1. Introduction

A Stepped Frequency-Modulated (Stepped FM) Strobe pulse-pair technique was developed and tested with the University of Oklahoma Rapid scanning X-band polarimetric Doppler weather radar (RaXpol) to effectively eliminate beam-smearing during high speed scanning (Pazmany et al. 2011, Bluestein et al. 2012). The dwell time of weather radars with frequency hopping transmit waveforms is proportional to the desired number of independent samples and Pulse Repetition Interval (PRI). In order to maintain an angular resolution comparable to the antenna beam-width, the dwell time is limited to the time it takes the antenna to scan one beamwidth. However, at very high scan rates with narrow antenna beams, this dwell time limit is insufficient to provide adequate range coverage while collecting enough samples for the precise estimation of the radar parameters. Strobe mode decouples the dwell time from independent sample count by transmitting a series of frequency shifted sub-pulses within a single radar waveform. The sub-pulses, which contain independent estimates of the weather echo, are processed separately using a bank of digital filters, and then averaged. This technique opens up the possibility of developing narrow-beam mechanically-scanned weather radars with very high scan rates.

This paper outlines the fundamental limitations of using conventional transmit waveforms with rapid scanning weather radars, describes strobe mode, analyzes the benefits and drawbacks of the technique and compares the angular resolution of RaXPol data collected in rapid scan conventional and strobe modes from thunderstorms.

2. Conventional Frequency Hopping Pulse Pair Mode

In standard rapid-scan pulsing mode, the radar transmits uniformly spaced pulse-pairs (or staggered pulse-triplets), while shifting the frequency of each group by at least the pulse bandwidth to ensure independent sampling, as shown in Figure 1. The dwell (or integration) time in this pulse pattern is a product of the number of pulses per group, the number of pulse groups (N) and the Pulse Repetition Interval (PRI). It is desirable to minimize the dwell time to maintain an angular resolution comparable to the antenna beam-width, but reducing the number of samples degrades measurement precision and PRI is determined by the desired unambiguous range coverage ($R_{max}$), according to $PRI=\frac{2R_{max}}{c}$; where $c$ is the speed of light. The resulting beam smearing ($\theta_{bs}$), or angular averaging interval for a given pedestal scan speed ($V_{ped}$), can be approximated as $\theta_{bs}=4V_{ped}NR_{max}/c$. The resulting loss of angular resolution is insignificant as long as $\theta_{bs}$ is less than the antenna beam-width ($\theta_{abl}$), but with rapid scanning radars with narrow pencil beams, such as the OU RaXpol radar it can be significant. In a typical deployment near a tornadic storm, the 1˚ beam-width RaXpol antenna is scanned at 180 deg/sec, 12 pulse pairs are averaged in a dwell and the PRI is configured to be able to observe to about 40 km, so $\theta_{bs}=1.2^\circ$, which effectively broadens the angular resolution by about 40% (Doviak and Zrnic 1984). This loss in resolution using conventional pulsing mode would be even more severe with possible future rapid scanning radars with even narrower antenna beams and higher scan rates. Strobe pulsing mode decouples the dwell time from independent sample count, thereby allowing the development of weather radars with faster update rates and finer resolution.

![Figure 1](image)

**Figure 1.** In standard rapid-scan mode, the radar transmitted frequency is hopped (frequency shifted) by at least the pulse bandwidth after each pulse-group to ensure independent sampling during the averaging interval. To avoid second-trip echo contamination, V- and H-channel power ($P_V$ and $P_H$) and correlation coefficient ($\rho_{HV}$) are estimated from the first sample in each pair.
3. Strobe Mode

There are two Strobe mode options to speed the acquisition of independent samples while maintaining sensitivity and without changing the transmitted power: 1) Range Averaging of high resolution pulse compressed data or 2) Stepped-FM (Frequency Modulated) pulses in combination with a bank of digital receivers.

Range Averaging strobe mode is illustrated in Figure 2. It is a straightforward technique of transmitting $N*PW$ duration frequency modulated (chirped) pulses with $N/PW$ bandwidth, compressing the received signal to a $PW/N$ sub-cell pulse length and then summing the radar parameters of $N$ neighboring sub-cells to obtain an averaged $PW$ pulse length equivalent range gate. Disadvantages of this technique over conventional frequency hopped pulse pair mode are that range side-lobes extend well beyond the original $PW$, a slight loss of sensitivity due to TX pulse amplitude tapering and finite compression filter efficiency, and that minimum range is extended due to the longer transmit pulse length. Another potential drawback of this technique is that the effective number of independent samples can be much less than $N$ if there is a large variation in sub-cell reflectivity. This is because the weather return power standard deviation equals the mean (exponential distribution), so a few highly reflective sub-cells can dominate the fading and consequently the standard deviation of the estimated radar parameters.

Figure 2. Range averaging technique to reduce fading while maintaining sensitivity and range resolution.

Another strobe option is Stepped FM, shown in Fig. 3. The idea is to combine all the pulse-pairs of the averaging interval of a standard pulse pattern shown in Figure 1 to a single stepped frequency strobe pulse pair (Fig. 3), such that the first strobe pulse contains all the energy of the first pulses of the standard 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. The radar receiver bandwidth and data-acquisition sampling-rate also has to increase to be able to capture all the pulse segments simultaneously. The received signal from the various 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. Fig. 4 illustrates a RaXPol received Stepped FM strobe pulse signal and one of the sub-pulse components obtained after digital filtering.

The drawbacks of the Stepped FM strobe technique are similar to Range Averaging: range side-lobes due to finite isolation between the sub-pulses, slight loss of sensitivity due to the amplitude tapering of the sub-pulse segments, and an increased minimum range due to the longer strobe pulses. But unlike Range Averaging, the Stepped FM pulse segments can be frequency shifted further than $1/PW$ to improve sample independence. However, this extra bandwidth also requires the radar transmitter, receiver, and data system to support wider bandwidth to be able to transmit and receive all the frequency-spaced sub-pulse segments simultaneously.
Fig. 3. The Stepped FM strobe mode combines the pulse pairs into a single pair of much longer stepped frequency-modulated pulses, with each sub-pulse segment amplitude tapered and frequency shifted. The backscattered signal is processed using a bank of digital receivers, the radar parameters corresponding to each sub-pulse segment are calculated and finally the data from all the pulse segments are averaged.
4. Data Collected

The *Stepped FM* strobe technique was tested with RaXPol on a small thunderstorm in Oklahoma on 12 July 2011. The antenna was rotating at close to 190° s\(^{-1}\), and the 1 µs, 11 sub-pulse strobe-pattern shown in Fig. 4 was used to obtain 11 independent samples for the estimation of each radar parameter 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 reflectivity images comparing conventional pulsing mode (left) with *Stepped FM* strobe mode (right) is shown in Fig. 5. The two data sets were collected about a minute apart so we assume that there was little change in the rain field. The absence of beam smearing in the *Stepped FM* image (right) is evident by the higher reflectivity gradients at the edges of the rain shaft.

**Fig. 4.** Stepped FM strobe mode received signal including the transmitted pulse (black), one of the isolated sub-pulse segments (red) and the corresponding zero range gate (green line).

**Fig. 5.** Radar reflectivity images collected a minute apart from a thunderstorm on July 12, 2011 in Oklahoma using conventional pulsing mode (left) and Stepped FM strobe mode (right).
Conclusion

To the best of our knowledge, this is the first Stepped FM strobe mode data set collected to eliminate beam smearing with scanning weather radar. The extra frequency separation between sub-pulses segments helps ensure sample independence, resulting in high quality data.

Acknowledgment

This work was supported by the National Science Foundation MRI Grant ATM-0821231 and Grant ATM-0934307 to the University of Oklahoma. We also thank John Meier (OU ARRC) for maintaining the radar.

References

