EEC's Next Generation Weather Radar: Solid-State Polarimetric Weather Radar With Advanced Time–Frequency Multiplexing Waveform Design

Qing Cao, Michael Knight, Jim Helvin, Robert Stafford, Albert Free
Enterprise Electronic Corporation (EEC)
Enterprise, Alabama, USA
qingcao@eecweathertech.com

Abstract— **The current article introduces the novel hardware design and signal processing of EEC's latest X-band solid-state polarimetric weather radar: Ranger system (X1/X5), including the implementation of pulse compression technique with the advanced time-frequency multiplexing (TFM) waveform design. The effects/limitations of radar configurations (e.g., pulse width, transmitter power, and bandwidth) for the implementation of pulse compression/TFM and the concept of optimizing the waveform design are also discussed.**

Keywords—polarimetric weather radar, solid-state radar, pulse compression, time-frequency multiplexing waveform

I. INTRODUCTION

The solid-state radar design has recently attracted a lot of interest in the weather radar community due to the superiority of a solid-state transmitter: low power, high reliability, and lower cost compared to traditional radar. As a result of the lighter weight and compact size, the infrastructure cost is greatly reduced as well. A few types of research and commercial solid-state polarimetric weather radars have been developed in the past several years and demonstrated great potential in atmosphere surveillance. As one of world leading weather radar manufacturers, Enterprise Electronics Corporation (EEC) has successfully developed the novel X-band solid-state polarimetric weather radar—The Ranger series. The Ranger system features dual-polarity accuracy, solid-state transmitters, low power consumption, and sealed-for-life zero maintenance motion components, all in one affordable and portable unit. Current Ranger series include Ranger-X1 and Ranger-X5, which use dual-transmitters with peak power of 100W and 500W, respectively. The pulse compression technique has been applied in the Ranger system to improve the radar sensitivity. To optimize the performance, X1 and X5 have used the waveform design based on an advanced time-frequency multiplexing (TFM) waveform scheme [1-3].

Targeted at providing alternative solutions for larger, nationwide radar networks, EEC applied the same proven technology from Ranger in the development of an S-band solid-state weather radar with higher power transmitter (several kWs), which could potentially replace the current magnetron or klystron S-band or C-band radars used in many national networks around the world. Although the initial costs of an equivalent solid state transmitter is higher than a magnetron based transmitter, Ranger has demonstrated the technology will yield the performance and reliability to make the option more affordable over the product service life.

The prototype Ranger system was developed over two years ago [3]. From the prototype, hardware and software modifications have improved the sytem performance and made the Ranger series to be mature commercial systems. A notable modification was using the optimized non-linear frequency modulation (NLFM) waveform to replace the linear frequency modulation (LFM) waveform in the Ranger prototype. Modifications on the waveform generator, up-down converter (UDC), transmitter, receiver, radar motitoring system, and other IF/RF components have made Ranger system more reliable and also capable of 500W transmission peak power in Ranger-X5.

II. SYSTEM DESCRIPTION

A. System Overview

The Ranger radar system (Figure 1) was developed in partnership with the University of Oklahoma (OU) Advanced Radar Research Center (ARRC). Ranger has been designed using the very latest technology available in the industry and the technical and manufacturing experience gained through over four decades of successful radar system design and production at EEC.

Figure1. Examples of Ranger-X1 and Ranger-X5 systems with 1-meter antena (up to 2.44-meters antenna).

The entire Ranger design concept emphasizes precision, stability, reliability, and value using proven solid state technology combined with the most advanced motion control system ever conceived for weather radar. The system

978-1-4799-8232-5/151$31.00@2015IEEE

configuration is flexible in the choice of transmitter power, antenna size, and waveform design (Table 1). Figure 2 shows the high-level block diagram of Ranger system. It is worth noting that the dual transmitter design allows flexible transmission modes.

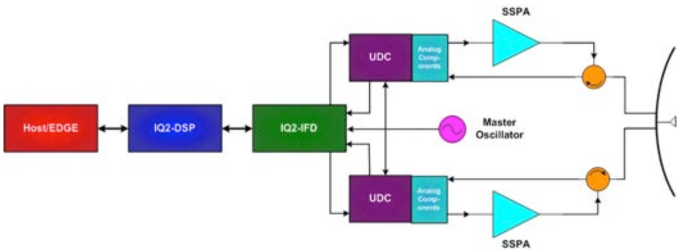

Figure 2. A high-level block diagram of Ranger system.

Table1. Specifications for Ranger Series

	Ranger-X1	Ranger-X5
Operating Frequency	9200-9700MHz	9200-9700MHz
Pulse Width	0.4-100.0 µsec	0.4-100.0 µsec
Pulse Repetition Frequency	100-2500Hz	100-2500Hz
Dual-Polarization	Simultaneous H/V	Simultaneous H/V
Trasmitter Peak Power	100W /channel	500W /channel
Sensitivity	18 dBZ@50km	18dBZ@120km
3-dB Range Resolution	60-125 m	60-125 m
Receiver Band Width	~5 MHz	~5MHz
Antenna Size (Diameter)	1m/1.8m/2.4m	1m/1.8m/2.4m
Antenna Gain	37-45 dBi	37-45 dBi
3-dB Beam Width	2.3°/1.3°/0.95°	2.3°/1.3°/0.95°
Pulse Compression Waveform	TFM, NLFM	TFM, NLFM
Theoretical Range Sidelobe Level	Up to -86 dB	Up to -86 dB
Sensitivity Loss	Up to 2 dB	Up to 2 dB

B. Solid-state Transmitter

Leveraging a mature market and the advancements made in solid-state amplifier technology, EEC is able to produce radars that match the sensitivity performance of higher power systems, while adding the capabilities of advanced radar waveform design. A 100/500-watt X-band solid-state amplifier is used for each radar channel. By utilizing solid-state technology, longer duty cycles can be achieved and sensitivity is maintained despite transmitting at significantly lower powers. The Ranger system is capable of producing waveforms with duty cycles up to 15% and pulse widths up to 100-µsec utilizing pulse compression techniques. Control and trigger signals are generated within the transmitter assembly by the transmitter control unit.

C. Digital Receiver

The transceiver subsystem houses the radio frequency (RF) up/down converter (UDC) and solid-state power amplifier (SSPA) for each polarization channel. Included in the transceiver component network is a RF coupler that allows for the transmitted burst signal to be passed through the down-conversion network and sampled by the IQ2-IFD Intermediate Frequency Digitizer (digital receiver).

The EEC IQ2 Digital Signal Processor (DSP) is based on modern digital processing technology and the industry standard PC – LINUX platform. The IQ2 DSP from EEC is the latest generation in advanced signal processing technology. Developed in conjunction with, and tested by the University of Oklahoma, the IQ2-DSP is the most advanced weather radar signal processor available in the weather radar industry.

Figure 3. Transceiver modules/assembly of Ranger-X1

D. Antenna System

Ranger uses a composite parabolic reflector in conjuction with an orthogonal polarimetric feed horn (Figure 4). The antenna can be configured with different size reflectors to accommodate users' need for beam width (Table 1).

Figure 4. Ranger antenan dish and pedestal modular design.

The Ranger system is designed for constant outdoor exposure and 24/7 unattended operations. Utilizing multiple O-ring seals and weather tight compartments prevents contaminants from entering the pedestal from the outside environment. The motor drives used in both azimuth and elevation utilize a wave generator and circular spine, eliminating traditional gearing found in most pedestal systems. Since the motor drives are sealed and permanently lubricated, there is no periodic maintenance required. Additionally, this technology eliminates backlash and the subsequent need to adjust backlash, and provides exceptionally high positional accuracy and repeatability.

E. *Software*

Ranger system applies the EEC patented Enterprise Doppler Graphics Environment (EDGE) software for radar control, data analysis, and display. The EDGE user interface provides access to the configurations of the radar signal processor (IQ2) and radar control unit (RCU).

III. WAVEFORM DESIGN

To compensate for the low power output of the solid-state transimitter, pulse compression technique is desirable for solid-state radars. However, traditional pulse compression has the “blind region” problem, for which reception is disabled during the transmission of the long pusle. To resolve this problem, the time-frequency multiplexing (TFM) technique has recently been implemented [1-3].

A. *Time-Frequency Multiplexing Waveform Design*

The major idea of TFM is to generate multiple pulses (with different pulse lengths) to simultaneously accomplish the pulse compression of long pulses and fill the blind region of long pulse using a short pulse. The usage of TFM technique avoids the increase of effective pulse repetition time (PRT) by transmitting multiple pulses. Ranger prototype initially employed two pulses for TFM waveform design. However, due to the sensitivity requirement in the blind region, the three-pulse TFM waveform was designed for current Ranger systems. An example of the three-pulse TFM waveform is shown in Fig. 5. The long, median, and short pulses are 78, 20, and 2 micro-seconds and apply NLFM, NLFM, and LFM, respectivity. The median pulse fills the blind region of the long pulse, and the short pulse fills the blind reigon of median pulse.

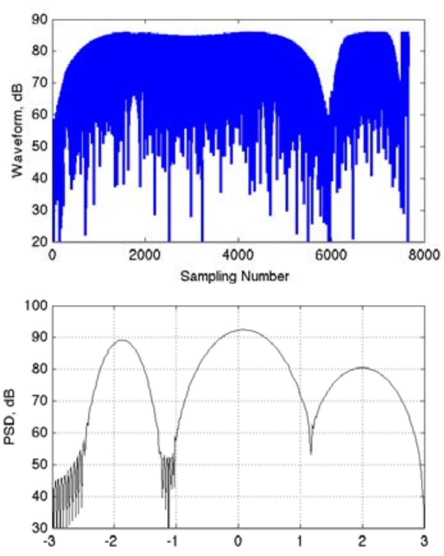

Figure 5. An example of the three-pulse TFM waveform (upper row) and its spectrum (lower row)

The radar echoes for different pulses can be seperated in the spectrum. As Fig. 5 shows the spectrum, the long pulse is located at the center, and the median/short pulses are on the left/rigth side. The isolation between long and median pulses are more than 50 dB and the contamination with each other is well suppressed. However, due to the limitation of receiver band width, the short and long pulses are not sufficiently isolated. Weak contamination might exist in short pulse region when radar echoes are strong. EEC plans to improve the Ranger receiver bandwidth to 10 Mhz. Utilizing a wider frequency band, the TFM waveform design will be improved.

B. *Optimized Nonlinear Frequency Modulation (NLFM)*

The major issue of the pulse compression technique is the range sidelobe level of designed waveform. Range sidelobes will greatly affect radar data quality [4-7]. EEC applies an optimized NLFM waveform design method for the Ranger system. This method, being EEC’s intellectual property (IP), uses the matrix computation approach to find the optimized waveform with the designed spectrum and the lowest range sidelobe. The theoretical range sidelobe level is better than -80 dB given the hardware capability (Fig. 6). The sensitivity loss is no more than 2 dB, depending on various configurations for different Ranger systems. Practically, the real system could experience a slight degardation of range sidelobe level due to the noise and distortion introduced into the burst signals.

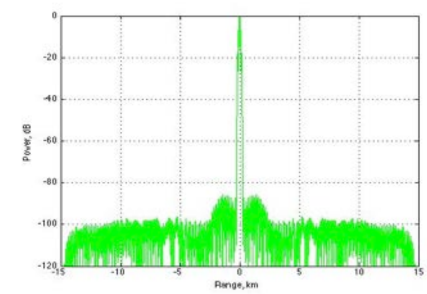

Figure 6. The theoretical range sidelobe pattern for one of NLFM waveform designs.

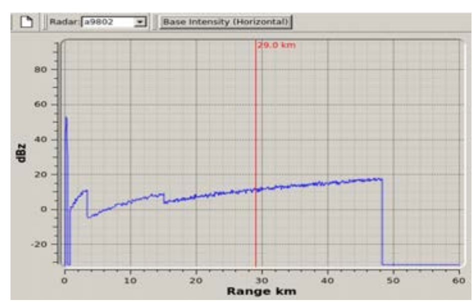

Figure 7. The sensitivity of Ranger-X1 shown in the EDGE A-scope display of base reflectivity

Fig. 7 shows an example of the sensitivity of the Ranger-X1 system. The EDGE A-scope display shows the real noise level of the system. It is noted that the radar range is configured as ~48 km with pulse compression functioning. The sensitivity within the three pulse regions changes in different gradients along the beam path. As the figure shows, the sensitivity is discontinuous at the ranges of 3 km and 15 km. It is apparently that with the help of median and short pulses the blind region (<15km) has been filled with reasonable sensitivity. This is the benefit of applying the TFM technique.

C. Waveform Pre-Distortion

Amplifiers inherently add distortion in both amplitude and phase to the transmitted signal. In order for pulse compression signal processing to approach theoretical performance, the transmitted waveforms must be known and used by the matched/mismatched filter in the receiver. Distortion produced by the amplifier and UDC may reduce the effectiveness of pre-defined pulse compression waveforms. By including the RF coupler in the design, Ranger provides the capability to monitor the distortion introduced in the RF section. A pre-distortion process has been applied to compensate for the distortion by modifying the waveform generation and therefore minimizing the effects of matched/mismatched filter performance degradation.

IV. RADAR OBSERVATIONS

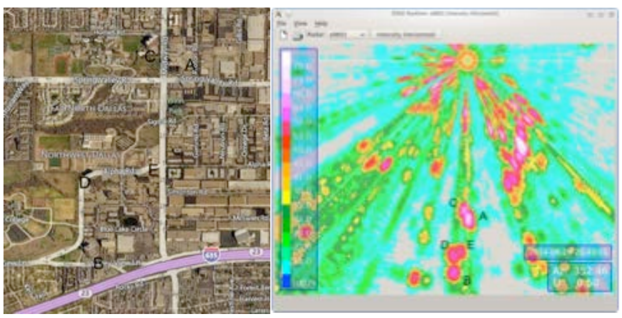

Figure 8. Example of clutter measurements used for the calibration of antenna azimuth angle.

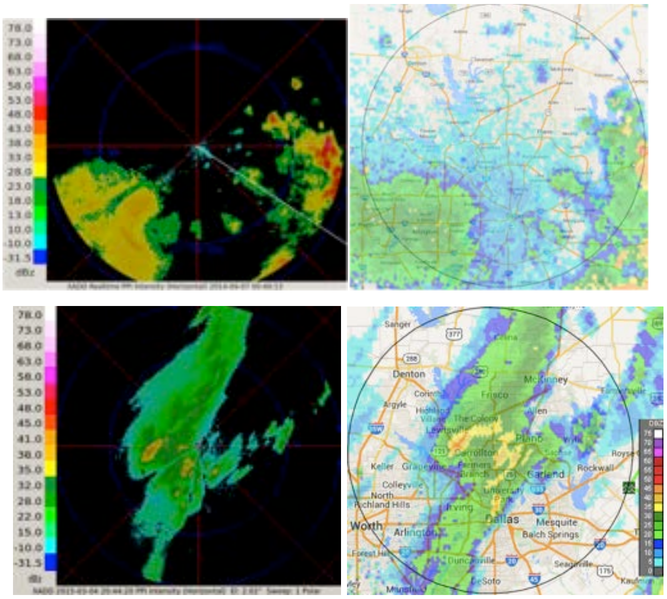

Figure 9. Comparison of reflectivity measurements from Ranger-X1 (left) and NEXRAD KFWS radar (right).

This section shows some examples of radar observations from a Ranger-X1 system recently installed in the Dallas/Fort Worth area for the U.S. Collaborative Adaptive Sensing of Atmosphere (CASA) center.

Figure 8 shows the near range clutter observations (several kilometers) of Ranger-X1 in order to do a calibraiton of azimuth orientation. Locations of several high buildings can be found in the radar reflectivity image and are compared with their exact locations (latitude and longitude in the map). The angle of the antenna beam can then be accurately calculated and used for radar antenna alignment.

Figure 9 shows comparisons of radar refletivity meauserd by X-band Ranger-X1 radar and S-band NEXRAD KFWS radar. The data for two cases were collected at 0040UTC on 07 September 2014 and at 2044UTC on 04 March 2015, respectively. It is noted that the storm features observed by both X-band and S-band radars match well. The measurement difference is mainly attributed to different elevation angles and range volumes between X-band and S-band radars. Considering Ranger-X1 radar only has 100W transmitters, it is amazing that its measurements are comparable with the high power (~500kW) NEXRAD radar system.

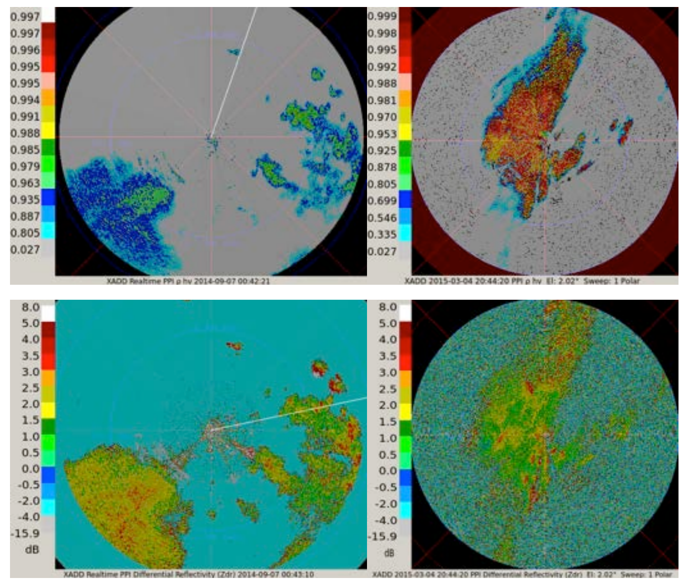

Figure 10. Dual-pol measurements ρ_{hv} and Z_{DR} for case 09/07/2014 (left) and case 03/04/2015 (right)

Figure 10 displays dual-polarization moments correlation coefficient (ρ_{hv}) and differential reflecitivty (Z_{DR}). The first case was using the legacy estimator while the second case applied the novel multi-lag signal processing method for estimating ρ_{hv} and Z_{DR} [8]. As expected, the ρ_{hv} reduction and Z_{DR} bias attributed with the low SNR have been mitigated with the multi-lag signal processing.

Figure 11 gives another example (1700UTC, 22 February 2015) of Ranger-X1 measurements. Due to the larger coverage of the storm cell, beam blockage is evident in several directions (e.g., northeast, southwest, south, and east). The beam blockage is caused by the trees around the radar, which has been deployed only about 12 meters above the ground. The blind region, which is a common problem for solid-state radar, has been well filled with the design of three-pulse waveform. The sensitivity discontinuity is hardly discerned in radar data and only can be seen in ρ_{hv} measurement (raw ρ_{hv} without correction). This makes sense because ρ_{hv} is a good indicator of data quality. The Ranger system applies a Φ_{dp}-based attenuation correction algorithm. The comparison of raw and corrected reflectivity is shown in the first two panels. The signal quality index (SQI) image generally shows moderate to large values in the precipitation region and is useful to identify the turbulence in the storm. All these results imply Ranger's exceptional capability in weather surveillance.

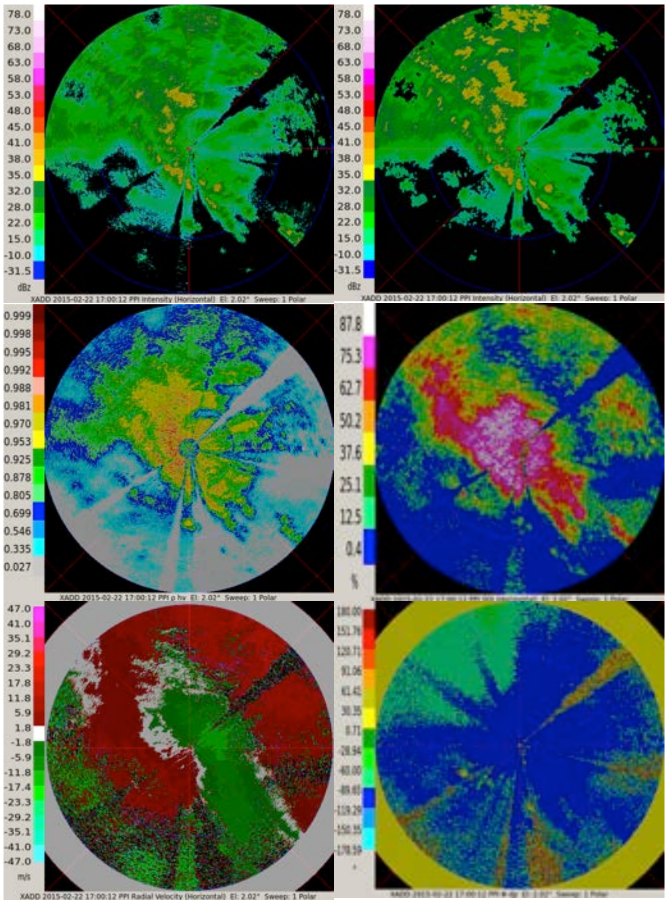

Figure 11. Ranger-X1 measurements (from top to bottom, left to right): raw Z_H, corrected Z_H, ρ_{hv}, SQI, v_h, and Φ_{dp}.

V. DISCUSSIONS AND CONCLUSSIONS

The current paper shows some datasets collected with a 100W operational Ranger-X1 system and demonstrates Ranger-X1's good performance in weather surveillance within the range of 50km. Recently EEC delivered several 500W Ranger-X5 systems. One Ranger-X5 was deployed for local TV station (KLTV) in Tyler, TX and has also shown good observations beyond 100km in its operational mode.

With the success in Ranger system development, EEC is extending its design for higher power solid-state radar with C-/S-band capability. As compared to a traditional transmitter with 0.8 µs pulse, the current Ranger design can achieve a pulse compression ratio (PCR) from 60:1 to 90:1, depending on system configurations. That is to say, a 5.6-8.3kW solid-state radar system can achieve similar performance compared to a 500kW tranditional radar, which is currently popular in many national radar networks. Overall, the solid-state radar design is a promising approach for future radar networks. The radar power can be effectively reduced by using the pulse compression technique. More importantly, the reliability and useful lifetime of radar can be enhanced as well.

In summary, Ranger-X1/X5 series are EEC's next generation X-band polarimetric weather radar systems. Ranger combines advanced solid-state design with pulse compression techniques, and a maintenance-free mechanical design, all in a compact, lightweight assembly. The unique TFM waveform scheme and optimized NLFM waveform design enable Ranger to achieve exceptionally high performance in weather surveillance. EEC is leveraging this experience and these techniques in the design of higher power solid-state radar for long-range surveillance applications.

ACKNOWLEDGMENT

The authors would like to acknowledge the Ranger production team at EEC for their hard work on the Ranger series radar systems. The authors would also like to thank Dr. Brad Isom at National Severe Storms Laboratory, Dr. Robert Palmer, Dr. Boon-Leng Cheong, Redmond Kelley, and Dr. Yan Zhang at the Advanced Radar Research Center, University of Oklahoma, and Scott Harper and Edoardo Vitali from ELDES company for their contributions to the development of Ranger prototype.

REFERENCES

[1] B. Cheong, R. Kelley, R.D. Palmer, Y. Zhang, M. Yeary, T. Yu, "PX-1000: A Solid-State Polarimetric X-Band Weather Radar and Time–Frequency Multiplexed Waveform for Blind Range Mitigation," Instrumentation and Measurement, IEEE Transactions on , vol.62, no.11, pp.3064,3072, Nov. 2013

[2] N. Bharadwaj, V. Chandrasekar, "Wideband Waveform Design Principles for Solid-State Weather Radars." *J. Atmos. Oceanic Technol.*, 29, 14–31, 2012

[3] B. Isom, J. Helvin, M. Jones, M. Knight, "A New Compact Polarimetric Solid-State X-Band Radar: System Description and Performance Analysis," pre-print, *93rd AMS annual meeting*, Austin, TX, 5-10 January 2013

[4] Mudukutore, A.S.; Chandrasekar, V.; Keeler, R.J., "Pulse compression for weather radars," Geoscience and Remote Sensing, IEEE Transactions on , vol.36, no.1, pp.125,142, Jan 1998

[5] M. Shinonaga, J. Suzuki, S. Yajima, S. Nishimoto, "New weighting method to synthesize a zero sidelobe correlation filter for burst signals." *Electron. Comm. Jpn.* Pt. I, 90: 25–35, 2007.

[6] Gran, F.; Jensen, J.A., "P2F-6 Designing Non-Linear Frequency Modulated Signals for Medical Ultrasound Imaging," Ultrasonics Symposium, 2006. IEEE , vol., no., pp.1714,1717, 2-6 Oct. 2006

[7] J. Kurdzo, B. Cheong, R.D. Palmer, G. Zhang, "Optimized NLFM Pulse Compression Waveforms for High-Sensitivity Radar Observations," IEEE, 2014 Radar conference, Cincinnati, OH, May 19-23, 2014

[8] Q. Cao; G. Zhang; R.D. Palmer; M. Knight.; R. May; R.J. Stafford, "Spectrum-Time Estimation and Processing (STEP) for Improving Weather Radar Data Quality," *Geoscience and Remote Sensing*, IEEE Transactions on , vol.50, no.11, pp.4670-4683, Nov. 2012