Design considerations for improved tornado detection using super-resolution data on the NEXRAD network

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1 Introduction

Legacy-resolution base data on the NEXRAD network consists of reflectivity on a 1 km-by-1 deg polar grid and Doppler velocity and spectrum width on a similar 250 m-by-1 deg grid. It has been shown that mesocyclone and tornado signatures can be detected at ranges about 50% greater than the current detectable ranges using base data with finer resolution on a 250 m-by-0.5 deg grid (Brown et al. 2002.) Data produced this way is termed super-resolution data. The U.S. National Weather Service tasked the National Severe Storms Laboratory (NSSL) with evaluating the benefits of super-resolution data and formulating the best implementation approach. This paper addresses engineering design considerations, presents the recommended signal processing solution with some of the associated trade-offs, and quantifies the improvement in tornado detection that is expected once super resolution becomes operationally available.

2 The resolution of super resolution data

Achieving super resolution on the NEXRAD network involves producing spectral moment estimates on a finer grid (250 m-by-0.5 deg) and also reducing the size of the corresponding resolution volumes. Along range, the depth of the resolution volume is dictated by the transmitter pulse shape and the receiver filter response. The combination of the short pulse (1.57 μs) and a receiver matched filter already provides a range resolution of 250 m (Doviak and Zrnić 1993). On the other hand, resolution volume dimensions in azimuth and elevation are determined by the effective antenna pattern.

2.1 Effective antenna pattern

The effective antenna pattern of a scanning radar defines the angular extent of the resolution volume and describes how hydrometeor contributions to the spectral moment estimates are weighted based on their azimuth and elevation relative to the center of the beam. The effective antenna pattern is analogous to the range weighting function (e.g., Zrnić and Doviak 1978) and depends on the intrinsic antenna beam pattern, the antenna motion, the number of samples used for integration to produce a radial of base data, and the weighting (i.e., the data window) applied to those samples in the signal processing.

For an antenna that moves at a constant elevation angle, the effective pattern along the elevation axis is simply the intrinsic antenna beam pattern. Further, the analysis of Zrnić and Doviak (1976) can be extended to show that the azimuthal effective antenna beam pattern $f_{eff}^4(\phi)$ corresponding to processing M samples with a data window d is given by

$$f_{eff}^4(\phi) = \gamma \sum_{m=0}^{M-1} f^4(\phi - m \cdot \Delta\phi) d^2(m), \qquad (1)$$

where ϕ is the azimuthal angle relative to the beam center, $f^4(\phi)$ is the intrinsic two-way antenna beam pattern, γ is a normalization factor such that $f_{eff}^4(0) = 1$, and $\Delta\phi$ is the azimuthal angle that the antenna moves in the time between samples (note that $\Delta\phi$ is related to the antenna rotation rate α by $\Delta\phi = \alpha T_s$, where T_s is the pulse repetition time.) In other words, the azimuthal effective antenna pattern is the convolution of the intrinsic antenna beam pattern with the square of the data window.

Fig. 1 shows the azimuthal effective antenna patterns corresponding to legacy- and super-resolution processing for a Gaussian intrinsic antenna beam pattern with a two-way 6-dB beamwidth of 0.89 deg. The effective pattern for legacy resolution was obtained with M = 32 pulses, a rectangular window, and $\Delta\phi = M^{-1}$ deg. The effective pattern for super-resolution was obtained using the same parameters except that M = 16 (i.e., half the number of samples used in the legacy-resolution radial).

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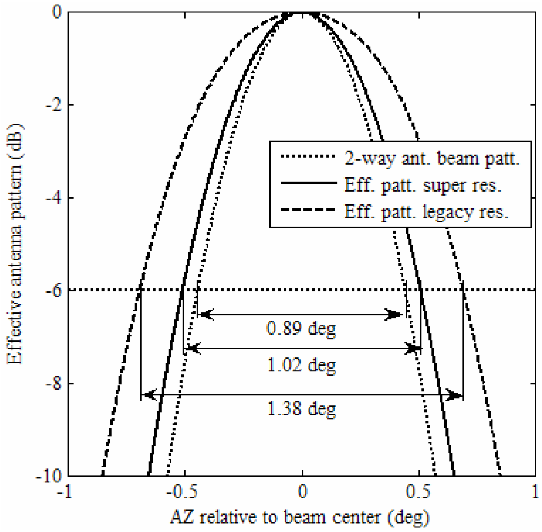

Fig. 1. Effective antenna patterns corresponding to legacy- and super-resolution processing for a Gaussian intrinsic antenna beam pattern with a two-way 6-dB beamwidth of 0.89 deg.

2.2 Required azimuthal resolution

It is evident that without advanced signal processing techniques, the angular extent of the resolution volume cannot be smaller than what is dictated by the antenna beam pattern (the 6-dB two-way antenna beamwidth average for all radars in the NEXRAD network is 0.89 deg). Indeed, for legacy-resolution data, the antenna moves azimuthally 1 deg per radial (during the dwell time) and there is no data window applied to the samples, leading to an effective beamwidth of 1.38 deg.

The initial concept for producing super resolution was envisioned as splitting every legacy 1-deg radial into two 0.5-deg radials, each with half the samples from the original 1-deg radial. Herein, this is referred to as conventional super resolution. Because of this initial concept, the goal for super resolution is to have the effective beamwidth of conventional super resolution; i.e., 1.02 deg (see Fig. 1.)

The key for designing an operational implementation of super resolution is achieving the desired effective beamwidth within the constraints imposed by the system limitations and the users' needs.

3 The errors of super resolution data

Referring back to the original concept for super resolution, it is easy to see that a smaller effective beamwidth comes with larger errors of estimates. That is, compared to legacy-resolution data, using half the number of samples for the 0.5-deg radials of conventional super resolution increases errors in the estimation process by a factor of about $2^{1/2}$. This is true not only for conventional super resolution but also for any combination of number of samples per radial and data window that results in the same effective beamwidth. In general, errors of base data estimates are inversely proportional to the effective beamwidth. Thus, for a given effective beamwidth, increasing the number of samples does not reduce the errors of estimates. If super resolution data is bound by the same data quality requirements of legacy resolution data, advanced signal processing techniques such as range oversampling and whitening (Torres and Zrnić 2003) must be employed. In theory, a modest oversampling factor is enough to bring the errors of super resolution data down to acceptable levels (matching legacy-resolution data).

4 Implementation of super resolution

The operational implementation of super resolution must satisfy the fundamental scientific goals within the system constraints. Brown et al. (2002) concluded that the benefits of super-resolution data can be fully realized through finer range and azimuthal sampling in conjunction with a narrower effective antenna pattern (i.e., a smaller effective beamwidth). Finer sampling is simply achieved by centering time-series data radials on 0.5 deg azimuthal increments and bypassing range averaging (required for the legacy-resolution data) to maintain a 250-m resolution in range. On the other hand, reducing the effective beamwidth can be done in a number of ways. An obvious approach is to reduce the azimuthal extent of the radials, either by collecting fewer samples per radial or by reducing the antenna rotation rate. Another way is to apply a tapered weighting to the samples in the radial (i.e., windowing the data.) If other legacy operational goals are to be maintained (e.g., volume update times, maximum unambiguous range and velocity, etc), the only parameters that can be modified are the number of samples per radial and/or the data window.

To ensure compatibility with other algorithms (especially those that operate in the spectral domain), the number of samples per radial cannot be smaller than that used to generate legacy-resolution data. Increasing the number of samples per radial is also not a viable option if the goal is to conserve processing capabilities, an important consideration for a system with several planned signal processing improvements and limited hardware upgrades. Thus, by maintaining the number of samples per radial used for the legacy-resolution data, the only remaining alternative to reduce the effective beamwidth is to apply a suitable data window.

The desired resolution is the one obtained with conventional super resolution (an effective beamwidth of 1.02 deg). The von Hann window works best in this situation because for the same antenna rotation rate and pulse repetition time, the resolution provided by a von Hann window on M samples is equivalent to that of a rectangular window on $M/2$ samples (conventional super resolution). However, for compatibility with the spectral clutter filtering function, the more aggressive Blackman window must be substituted for the von Hann window, leading to larger errors of estimates.

Because Radar Product Generation (RPG) algorithms that ingest NEXRAD base data are designed to operate on legacy-resolution data, super-resolution data will be initially used only for visualization purposes (a long-term goal is to modify some of the RPG algorithms to benefit from the super-resolution data stream.) It was experimentally determined that, for visualization purposes, the higher errors of estimates that come with a narrower effective beamwidth are operationally acceptable. However, the algorithms still need a legacy-resolution-like data stream. Hence, super-resolution data needs to be "down-sampled" to the legacy-resolution grid to produce suitable inputs to the algorithms. Down-sampling of super-resolution data involves recombining the information from two azimuthally adjacent and four consecutive range gates to produce base data on a legacy-resolution grid with acceptable quality.

4.1 Recommended implementation

Selective data windowing

To obtain the desired azimuthal resolution and maintain compatibility with existing signal processing functions, the following scheme is proposed. Overlapping 1-deg radials are collected every 0.5 deg and range averaging is bypassed. This provides the finer sampling grid. Additionally, for each range gate apply the von Hann window if clutter filtering is not needed (this provides the desired azimuthal resolution) or the Blackman window if clutter filtering is needed (this exceeds the desired azimuthal resolution, provides the required clutter suppression, but leads to larger errors of estimates).

Radial recombination

As discussed before, super-resolution data has larger errors due to the smaller effective beamwidth. To maintain the data quality that the algorithms are accustomed to getting with legacy-resolution data a simple down-sampling of the super resolution data is not enough. Azimuthal radial recombination takes two 0.5-deg radials and combines them into one 1-deg radial. The recombination algorithm assumes a bimodal Doppler spectrum model. That is, the spectral moments (signal power, Doppler velocity, and spectrum width) of each 0.5-deg radial completely characterize the underlying Doppler spectrum density (Gaussian assumption), and the spectral moments of the recombined 1-deg radial correspond to a composite Doppler spectrum that is the average of the two 0.5-deg radial Doppler spectra. The challenge here is that recombination occurs after base data has been thresholded based on the signal-to-noise ratio and quantized for efficient transmission and storage. Fig. 2 shows the reduction of Doppler velocity errors that is achieved using radial recombination. For all spectral moments, recombined data has almost the same accuracy of the legacy-resolution data.

5 Tornado detection using super-resolution data

Tornado vortex signatures (TVS) are characterized by extreme Doppler velocity values of opposite sign (Brown et al. 2002). The tornado detection algorithm (TDA) implemented in the RPG searches for gate-to-gate Doppler velocity differences (shear) in azimuthally adjacent radials at a constant range. One of the conditions for detecting a TVS is that the gate-to-gate velocity difference (Δv) exceeds a pre-defined threshold (Δv_{th}). Using simulated Doppler velocity fields, Brown et al. (2002) showed that super-resolution data has the potential of enhancing Δv, or in other words, to increase the range of detection. However, the limitation of using simulated fields is that different signal processing schemes cannot be tested or compared. A simulation was developed to produce tornadic time-series data that can be processed using various signal processing techniques. The simulation analyzes the estimated (not simulated) Doppler velocity field to compute Δv for different tornado vortex locations and signal processing schemes.

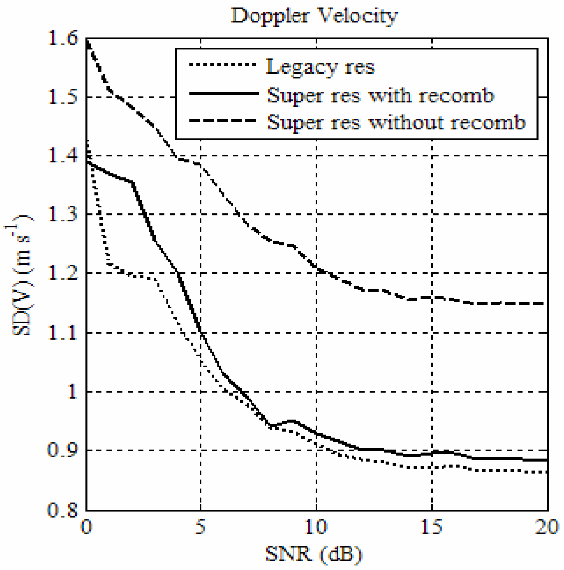

Fig. 2. Standard errors of Doppler velocity estimates as a function of the signal-to-noise ratio (SNR) for legacy resolution and super resolution with and without radial recombination. Quantization noise is included in the simulation. M = 52, T_s = 0.987 ms, and σ_v = 4 m s^{-1}. For these parameters, NEXRAD technical requirements call for SD(V) < 1 m s^{-1} for SNR ≥ 8 dB.

5.1 Simulation procedure

Our tornadic time-series simulation is based on a "scattering center" model. Scattering centers are generated on a 50 m-by-M^{-1} deg grid. The Doppler spectrum of each scattering center is computed by using a much finer grid of point scatterers that move according to a modified Rankine combined vortex model (Brown et al. 2002) and have uniform reflectivity. The tornado model is such that vortex size, strength, and location can be easily controlled. Time-series data is produced for each scattering center, and these are combined in range and azimuth using the pulse shape and the antenna beam pattern, respectively. The combined set of time-series data simulate the complex voltage samples at the radar receiver's front end. Time-series processing begins by applying either a matched filter or a pseudowhitening transformation (Torres et al. 2004) on the 5-times range-oversampled time series. Doppler velocities are estimated using the classical pulse-pair algorithm and the resulting field is analyzed to extract a value of maximum azimuthal velocity shear or Δv.

5.2 Simulation results

Tornadic time-series data were simulated for 30 range locations along the radial (every 5 km, from 5 km to 150 km.) For each range location, the tornado vortex was simulated at 100 random positions in the resolution volume. Fig. 3 shows the mean value of Δv for the 100 realizations as a function of range location. For this case, the vortex core diameter is 200 m and the maximum tangential velocity is 50 m s^{-1}. For each realization, the same 64 samples of time-series data were processed using a matched filter and a pseudowhitening transformation on range oversampled data. Additionally, matched-filtered data was used to produce both legacy- and super-resolution data. The improvement in tornado detection can be easily quantified using this figure. For example, for a Δv_{th} of 30 m s^{-1}, legacy-resolution data allows a TVS detection until about 54 km and super-resolution until about 79 km (a 46% improvement.) Using range oversampling and pseudowhitening slightly reduces the improvement to about 74 km because the associated range weighting function is flatter and leads to a "blurred" signature. However, as shown in Fig 4., the standard error of Δv is greatly improved by this technique. Note also that, as predicted, the errors of super-resolution data without radial recombination are larger compared to legacy resolution.

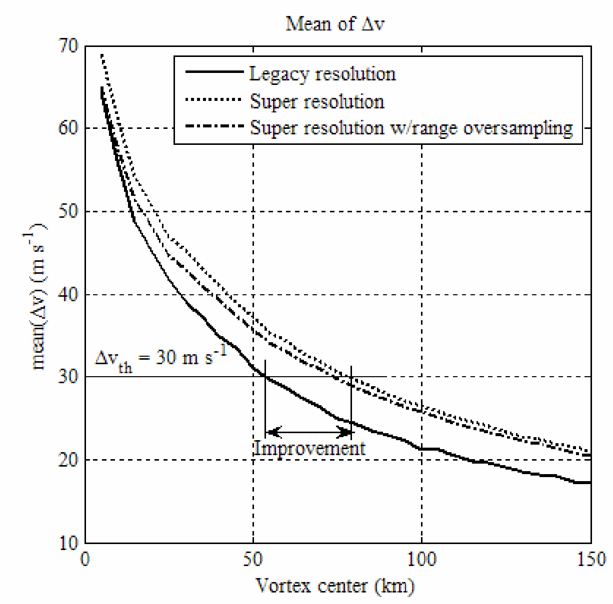

Fig. 3. Doppler velocity shear (Δv) as a function of tornado vortex location for legacy resolution and super resolution with and without range oversampling techniques.

6 Conclusions

Producing super-resolution data involves balancing the scientific and operational gains with the constraints imposed by the existing system and compatibility issues associated with other techniques scheduled for inclusion on the NEXRAD network. The main challenge is to meet base data error requirements with the narrower effective antenna beamwidth that is needed to fully realize the benefits that super resolution offers. Super resolution will become available in upcoming updates of the NEXRAD network and should lead to increased warning times and reductions in property damage, injuries, and loss of life. Near-term goals are to use super-resolution data fields for visualization only. In this case, radial recombination is necessary to feed legacy-resolution data to the algorithms. Longer-term goals include modifying some of the RPG algorithms to take full advantage of super-resolution data. To maintain data quality, super-resolution data will be produced using range oversampling followed by a pseudowhitening transformation.

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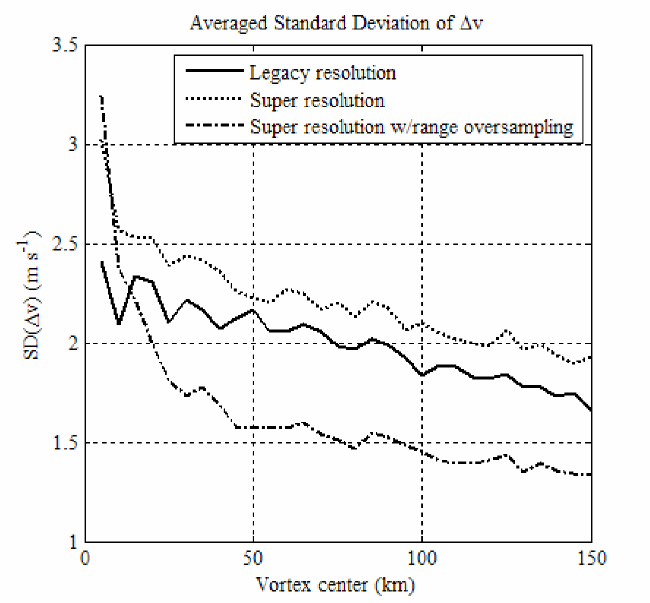

Fig. 4. Standard error of Doppler velocity shear (Δv) as a function of tornado vortex location for legacy resolution and super resolution with and without range oversampling techniques.

References

Brown, R. A., V. T. Wood, and D. Sirmans, 2002: Improved tornado detection using simulated and actual WSR-88D data with enhanced resolution. *J. Atmos. Oceanic Technol.,* **19**, 1759-1771.

Doviak, R. J., and D. S. Zrnić, Doppler radar and weather observations, San Diego: Academic Press, 1993. 2nd ed.

Torres, S. M., and D. S. Zrnić, 2003: Whitening in range to improve weather radar spectral moment estimates. Part I: Formulation and simulation. *J. Atmos. Oceanic Technol.,* **20**, 1433-1448.

Torres, S. M., C. D. Curtis, and J. R. Cruz, 2004: Pseudowhitening of weather radar signals to improve spectral moment and polarimetric variable estimates at low signal-to-noise ratios. *IEEE Trans. Geosci. Remote Sensing*, **42**, 941-949.

Zrnić D. S., and R. J. Doviak, 1976: Effective antenna pattern of scanning radars. *IEEE Trans. Aerosp. Electron. Syst.*, **AES-12**, 551-555.

Zrnić D. S., and R. J. Doviak, 1978: Matched filter criteria and range weighting for weather radar. *IEEE Trans. Aerosp. Electron. Syst.*, **AES-14**, 925-930.