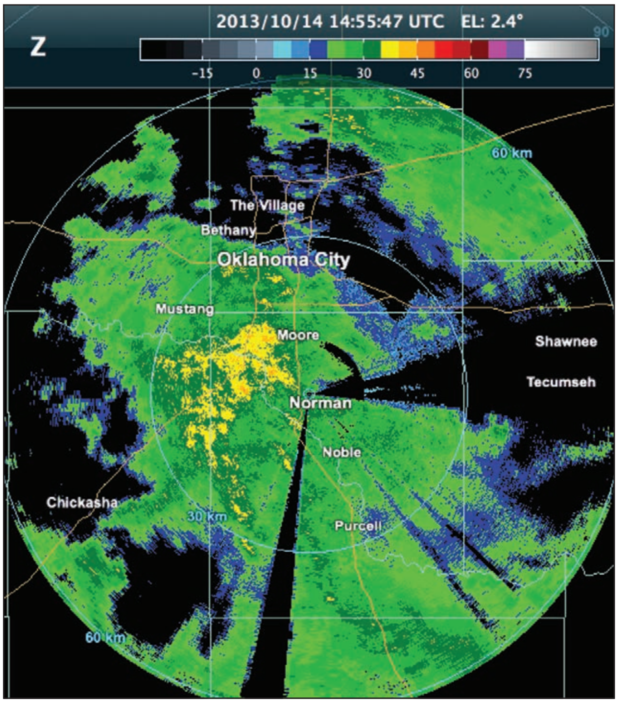

Fig. 2. Radar imagery of a storm in a 60 km radius of Norman, OK. Differing from tube type amplifiers, a novel solid-state power amplifier approach was used with unique waveform designs achieved with software defined radio techniques.

not a viable approach; hence, real-time digital filtering is the focus of this effort. As the density of electromagnetic environments continues to increase, innovative antenna concepts may be employed to provide solutions by filtering in the spatial domain, as opposed to the temporal domain. For example, nulls may be steered in the direction of unwanted contamination.

The Advanced Radar Research Center at OU and PX-1000

To begin, an example of pulse compression is presented. An in-house designed and developed radar at OU is the PX-1000, named in 2008 after the idea of implementing polarimetric X-band radar, in which the number 08 in binary representation is 1000 [6]. The radar uses two 100-W solid-sate power amplifiers (SSPA) as transmitters and has two independent arbitrary waveform generators and two up-down-conversion chains. Each of them operates independently but synchronously. The flexibility allows us to operate the radar in many waveform diversity and polarization configurations that no weather radar has seen to date. The radar is constructed on a transportable trailer that any consumer-grade full-size truck can tow. While being a compact system, all of the essential components of radar, i.e., various controllers, signal processing and data archiving, are implemented locally and are ready to operate as a complete system. In the field, the radar needs only a power supply and a network connection for remote operations.

The PX-1000 utilizes many intellectual properties developed by ARRC faculty, research scientists, and students. In particular, they include a non-linear frequency modulation (NLFM) waveform, optimized through genetic algorithm, for pulse compression, a time-frequency multiplexing (TFM) technique for blind-range filling, multilag moment estimator for radar product generation and a suite of in-house developed software tools for control, distribution, and visualization. The radar has participated in a number of experiment campaigns, e.g., to aid the wind shear study using the multifunction phased array radar in Norman, Oklahoma, in an investigation of lightning during precipitation in Magdalena, New Mexico and for a winter quantitative precipitation study near Seoul, South Korea.

Fig. 3. A photograph of the atmospheric imaging radar (AIR) truck that was designed, built, and tested at the University of Oklahoma.

Fig. 2 shows a reflectivity image retrieved from the PX-1000 radar. By using the TFM technique, the blind range limitation inherent in pulse compression radars is eliminated providing continuous coverage out to 60 km. The short pulse is 1.5 μs (single tone), long pulse 67 μs (2.2 MHz) using a NLFM waveform. For a peak power of 100 W, the average transmit power is about 13 W (calculated using 67 μs pulse width and pulse repetition frequency = 200 Hz). The two waveforms are multiplexed as a single waveform through time-frequency multiplexing (TFM) so there is no loss in pulse repetition time. Incidentally, a tall object produced beam blockage in the southerly direction for this experiment. More details are in [6].

Atmospheric Imaging Radar

The Atmospheric Imaging Radar (AIR) is a mobile X-band imaging platform designed for extremely rapid volumetric scanning of severe convective storms and tornadoes [7]. A recent photo of this system is depicted in Fig. 3. Tornadoes can form, evolve, and dissipate on the order of seconds, and many tornadoes have a lifetime less than the temporal resolution of the NEXRAD network. While typical weather radars must steer a pencil beam across all relevant azimuths and elevations to complete a volume scan, the AIR transmits a vertical fan beam 20 degrees in elevation and utilizes a 36-channel array to digitally form 1-degree receive beams. This technique results in a nearly instantaneous range-height indicator (RHI) from a single pulse, negating the need to steer the beam in the vertical dimension. The transmit feed horn and receive array are mounted on a pedestal that can cover 180 degrees in azimuth at approximately 15 degrees per second, leading to a

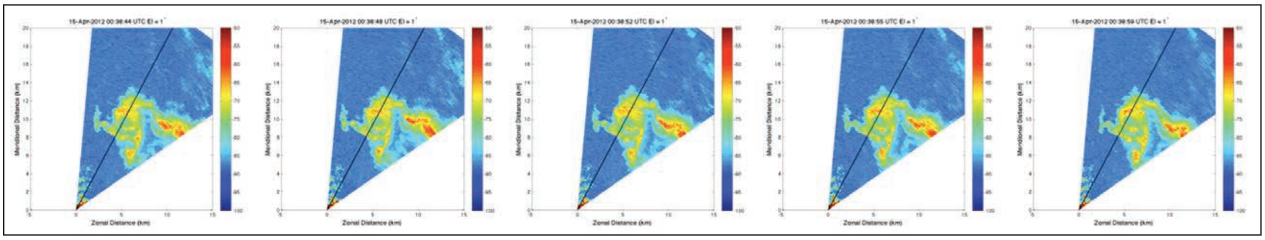

Fig. 4. A sequence of reflectivity plots by beam forming using the Fourier method. Each instantaneous frame is about 3.5 seconds apart.

180 x 20 degree volumetric scan every 12 seconds. Additionally, through the use of pulse compression, a native range resolution of 37.5 m (oversampled to 30 m) provides one of the highest combinations of temporal/spatial resolution at tornado scale in the world for full volume scans.

From a meteorological aspect, the AIR provides multiple new avenues for research of severe convective storms and tornadoes. Stunning detail of vortex generation, debris lofting, horizontal vorticity rolls, and other seldom-seen phenomena have been observed in recent field campaigns. Due to the nearly instantaneous RHI scans, the vertical structure of a tornado can be observed with virtually zero advection of the vortex at upper levels, something that is impossible with a dish antenna. The AIR provides a unique opportunity to study 3-dimensional evolution of convection and could assist in solving long-standing questions regarding tornado genesis, vortex dynamics, and tornadic debris loading.

Digital beam forming employed in AIR allows simultaneous measurements within the field of view (FOV) of the radar with an infinite number of beams. High temporal resolution with an RHI update time of less than 1 second are possible. Clutter rejection via adaptive array processing is also possible, which includes null steering for non-stationary clutter. The radar observed a tornado near Carmen, Oklahoma on April 14, 2012. A mechanical azimuth scan with an update time of approximately 3.5 seconds was achieved, with simultaneous beams formed in elevation. Fig. 4 shows reflectivity plots by beam forming using the Fourier method; see [7] for more details.

Cylindrical Polarized Phased Array Radar (CPPAR)

By incorporating a variety of the aforementioned topics, such as phased array technology, innovative beam forming, polarimetry, and pulse compression of a cylindrical, dual-polarized, phased array radar for weather observations has been studied [8]. A laboratory photograph of this radar is in Fig. 5. The radar stays on principle plane by beam commutation, and it is frequency steered in elevation for cost reduction [8]. In particular, a 90-degree sector is energized and commutated around the cylindrical surface of the array. At any one time, the radar's principle beam is normal to the surface. The prototype radar has an operating range in the S-band of 2.7 to 3.1 GHz, and it transmits 1.5 kW peak. It has a meteorological sensitivity of 20 dBz at 40 km. The size of the array is 1 m tall and 2 m in diameter, which projects a 4.5° beam. The flexible electronics testbed can be used for many phased array applications, as its 192 channel radar backend provides an abundance of data for innovative beam forming algorithms and studies of the atmosphere. Finally, the beauty of this instrument is that it provides rapid 360 degree of coverage with inertia-less beam steering in a manner that manifests reduced complexity calibration for dual-polarized measurements.

Conclusions

Now is the time for new weather radar systems, either by governmental agencies or private industry, because radar applications have matured and are transitioning from scientific demonstration tools into operational systems. Civilian radar systems are uniquely positioned to assist with natural disaster mitigation from early warning and risk assessments through disaster response. Natural disasters (earthquakes, storms, floods, hail, etc.) caused insured losses of $15 billion across the globe. Radar's ability to operate in all weather and penetration capabilities make it an essential tool for understanding the earth and addressing questions of societal importance.

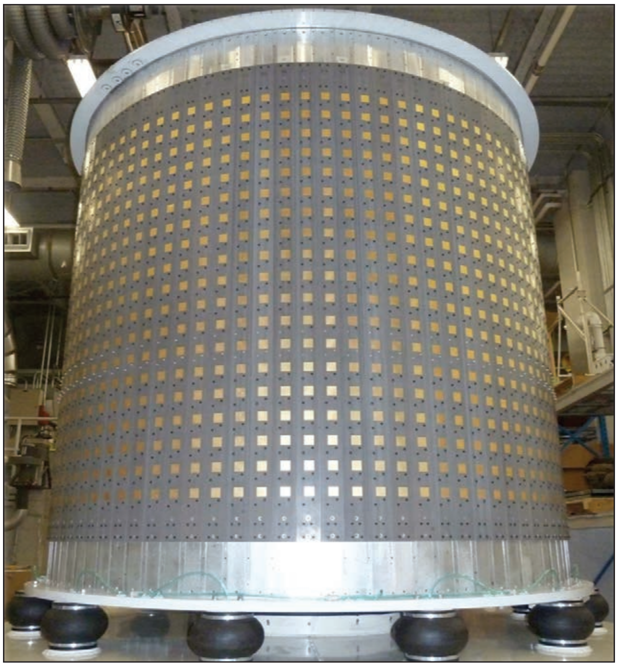

Fig. 5. Prototype phased array radar on a conformal cylinder. The size of the array is 1 m tall and 2 m in diameter and operates in a band near 3 GHz.

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