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A NEW COMPACT POLARIMETRIC SOLID-STATE X-BAND RADAR: SYSTEM DESCRIPTION AND PERFORMANCE ANALYSIS

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Abstract

Incorporating the latest in weather radar technology, the new Ranger series of X-band radar available from Enterprise Electronics Corporation (EEC) delivers a compact, powerful system capable of providing a wide array of radar products for the protection of people and assets. The X-band's dual-polarization capability approaches the performance of larger systems, but has the added advantage of advanced waveform design through the use of dual solid-state power amplifiers (SSPA). Frequency modulated waveforms allow for traditional sensitivity levels to be reached, while minimizing range sidelobes through the use of pulse compression techniques. A frequency-diverse wideband waveform design provides a solution to the blind zone typically associated with low-power systems. A choice of power levels provides a tiered array of options for a variety of anticipated applications. Polarimetric radar products utilize advanced techniques to accurately estimate rainfall and classify scatterer returns. A powerful suite of radar products is provided by the IQ2 signal processor, ready to be incorporated into a variety of applications including city flood planning, sports stadiums or events, deep sea oil platforms, and mobile applications. A brief system description will be presented as well as preliminary data collections demonstrating the capabilities of the radar. The new Ranger series X-band radar designed through a partnership between EEC and the University of Oklahoma (OU) Advanced Radar Research Center (ARRC) is a step forward in commercial weather radar production and extends the availability of high-quality rainfall estimation and asset protection to a new array of users.

1. Introduction

Over the last few decades, weather radars have solidified their presence in the field of meteorology and have become instrumental to the growth of weather knowledge. A wide variety of radar systems have been developed at various frequencies and power levels, with a diverse set of waveform designs. Traditional high-power radar systems are able to collect weather data at hundreds of kilometers, which is suitable for applications requiring observations over a large coverage area. Long-range systems, however, have an unfortunate side effect that manifests in the inability to observe the extreme lower regions of the atmosphere for much of the coverage area. Earth curvature and beam refraction cause the height of the radar beam to increase as it travels, making near-surface observations difficult to capture (Doviak and Zrnić 1993). Recently, smaller, high frequency systems have been designed for use in gap filling or location-specific applications.

Of the available frequencies for weather radar systems, X-band has seen an increase in popularity in recent years. X-band provides a compromise between size and hydrometeor detection that is acceptable in many radar applications. Higher frequencies incur greater atmospheric attenuation, which is more pronounced in the presence of rain. The use of dual-polarization in weather radar data collection helps to reduce the impact of attenauation, thus making higher frequencies more applicable (Bringi et al. 2001). Polarimetric radars also provide the capability to obtain more accurate rainfall estimates (see Table 2) (Ryzhkov et al. 2005), as well as classify hydrometor type (Straka et al. 2000). The use of higher frequencies produces an added benefit of reducing the size of the antenna and RF components within the radar system. Thus, the overall size of the system decreases, resulting in a dramatic reduction in the infrastructure requirements, expanding the possibilities for radar system siting.

Reducing the size of the radar caters to many applications, one of which being mobile radar systems. Mobile systems are typically used to gather severe storm data, namely tornadoes, given their capability to travel to the phenomena of interest in a relatively short period of time. Several mobile radars created for research purposes have made use of the X-band frequency, including, the Center for Severe Storm Research Doppler on Wheels (Wurman et al. 1997), PX-1000 developed at OU by the ARRC (Cheong et al. 2009), the National Severe Storm Laboratory NOAA-XP (Schwarz and Burgess 2010), the University of Massacheusetts-Amherst X-POL (Venkatesh et al. 2008), and OU's Raxpol (Pazmany and Bluestein 2009). Large, organized experiments, such as the Verification of the Origins of Rotation in tornadoes Experiment (VORTEX), have made use of fleets of mobile systems and have successfully engaged in the study of tornadoes for better understanding and increased protection of people and property (Wurman et al. 2012).

Another application for smaller, more compact X-band radar designs caters to situations that desire accurate weather information, but on a more localized scale. This idea is being explored by the network of Collaborative Adaptive Sensing of the Atmosphere (CASA) radars, which utilize X-band frequencies to provide coverage of specific, high-risk locations where complex collection schemes and high resolution are preferred (Mclaughlin et al. 2009). The experimental network of CASA radars is designed to provide weather data in areas which are not adequately covered by existing networks of high-power, long-range radars. Typically, power levels for gap filling radars are reduced because the desired retrieval range is decreased to facilitate near-ground observations, i.e., to keep the beam height close to the ground. This fact, coupled with new technologies, such as SSPAs with high duty cycles, allow radars to significantly decrease the output power of the system by transmitting longer pulse widths while still maintaining high spatial resolution through pulse compression.

Pulse compression technology has been utilized in weather radars for some time and several X-band systems have incorporated long, frequency modulated pulses into their waveform designs (Mudukutore et al. 1998). Among those mentioned previously, the Raxpol and PX-1000 radars utilize pulse compressed waveforms to maintain sensitivity while transmitting less power. One drawback of utilizing long waveforms is the so-called 'blind range', which is proportional to the length of the transmit pulse and refers to the period of time during which the receiver is saturated by the transmitted pulse. To combat this issue, developments in pulse compression technology has been achieved through the Colorado State University Wideband Experimental X-band radar in the form of frequency diverse waveforms (Bharadwaj and Chandrasekar 2012). A similar technique was developed at OU on the PX-1000 (Cheong et al. 2013). Frequency diversity, or Time-Frequency Multiplexing (TFM), mitigates the effect of the blind range by utilizing a second (or third), frequency separated pulse to observe the region obscured by receiver saturation. It has been this breakthrough that has allowed low-power SSPA systems to expand into a wide variety of applications.

A new, low-power, compact X-band radar system developed through a partnership between EEC and OU is presented in this paper. The Ranger-X1 represents one in a series of compact X-band systems produced by EEC that are designed to fit an array of applications, including, biological studies for wind turbine siting, oil platform weather observations, urban flood management, terrain-related gap filling needs, mobile and research related studies. Incorporating the latest in radar technologies, the Ranger-X1 provides a unique approach to providing accurate weather radar products for a wide variety of end users. A discussion of pulse compressed waveforms is given in the next section, followed by a technical description of the Ranger-X1. A presentation of initial weather data collected with the radar is given in Section 4, followed by concluding remarks.

2. Waveform Design

As mentioned in the previous section, pulse compression technology is one of the main features that allows the Ranger-X1 to acquire high-quality weather data while maintaining a compact physical footprint. Much effort has been spent in the research community toward the development of waveforms that not only provide the sensitivity and resolution necessary to collect meaningful weather data, but are able to reduce problematic range sidelobes and combat amplifier distortion effects.

One straightforward approach to pulse compression lies in the linear frequency modulated (LFM) waveform (Skolnik 2001). Typical LFM waveforms are relativley long pulses that exhibit a linear increase (or decrease) in frequency over the pulse length. Compression is achieved through waveform match filtering on the received signal, where the width of the received pulse is reduced and is inversely proportional to the bandwidth of the waveform. The compression is not without side effects, however, and will produce range sidelobes, which are similar to sidelobes incurred through signal or array processing. As in the realm of signal processing, the application of amplitude tapers (window functions) reduces the impact of sidelobes, but also reduces the sensitivity of the waveform by depressing power at the edges of the frequency band.

Seeking to mitigate the loss in sensitivity incurred through amplitude tapered LFM waveforms, alternative non-linear frequency modulated (NLFM) waveforms were devised that achieve a similar reduction in sidelobe level without significantly sacrificing transmit power, thus improving the sensitivity of the radar system (Millett 1970). Further steps can be taken to improve the performance of the radar through waveform optimization. One method currently being developed at the ARRC at OU involves the use of genetic algorithms to produce a waveform that is specifically designed to reduce the impact of transmitter/amplifier distortion typically incurred in radar systems (Kurdzo et al. 2013).

Blind zone mitigation is an important issue with pulse compression and has been explored with two research radars recently (Bharadwaj and Chandrasekar 2012; Cheong et al. 2013). Low power systems, like the Ranger-X1, typically use pulses on the order of 50 to 100 μs to achieve appropriate sensitivity. This means that the blind zone will occupy the first 7.5 to 15 km of the observable range of the radar, which is an unacceptable compromise for many applications. Mitigating this effect is paramount to the versatility of the low-power X-band series of radars. Working with the ARRC at OU, a basic TFM waveform was generated with the long pulse spanning 2.2 MHz and the second, fill pulse occupying a single tone, but separated by 1 MHz. Preliminary weather data gathered with this waveform is presented in Section 4.

3. Technical Description

General specifications for the Ranger-X1 system are given in Table 1 and a system level block diagram is presented in Figure 1. The parameters in the table, and the subsequent description in this section, represent the prototype system used to collect the weather data presented in this paper. Component alternatives, such as the antenna size and amplifier power level, are available in production models. The following description of the radar hardware is organized by subsystem, beginning with the antenna and pedestal.

TABLE 1. System Specifications

Parameter	**Value**
General	
Operating Frequency	9200→9500 MHz
PRF	200→2400 Hz
Observation Range	18 dBZ @ 50 km (0-dB SNR)
Antenna	
Gain	>38 dBi
Diameter	1 m
3-dB Beamwidth	<1.95°
Polarization	Dual linear
Pedestal	
Type	Elevation over azimuth
Accuracy	0.025°
Fiber-Optic Slip Ring	1000 Base-T+ Data
Receiver	
Bandwidth	0.1→10 MHz
Maximum Range Resolution	15.0625 m
Resolution	16-bit A/D
Transmitter	
Peak Power	100 W
Maximum Pulse Width	100 μs
Maximum Duty Cycle	15%

a. Antenna and Pedestal

A composite, 1-m parabolic reflector is used in conjuction with an orthogonal polarimetric feed horn. Waveguide connects the antenna and feed to the transmit/receive subassemblies on either side of the above-azimuth axis. A photograph of the prototype system is presented in Figure 2. In the photograph, the antenna and feed are visible, as is one of the two transceiver enclosures. The octagonal shape above the transceiver enclosure houses EEC's most recent advancement in digital receiver technology, the IQ2, temperature monitoring components, and master oscillator.

FIG. 2. A photograph of the Ranger-X1 prototype radar. The 1-m dish and polarimetric feed are shown, along with one of the two transceiver enclosures (other is hidden on opposing side). The pedestal structure is sealed against the elements, which is ideal for continuous outdoor operation.

The pedestal structure itself is sealed from the elements, making the Ranger-X1 ideal for continuous outdoor operation (radome option is available). Both azimuth and elevation axes utilize a wave generator, eliminating the bullgear and pinion component of traditional weather radar systems. The sealed drive assembly is permanently lubricated and requires no periodic maintenance. Additionally, the technology eliminates backlash, resulting in high positional accuracy and repeatability. The system is suited for a variety of mounting structures, including mobile and shipboard applications, and can operate in sustained winds of up to 33.5 ms^{-1}, and gusts up to 40.25 ms^{-1}.

The use of a fiber-optic rotary joint in the Ranger-X1 allows for high-speed data transfer between the upstairs digital equipment and the downstairs computing and product generation software. Additional communication and power distribution are facilitated through a military-grade, sealed slipring, which is designed for low-maintenance, continuous-operation applications.

Control of the azimuth and elevation motors is achieved through a newly developed servo controller at EEC: the Aquarian. Shedding the overhead typically present on commercially available controllers, the Aquarian caters specifically to weather radar applications, providing both smooth

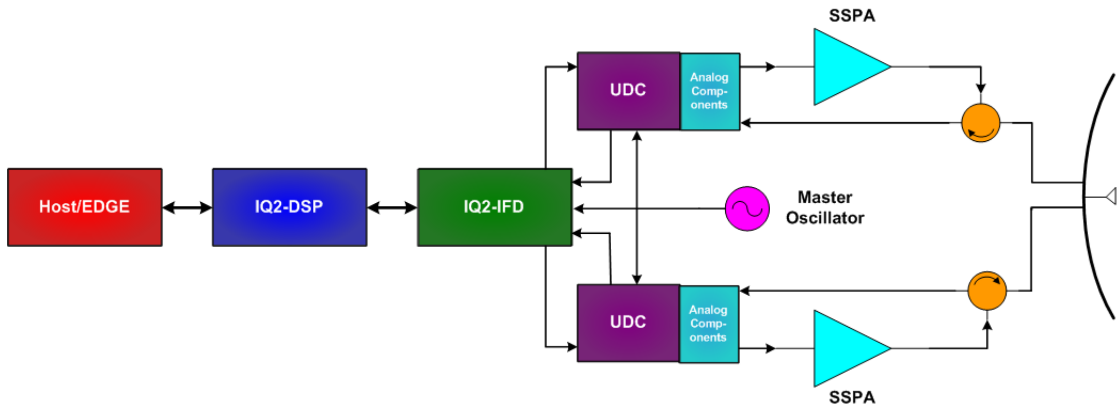

FIG. 1. A high-level block diagram of the Ranger-X1. A description of the subsystems is given in Section 3. Each transmit channel is equipped with an independent up/down converter and power amplifier.

velocity operation and precise position capabilities. Further, rapid positional feedback provides precise synchronization with recorded radar data products.

b. Receiver

The radar receiver operates in two modes to facilitate accurate pulse compression: transmit and receive sample. The first mode samples the transmit waveform via a coaxial coupler and high-speed RF switch. Immediately after the transmit signal is sampled, the second mode is engaged, allowing the received signal to travel from the antenna through the receiver chain. Sampling the transmit pulse allows for precise matched filtering in the digital domain, increasing the efficiency of the pulse compression and improving radar sensitivity.

Following the high-speed switch, the radar signal passes through a highly selective RF bandpass filter before entering the receiver portion of the Up/Down Converter (UDC). The UDC was designed through a collaboration with OU-ARRC and EEC, and is a compact, light-weight, printed circuit board replacement for traditional connectorized radar transceivers, providing the performance necessary for advanced radar systems. The RF-sealed enclosure protects both the receive and transmit chains from unwanted interference. The on-board phase-locked loop (PLL) and frequency synthesizer utilize the master oscillator reference frequency of 100 MHz, and allow for coherent mixing to and from the 60-MHz IF. The X-band operational frequency is selectable through a serial interface.

Following the conversion to IF in the analog domain, the signal is passed to the EEC IQ2-Intermediate Frequency Digitizer (IQ2-IFD), where the horizontal and vertical channels are sampled by a 16-bit A/D converter. The sampled data are then digitally mixed to produce the in-phase and quadrature components, filtered, and finally decimated to baseband. The data packets are then transferred via the fiber-optic cable to the IQ2-Data Processing Unit, which is housed in a weather-sealed enclosure external to the radar pedestal and mounting structure.

The primary function of the Data Processing Unit is to generate advanced, dual-pol radar products. Products are generated in real-time from the intermediate data provided through the IQ2-Digital Signal Processor (IQ2-DSP) and are available for display within the Enterprise Doppler Graphics Environment (EDGE) software suite. The IQ2-DSP makes use of PCIe technology within a server-style multi-core computer to produce an array of weather radar products. A list of some of the available single and dual-pol products is given in Table 2.

TABLE 2. Subset of Available Radar Products

Product	Description
Z_h, Z_v	Reflectivity
Z_{DR}	Differential Reflectivity
$V_{r,h}, V_{r,v}$	Radial Velocity
ρ_{hv}	Cross-correlation Coefficient
ϕ_{DP}	Differential Phase
K_{DP}	Specific Differential Phase
$R(Z), R(Z, Z_{DR})$, $R(K_{DP}), R(K_{DP}, Z_{DR})$	Rainfall Estimation
HMC	Hydrometeor Classification

Further development of the radar products was facilitated with the partnership with OU and led to the inclusion of an advanced radar algorithm: Spectrum-Time Estimation and Processing (STEP) (Cao et al. 2012). STEP improves the quality of radar data through a three-pronged approach. First, the data are analyzed for the presence of clutter in real time. Next, if clutter is detected, a bi-Gaussian clutter filter is applied. Finally, multi-lag processing is utilized, which reduces the impact of noise on weather radar data, improving sensitivity and data quality.

c. *Transmitter*

Through the use of LFM and NLFM waveforms, less power is required to achieve sensitivity similar to traditional commercial radar systems. Relatively low power SSPAs are utilized in conjunction with long pulse lengths to increase the average power of the system. The Ranger-X1 utilizes a 100 W SSPA capable of producing a 100-μs pulse and has a maximum duty cycle of 15%. Additional power levels are available in production units, for example, the Ranger-X5 utilizes a 500 W SSPA.

Compression waveforms are produced via the two waveform generator outputs on the IQ2-IFD. The 16-bit D/A converters provide the ability to produce advanced, independent pulsed waveforms for the horizontal and vertical radar channels at the 60-MHz IF. Due to the required long pulse width, a TFM waveform coupled with a LFM or NLFM chirp pulse design is utilized. Advanced waveform designs such as these are possible through the waveform generators within the IQ2-IFD.

Waveforms provided by the IQ2-IFD waveform generator output are then passed to the Ranger-X1 UDC. The up conversion portion of the UDC translates the complex waveform at IF to the X-band operational frequency, which is chosen by the user and selected through the serial interface. The UDC output is then passed to a preamplifier before entering the SSPA. Steps were taken to ensure that the transmit chain exercises the full bit-range of the IQ2-IFD waveform generator to reduce quantization noise on the pulse waveform outputs.

d. *Host Machine with EDGE Software*

Primary control of the radar is managed through the EDGE software. Antenna and pedestal position control as well as waveform selection and product generation are defined by the user in a powerful suite of software. Products generated via the IQ2-DSP are displayed in real time, allowing live and up-to-date visualization of the weather scenario, facilitating adaptability to dynamic meteorological phenomena. Dual-polarization products are utilized to provide accurate rainfall estimates and help identify potential hazards.

e. *Pulse Compression and Waveform Design*

Development of the waveforms used in the Ranger-X1 was carried out with a partnership with OU-ARRC. Following a formula similar to Bharadwaj and Chandrasekar (2012), a dual-pulse TFM waveform is used to provide sensitivity in the long range while providing meaningful data in the short range. Initial waveform designs are quite simple and utilize amplitude weighting functions for the long pulse. One of the major benefits of the use of SSPA technology and the level of control available with EDGE is the ability to utilize a variety of waveforms that can be adapted to the needs of the end user. Further, as new waveform designs emerge, they can easily be included by simply loading a new text file.

4. Meteorological Data - 11 Nov 2012

Initial tests were performed to ascertain the functionality of the radar system. As these were initial tests, rudimentary radar parameters were utilized. A list of the test parameters is given in Table 3. A simple, uniformly spaced PRT of 1400 Hz was used, meaning the aliasing velocity is quite low for this particular dataset (11.1 ms^{-1}). The velocity ambiguity can be improved with the use of staggered PRT algorithms (Torres et al. 2004). Only the horizontal channel was utilized during this data collection to simplify data validation. A suite of waveform designs were produced and could be loaded into the waveform generator on-the-fly. One of the waveforms utilized the TFM concept while the other two were simply 2-μs and 67-μs rectangular pulses for sensitivity comparisons.

TABLE 3. Data Collection Parameters

Parmeter	**Value**
Frequency	9500 MHz
Elevation	0.5°
Gate Size	31.25 m
PRF	1400 Hz
v_a	11.1 ms^{-1}
Waveform	
Modulation	LFM
Taper	Kaiser
TFM	Yes
Pulse Width	
Long	67 μs
Fill	2 μs
Bandwidth	
Long	2.2 MHz
Long/Fill Δ	1 MHz

The TFM waveform was generated using the methods and techniques indicated in Section 3e, and was a 67-μs, windowed LFM waveform occupying a 2.2-MHz bandwidth followed immediately by a 2-μs, single-tone fill pulse. The application of the amplitude taper window results in a loss in sensitivity (approximately 65% of the full power), but a significant reduction in the range-sidelobe level is achieved. Again, other, less lossy waveforms can be utilized but were not tested during this data collection.

Weather data were recorded during the afternoon on 12 November 2012. A photograph of the radar positioned on

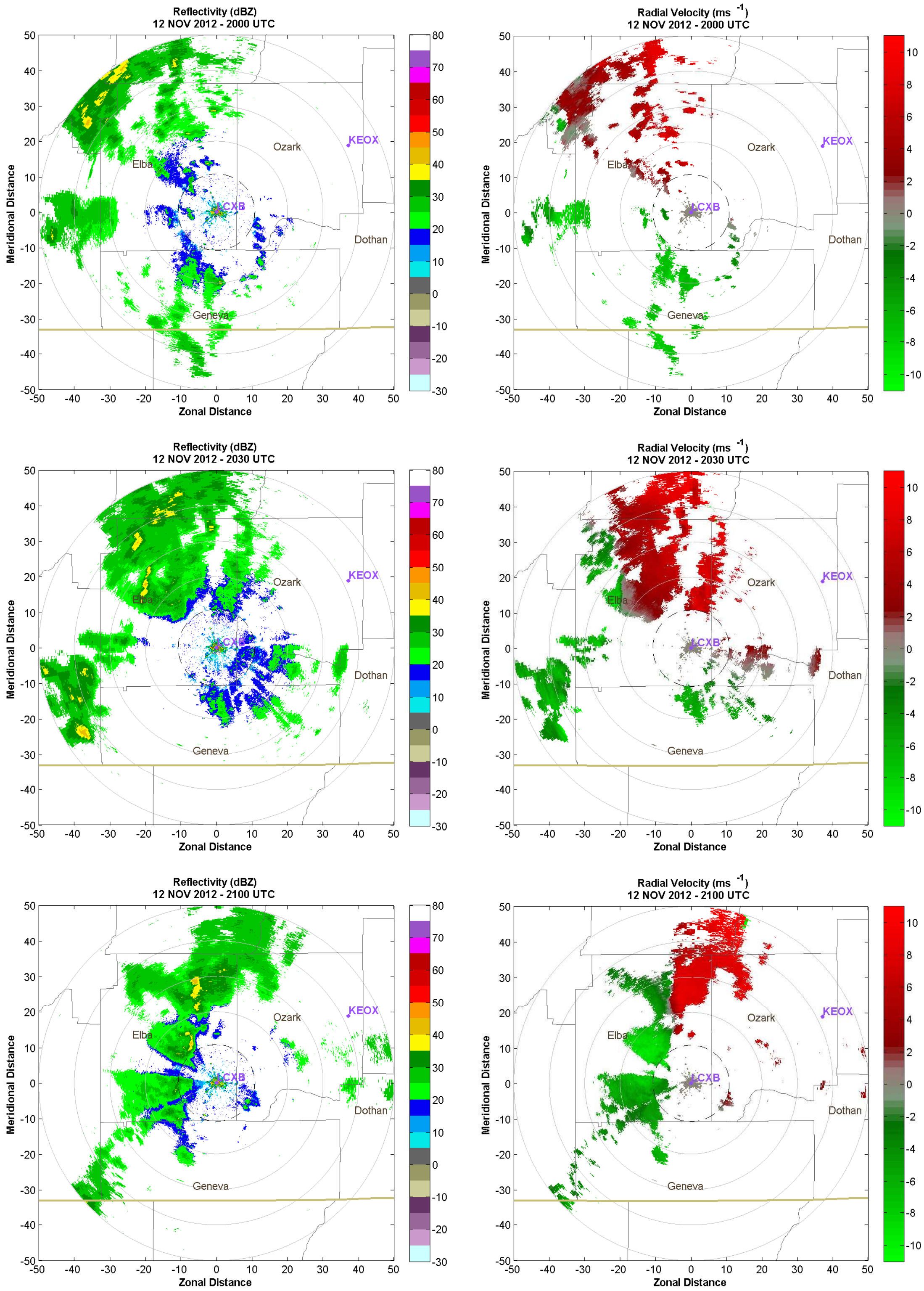

FIG. 4. Calibrated reflectivity and radial velocity from a 12 November 2012 rain event near Enterprise, AL. A windowed LFM long pulse was used in conjunction with a 2-μs fill pulse as a TFM waveform. The dashed circle near the center of the display denote the transition between the blind zone and the long pulse region. Subsequent range rings are shown every 10 km. Reflectivity is censored for 3-dB SNR. Moderate rain is visible beyond 50 km.

the tower is given in Figure 3. Though rainfall was steady,

FIG. 3. A photograph of the Ranger-X1 in Enterprise, AL. The location of the radar provided reasonable coverage, though some blockage was incurred due to a nearby tower.

the intensity of the rain was rather weak, with no significant portions of the event exceeding 40 dBZ. Still, with an amplitude tapered waveform, significant portions of the event are visible in the calibrated reflectivity data shown in Figure 4. Beam blockage is apparent to the west/northwest of the radar location, and additional blockage is present on the southeast side of the radar site, though not as significant as the former. Reflectivity data were censored for 3-dB SNR and radial velocity images are also given in Figure 4.

A comparison between the Ranger-X1 and a nearby KEVX WSR-88D radar reflectivity field is given in Figure 5. Ignoring the blockage incurred due to the radar siting and the three-minute time difference, good agreement between the radars is apparent. A good portion of the KEVX viewable area is filled with light rain (< 15 dBZ), which is not detected by the much lower power Ranger-X1. However, the X-band system is able to detect moderate rain at ranges that exceed 50 km. Again, this was achieved through the use of an amplitude tapered LFM waveform, which only utilizes approximately 35% of the full 100 W transmitter.

The use of the TFM waveform allowed Ranger to observe weather within the first 10 km of the radar (shown as the dashed circle). The use of the fill pulse is essential for applications requiring long and short range observations. Looking ahead, the use of NLFM and optimized waveforms will significantly improve the sensitivity of the radar system. Further, the use of multi-lag processing will provide additional improvement to the radar sensitivity.

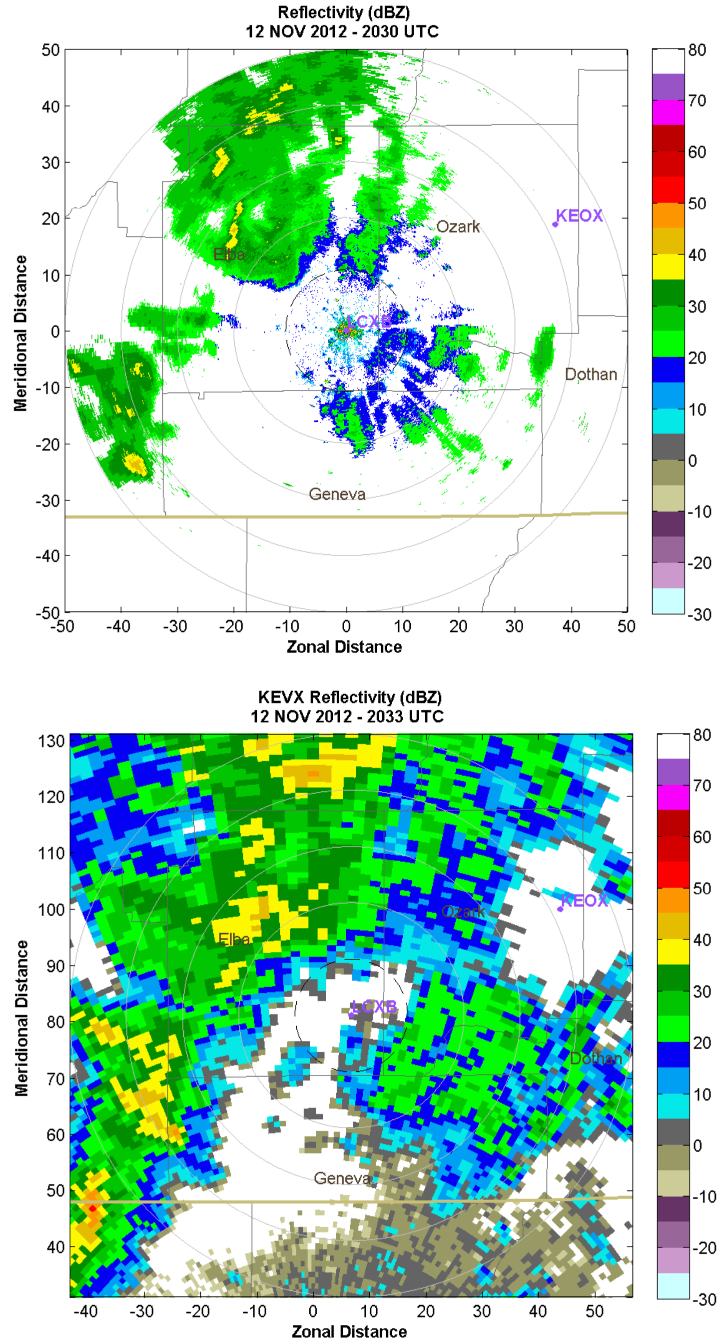

FIG. 5. Comparison between the Ranger-X1 and a nearby WSR-88D radar (KEVX). Significant blockage is visible to the west/northwest of the Ranger-X1 as well as to the southeast. Good agreement is observed between the two radars, though much of the light rain (< 15 dBZ) is not detected by the X-band system.

5. Conclusions

A detailed description of the Ranger-X1 radar was presented along with initial data collections. The quality of the radar data was compared with a nearby WSR-88D and good agreement was achieved. The Ranger-X1 system illustrated how a small, compact system can be utilized to gather high-resolution, meaningful weather data with basic waveform designs and scan strategies. The TFM waveform was shown to be a useful tool in mitigating the blind zone caused by the use of a long transmit pulse. Further improvement is anticipated with the use of staggered PRTs, NLFM and optimized waveforms, and STEP processing.

The Ranger-X1 represents a new family of commercially available radars capable of providing accurate weather data for a wide variety of applications. The low-power, compact, X-band system provides a complete set of high-quality single and dual-polarization products while minimizing infrastructure requirements. Utilizing the latest in waveform and amplifier technology, Ranger-X1 is able to achieve sensitivities approaching those of traditional radars. Combining over 40 years of weather radar experience with the latest in remote sensing technology, the Ranger-X1 provides a robust solution for meteorological needs.

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