16B.2 MOBILE RAPID-SCANNING X-BAND POLARIMETRIC (RaXPol) DOPPLER RADAR SYSTEM

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1. INTRODUCTION

ProSensing Inc., in collaboration with the University of Oklahoma (OU), developed a novel, X-band, rapid-scan mobile radar for severe-weather research. The key features of this new radar include a pedestal that can rotate in azimuth a 2.4 m diameter dual-polarized parabolic dish antenna at 180^o s^{-1}, and a frequency-agile, high-power transmitter. In a typical rapid-scan mode, the radar can complete a 10^o elevation-angle volume scan over 360^o in about 20 seconds, while maintaining a 1^o sampling resolution in azimuth. Standard data products include V and H-polarized reflectivity, Doppler velocity mean and standard deviation, H-V correlation coefficient and differential phase. This paper describes the RaXPol radar system and presents a small sample of data collected in the U.S. Central Plains during the 2011 spring tornado season.

2. SYSTEM DESCRIPTION

A simplified block diagram of the RaXPol radar system is shown in Figure 2 with the system parameters summarized in Table 1. A 10 MHz crystal oscillator, located in the *LO Signal Generator* section, serves as the reference to all the oscillators and timing circuits of the radar. Transmission is initiated by *Transmit Pulse Generator* circuit, which can produce a user defined RF pulse with arbitrary frequency modulation and amplitude taper. The only limitation on the transmitted pulse is the 40 MHz bandwidth of the transceiver and the 40 us maximum pulse length of the TWTA. The *TX Upconverter* section mixes the transmit pulse to the 9.73 GHz center transmit frequency and can hop the frequency from pulse-to-pulse to ensure independent radar parameter samples. The transmit pulse is amplified by the TWTA to 20 kW peak power and then split by a *Magic Hybrid T* to send equal power to the Vertically (V) and Horizontally (H) polarized ports of the 2.4 m diameter parabolic dish antenna. Each receiver channel contains a passive, two-stage (gas and solid-state) limiter, a 1 dB noise figure low-noise amplifier, a band-pass filter, and a single down-converter stage. The transmitted frequency hops are compensated by the receiver LO signal to keep the receiver output frequency centered at 90 MHz. The *Digital Receiver* samples the 90 MHz V and H received signals at a rate of 120 MHz and then uses a 90 MHz digital LO signal and a programmable low-pass filter to obtain the complex envelope (I and Q) samples. The complex series of V and H samples are decimated to a user selectable range-gate-spacing from 7.5 to 75 m, before transfer to the *Server PC* for processing.

Figure 1. RaXPol radar deployed in a severe thunderstorm on 14 June 2011 in central Oklahoma (photo by A. Pazmany).

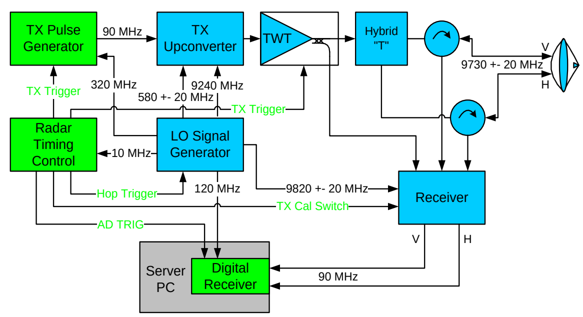

Figure 2. RaXPol radar simplified system block diagram.

3. DATA ACQUISITION SYSTEM

The server computer, using dual-quad core 2.66 GHz Xeon processors performs all the remaining signal processing: pulse compression, clutter filtering, the calculation of various moments, averaging and assimilation with auxiliary data (pedestal, GPS, system health, etc.). The data acquisition system can transmit large blocks of processed data via a network connection to client computers for gap-free real-time display and can record the raw I/Q time series from the digital receiver, averaged data products. These available data products include: V and H channel measured power (for estimating dBZ and Z_{dr}), complex autocorrelation at one or two lags (Doppler velocity mean and standard deviation) and zero-lag V-H Cross-correlation (ρ_{hv} and

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K_{dp}). The data system can also compute, display and record the power spectrum of the V and H received signals and V-H cross-spectra.

Table 1. RaXPol key system parameters.

Parameter	Value
Center Frequency	9.73 GHz +-20 MHz
Transmit Power	20 kW peak, 200 W ave.
Transmit Pulse Width	0.1 – 40 us
Transmit Waveform	RF Pulse, Linear or Custom Chirp
Transmit Polarization	Equal Power V&H
PRF	Uniform or Staggered
Antenna type	Dual-linear Polarized Parabolic Reflector
Antenna Diameter	2.4 m
Antenna Beamwidth	1.0^{o} Half-power
Antenna Gain	44.5 dB
Pedestal Type	Elevation over Azimuth
Pedestal Scan Rate	180 deg s^{-1} Az, 36 deg s^{-1} El
Receiver type	Dual-channel (V & H-pol)
Receiver Noise Figure	3 dB
Receiver Bandwidth	0.5 to 40 MHz, or Custom
Range Gate Spacing	7.5 to 75 m
IF Frequency	90 MHz
Digital Receiver	Dual-channel, 16 bit ADC
Dynamic Range	90 dB @ 1 MHz Bandwidth
Processor	Industrial PC, Dual Quad-core 2.66 GHz Xeon
Clutter Filter	Coherent, User Defined Bandwidth

4. RAPID-SCAN OPERATION

4.1 STANDARD MODE

In standard rapid-scan mode, the radar transmits uniformly spaced pulse pairs, or staggered three pulse groups, while shifting the frequency of each group by the pulse bandwidth to ensure independent sampling, as shown in Figure 3. At the 180 deg s^{-1} scan speed, the antenna moves a beamwidth (1 deg) in 5.6 ms, so the data acquisition is configured to average for 5 ms, to acquire data from 12 pulse pairs, each spaced 200 μs. Frequency hopping speeds the convergence of the averaged radar parameters to the mean, and reduces second trip echo contamination of data from the first pulse in each group.

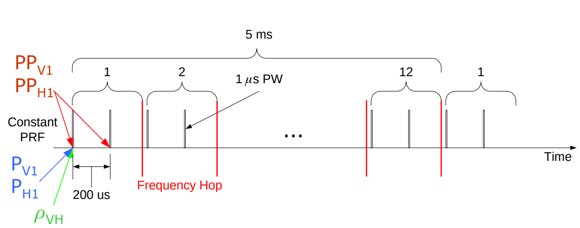

Figure 3. In standard rapid-scan mode, the radar transmitted frequency is hopped (shifted) by the pulse bandwidth after each pulse-pair to ensure independent sampling during the brief, 5 ms averaging interval.

In rapid-scan mode, the pedestal azimuth speed is fixed close to 180^{o} s^{-1}. In PPI scan mode, the antenna beam elevation is fixed, but in volume-scan mode it is changed after every azimuth sweep as shown in Figure 4. The elevation transition steps are programmed to occur towards the front of the truck so the continuous and constant elevation-scan sections are towards the rear, where there is a clear line of sight to the horizon.

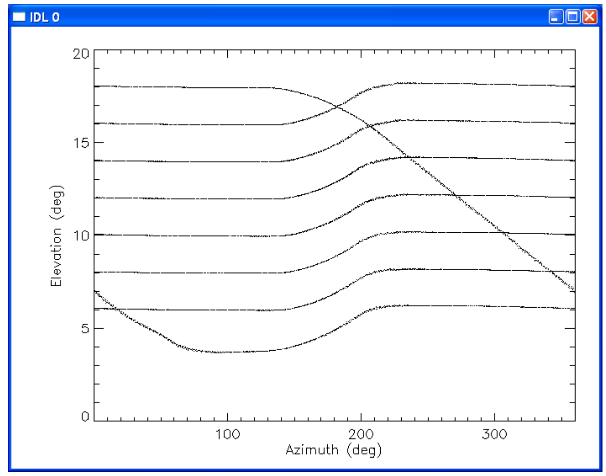

Figure 4. An example of a rapid-scan pattern with seven elevation steps, spaced 2^{o}. The clear line of sight is towards the rear of the truck, so the elevation is changed while the antenna rotates past the front of the truck.

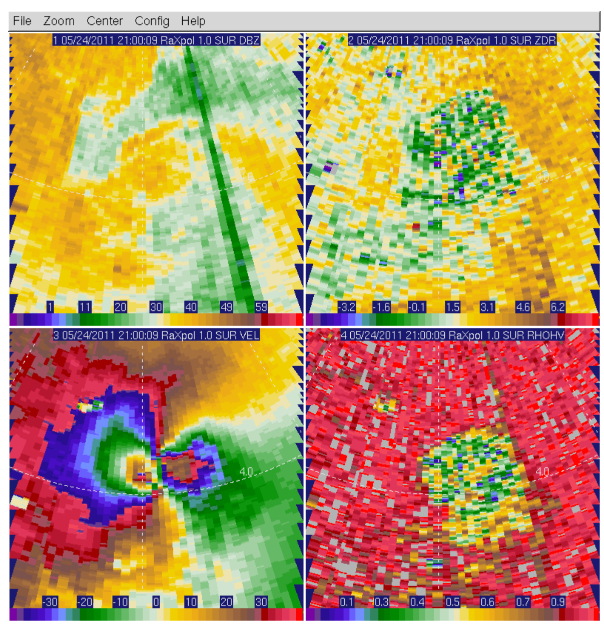

Figure 5. A data set collected at close range from an EF-5 tornado on 24 May 2011 in central Oklahoma, in standard rapid-scan mode. Elevation angle was 1^{o}. Top left: dBZ; Top right: Z_{dr}; Bottom left: radial velocity; Bottom right: ρ_{hv}. Vortex signature is seen (unfolded velocities), along with low Z_{dr} and ρ_{hv} debris signatures.

An example of data collected in rapid-scan mode in a large and powerful tornado is shown in Figure 5. The data were of high quality and show patterns in reflectivity, Doppler velocity, differential reflectivity, H-V correlation coefficient, standard deviation of Doppler velocity (not shown in the figure) and differential phase (not shown in the figure) that one would expect. Similar images were obtained every two seconds at each elevation angle; for a six-minute period, data were collected at low elevation angle every two seconds, affording unprecedented temporal resolution for the evolution of a strong tornado, including polarimetric parameters.

4.2 STROBE MODE

Temporal averaging, with mechanically scanned weather radars, smears the data in the scanning direction, consequently degrading the angular resolution of the radar images. This smearing can be especially significant at high scan rates unless the averaging time can be kept very short. RaXPol only averages data from 12 pulse pairs in rapid scan mode, when using 5 kHz PRF (30 km unambiguous range), yet still degrades angular resolution by an additional beamwidth, to approximately 2^{o}. In attempt to practically eliminate beam smearing, a novel *Strobe* technique was tested with RaXPol, which reduces the averaging time to the absolute limit of just a single pulse pair and thus preserves the 1^{o} antenna beamwidth angular resolution.

The strobe technique is illustrated in Figure 6 through Figure 12. The idea is to combine all the pulse-pairs of the averaging interval of a standard pulse pattern shown in Figure 3 to a single Strobe pulse pair (Figure 6), such that the first Strobe pulse contains all the *first* pulses of the standard pulse pairs and the second Strobe pulse contains all the *second* pulses. Each Strobe sub-pulse segment is amplitude tapered, and the sub-pulse frequency shift is increased to improve the isolation between the sub-pulses and their corresponding backscattered signal, as shown in Figure 7 and Figure 8. The radar receiver bandwidth and data-acquisition sampling-rate also has to increase to be able to capture all the pulse segments simultaneously. The sub-pulse segments are separated using a bank of digital filters, each tuned to a specific sub-pulse center frequency. The isolated sub-pulse returns are then processed just like standard measurements. Figure 9 illustrates the received Strobe pulse signal and one of the sub-pulse components obtained after digital filtering. The corresponding averaged received power from all 11 sub-pulse segments is shown in Figure 10.

The few drawbacks of the Strobe technique are range side-lobes due to finite isolation between the sub-pulse segments, illustrated by the sub-pulse signal (red line) near the transmitted pulse in Figure 9, and increased minimum range due to the longer Strobe pulses. With 1 μs sub-pulse length and 11 pulse segments, this minimum range is $c\tau/2$ = 1.65 km. Furthermore, the radar transmitter, receiver and data system has to have much wider bandwidth to be able to receive all the frequency spaced sub-pulse segments simultaneously.

5. STROBE-MODE RESULTS

The strobe technique was tested with RaXPol on a small thunderstorm in Oklahoma on 12 July 2011. The antenna was rotating at close to 190 deg/sec, in the pattern shown in Figure 6, and the 1 μs, 11 sub-pulse strobe-pattern was used to obtain 11 independent samples for the estimation of each reflectivity and Doppler velocity data point. The sub-pulse segments were spaced 3 MHz, so a minimum of 34 MHz bandwidth was required for the measurement. The data system recorded raw I/Q samples at 40 MHz rate and the data were post-processed. An example set of radar images obtained from this data set is shown in Figure 11 and Figure 12.

We plan to follow up this successful proof of concept demonstration with the collection of point target (corner reflector) data for quantitative evaluation of the technique and for comparing angular resolution with data collected in standard pulsing mode.

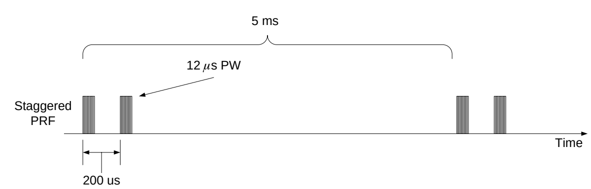

Figure 6. Strobe rapid scan pulse pattern. In this mode the pulse pattern of Figure 4 is condensed into two longer, stepped frequency pulses to eliminate the beam smearing associated with the 5 ms averaging interval.

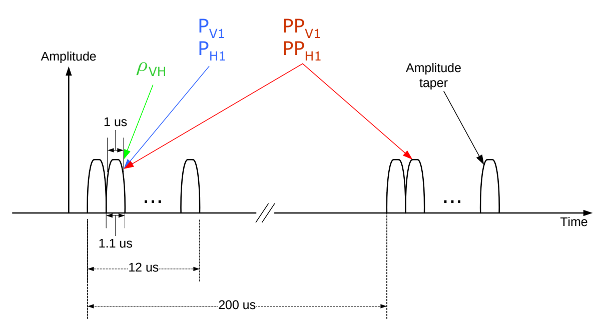

Figure 7. The sub-pulse segments of the Strobe mode pulse pattern. Each Strobe pulse is made up of amplitude tapered and frequency shifted sub-pulses.

6. CONCLUDING REMARKS

Since the delivery of RaXPol to OU in April 2011, it has been used to document three tornadoes during a tornado outbreak in central Oklahoma on 24 May, a supercell in southwest Oklahoma that produced the largest hail ever recorded in the state (and a funnel cloud) on 23 May, a damaging microburst and hailstorm in central Oklahoma on 14 June when co-located with the S-band polarimetric Doppler radar KOUN, bats emerging from their cave in Texas in late June, and the landfall of Hurricane Irene in North Carolina on 27 August. Results from these cases will be presented in the future after analyses of the data have been completed.

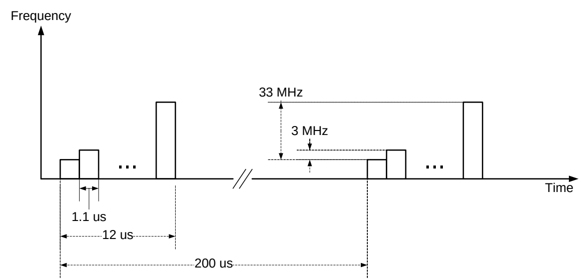

Figure 8. The Strobe mode was tested using 1 μs sub-pulse width and 3 MHz sub-pulse to sub-pulse frequency steps. With 11 sub-pulse segments, the total transmitted pulse bandwidth was 34 MHz.

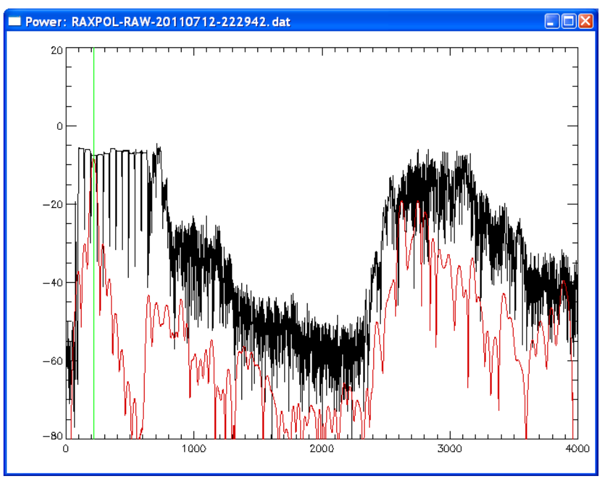

Figure 9. Strobe mode received signal including the transmitted pulse (black), one of the isolated sub-pulse segments (red) and the corresponding zero range gate (green).

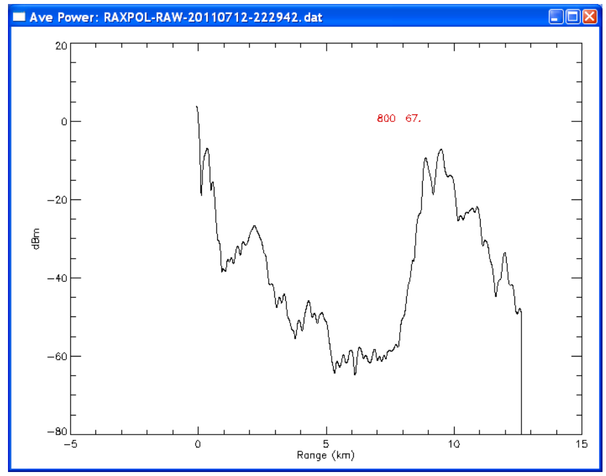

Figure 10. A single ray of averaged received power, obtained from a single Strobe pulse, made up of 11 sub-pulse segments.

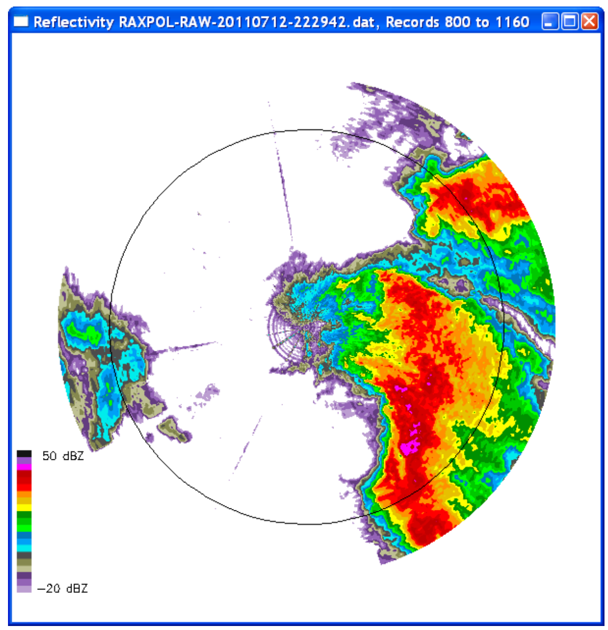

Figure 11. Rapid scan Strobe mode reflectivity image obtained from a thunderstorm on 12 July 2011 in Oklahoma.

7. ACKNOWLEDGMENTS

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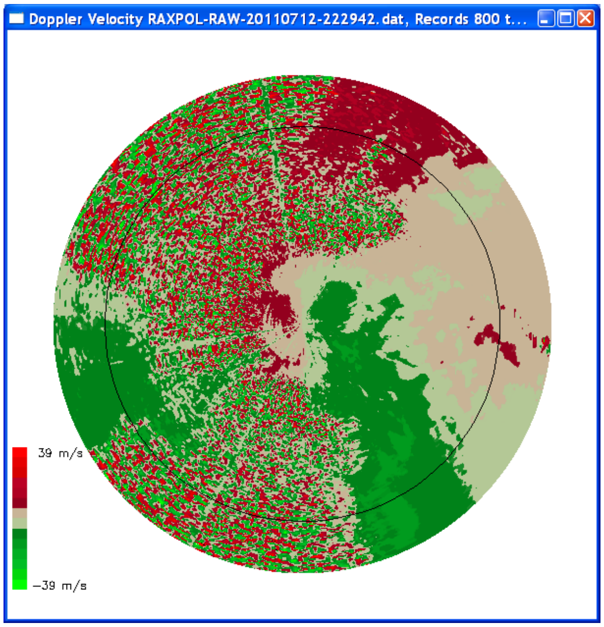

Figure 12. Rapid scan Strobe mode pulse-pair mean Doppler velocity image of the thunderstorm shown in Figure 11.