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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 through simulations that mesocyclone and tornado signatures can be detected at ranges 50% greater than the current detectable ranges using higher-resolution base data on a 250 m-by-0.5 deg grid (Brown et al. 2002). Data produced this way is termed super-resolution data. Super-resolution data 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.

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 (e.g., dual polarization). Due to the complexity of adding a new base data stream and the users' urgency for better tools to detect tornado and mesocyclone signatures, super resolution will be phased into the NEXRAD network in two stages.

Initially, super-resolution data will be available at the lower elevation scans where there is a higher likelihood of finding tornado and mesocyclone signatures at farther distances from the radar. Stage one of this project does not include modifying the algorithms in the Open Radar Product Generation (ORPG) subsystem to ingest super-resolution data. At this stage, super-resolution data will be available for visualization purposes only, and the algorithms will continue to operate on a legacy-resolution data stream. Stage two of this project focuses on long-term goals; that is, novel signal processing techniques will be implemented to produce super-resolution data with the required quality, and some of the ORPG algorithms will be modified so that the benefits of super-resolution data can be fully exploited.

This paper describes the "stage-one" implementation of super-resolution data on the NEXRAD network scheduled for operational inclusion in 2008. Additionally, it presents an overview of the plans for the stage-two implementation.

2. NEXRAD SUPER-RESOLUTION DATA

Achieving super resolution on the NEXRAD network involves producing spectral moment estimates

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(base data) 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 (Doviak and Zrnić 1993). The combination of the short pulse (1.57 μs) and a receiver matched filter already provides the desired range resolution of about 250 m. On the other hand, resolution volume dimensions in azimuth and elevation are determined by the effective antenna pattern (Zrnić and Doviak 1976). For a reflector antenna scanning at a constant elevation angle, the azimuthal effective antenna beam pattern corresponding to processing  $M$  samples with a data window  $d$  is given by

$$f_{\text{eff}}^A(\phi) = \gamma \sum_{m=0}^{M-1} f^A(\phi - m \Delta\phi) d^2(m), \quad (1)$$

where  $\phi$  is the azimuthal angle relative to the beam center,  $f^A(\phi)$  is the intrinsic two-way antenna beam pattern,  $\gamma$  is a normalization factor such that  $f_{\text{eff}}^A(0) = 1$ , and  $\Delta\phi$  is the azimuthal angle that the antenna moves in the time between transmitted pulses.

Super resolution requires an effective antenna beamwidth that is about 25% narrower than the one associated with legacy-resolution data. Narrowing the effective antenna beamwidth leads to better radar resolution but at the price of reducing the quality of the base data (Torres and Curtis 2006). In general, the statistical errors of base data estimates are inversely proportional to the effective beamwidth. Hence, without additional signal processing techniques, stage-one super-resolution data will exhibit sub-standard quality.

3. SUPER RESOLUTION IN THE ORDA

The Open Radar Data Acquisition (ORDA) subsystem produces base data (reflectivity, mean Doppler velocity, and spectrum width) from time-series data (in-phase and quadrature components). Four fundamental changes are required to generate super-resolution base data in the ORDA. These are discussed next.

3.1. Finer sampling grid

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 reflectivity) to maintain 250-m resolution in range. The former is

achieved by modifying the angle table used by the signal processor to define coherent processing intervals (CPI) within the time-series data stream. The latter involves shortening the signal processing pipeline by removing the function that performs range averaging of powers before computing reflectivity. Note that this function is currently needed to produce reflectivity estimates with the required accuracy; bypassing it will result in reflectivity estimates with the desired range resolution but higher statistical errors.

### 3.2. Selective data windowing

The operational implementation of super resolution must satisfy the fundamental scientific goals while staying within the system constraints. Reducing the effective beamwidth can be done in a number of ways by varying one or several parameters in (1). However, if other legacy operational goals are to be maintained (e.g., volume update times, maximum unambiguous range and velocity, etc), and compatibility with the existing clutter filtering function (GMAP) is to be assured, the only parameter that can be modified is the data window. To obtain the desired azimuthal resolution and maintain compatibility with existing signal processing functions, the system will collect overlapping 1-deg radials every 0.5 deg. Further, for each range gate the von Hann window will be applied 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 even larger errors of estimates).

The ORDA signal processor already uses selective data windowing: every clutter filter including the bypass filter (or no filtering) has a data window associated with it. Further, available clutter filters are easily specified via a configuration file.

### 3.3. Range unfolding of reflectivity

Range-ambiguous Doppler processing usually occurs in the second cut of split cuts (i.e., the Doppler cut). Range unfolding algorithms use unambiguous powers from the first cut of split cuts (i.e., the Surveillance cut) to correctly place in range (or unfold) potentially folded velocity and spectrum width estimates. Doppler-derived reflectivity is not normally produced as an output to the ORPG. However, as will be described below, the ORPG algorithm necessitates this data to produce a legacy-like stream from the super-resolution data stream. Modifications to the ORDA range unfolding algorithm are trivial: the same manipulation in range that is done to Doppler velocities and spectrum widths is extended to reflectivities.

It is important to note that aside from this modification and the bypass of averaging of powers along range, the signal processing pipeline is not altered on account of super-resolution data. However, radials have to be processed twice as fast requiring a higher throughput which the new signal processor in the ORDA is able to handle. Changes or additions of new

processing modes should remain nearly independent from the super-resolution implementation.

### 3.4. Addition of noise power to the metadata

Another parameter needed in the ORPG to produce a legacy-like stream is the receiver noise power ( $N$ ) measured by the automatic calibration function during every antenna retrace. The noise power is used in the ORDA to compute reflectivity and to censor non-significant returns based on their signal-to-noise ratio (SNR). Adding a new parameter to the header of the recently updated radial data message is straightforward.

## 4. SUPER RESOLUTION IN THE ORPG

The Open Radar Product Generation (ORPG) subsystem ingests base data received from the ORDA via wideband communications. A suite of base and derived products is generated and distributed to various users. In addition to the infrastructure needed to handle a new base data stream (initially for visualization and archiving only), the ORPG requires just a couple of additions to handle super-resolution data.

### 4.1. Radial recombination

Although it was experimentally determined that, for visualization purposes, the higher errors of super-resolution data are operationally acceptable, the algorithms still need a legacy-resolution-like data stream. A direct solution to this problem would be to produce both legacy- and super-resolution data streams at the ORDA. However, due to bandwidth limitations between the ORDA and ORPG subsystems, only one base data stream can be transmitted. Therefore, legacy-like resolution data must be produced within the ORPG from the super-resolution data stream. This process is referred to as radial recombination.

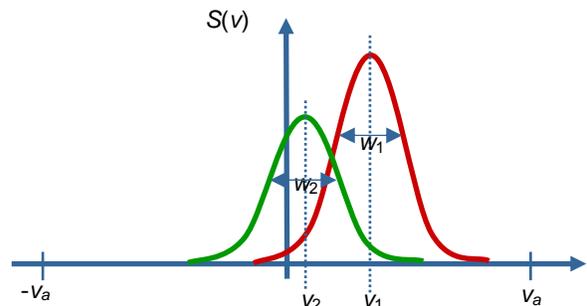


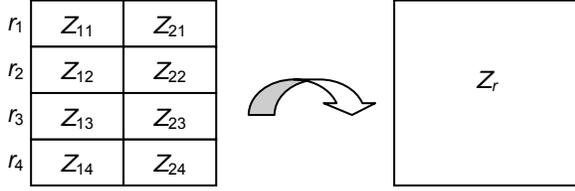
Fig. 1. Bimodal model used in the ORPG radial recombination algorithm.

Azimuthal radial recombination takes two super-resolution radials (indicated here with subscripts 1 and 2) and combines them into one 1-deg radial (indicated here with subscript  $r$ ). The recombination algorithm assumes a bimodal Doppler spectrum model as depicted in Fig. 1. That is, the spectral moments (signal power, Doppler velocity, and spectrum width) of each

super-resolution 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 super-resolution radial Doppler spectra.

#### 4.1.1 Base data recombination formulas

With the model described above, recombined reflectivity  $Z_r$  (in  $\text{mm}^6/\text{m}^3$ ) on a 1 km-by-1 deg grid is obtained by averaging the corresponding eight super-resolution reflectivities (also in  $\text{mm}^6/\text{m}^3$ ) on a 250 m-by-0.5 deg grid:



$$Z_r = (Z_{11} + Z_{12} + Z_{13} + Z_{14} + Z_{21} + Z_{22} + Z_{23} + Z_{24}) / 8, \quad (2)$$

where the range for  $Z_r$  is the midpoint between  $r_1$  and  $r_4$ , where  $r_j$  is the range corresponding to  $Z_{ji}$ .

Recombined velocity ( $v_r$ ) on a 250 m-by-1 deg grid is obtained from the super-resolution reflectivities and velocities on a 250 m-by-0.5 deg grid as:



$$v_r = \frac{Z_1 v_1 + Z_2 v_2}{Z_1 + Z_2}. \quad (3)$$

Before computing  $v_r$  from (3),  $v_1$  and  $v_2$  are dealiased to avoid improper averaging in the case that one velocity is aliased and the other one is not. After applying (3),  $v_r$  is re-aliased to the corresponding Nyquist interval.

The recombined spectrum width ( $w_r$ ) on a 250 m-by-1 deg grid is obtained from the super-resolution reflectivities, velocities, and spectrum widths on a 250 m-by-0.5 deg grid as:



$$w_r = \sqrt{\frac{Z_1 [w_1^2 + (v_1 - v_r)^2] + Z_2 [w_2^2 + (v_2 - v_r)^2]}{Z_1 + Z_2}}. \quad (4)$$

A challenging aspect of this algorithm is that radial recombination occurs in the ORPG, which is after the ORDA has thresholded the base data based on the signal-to-noise ratio, censored unrecoverable range-folded data, and quantized valid data for efficient transmission and storage. Most of the complexity of the

recombination algorithm arises from this fact and from several special conditions. Next, we describe the cases that require special handling.

- *Missing radial data.* This occurs if a radial pair is incomplete for a given antenna position. That is, if the closest available radial to complete a pair is separated by an azimuth angle larger than expected (fat radial). If only one of the super-resolution radials is available, the recombined radial is generated from it. That is, it is assumed that the missing radial is the same as the one available. If none of the radials in the pair are available, a recombined radial is not produced.
- *Beginning and end of elevation scan.* This occurs if a matching radial to form a pair simply does not exist. This would be the situation, for example, if the last radial in the elevation scan was the first radial in a pair. The recombination algorithm treats these cases as a missing radial data case.
- *PRF sector boundary.* This occurs if radials in a pair are collected with different pulse repetition times (PRT). This case is also treated as the missing radial data case with the stipulation that the radial with the smaller Nyquist velocity (longer PRT) is considered missing (the radial with the larger Nyquist velocity is retained).
- *Input anomalies.* This occurs if individual bins have missing data either due to non-significant returns (low SNR) or range folded data (purple haze). Handling input anomalies for each spectral moment is described in the following subsections.
- *Output anomalies.* This occurs if recombined bins require non-significant return or range folding censoring. After recombination, powers are re-evaluated against corresponding SNR thresholds to determine whether the recombined spectral moment is significant or not. Other censoring conditions are presented below. Note that censoring of recombined velocity and spectrum width occurs on a 250-m basis, unlike the true legacy data, which is censored on a 1-km basis.

Next, we discuss in detail the rules to handle input and output data anomalies. Two classes of data anomalies are considered: non-significant returns and range-folded data. The radial recombination algorithm must deal with both input data anomalies and the tagging of recombined data as valid, non-significant return, or range folded.

#### 4.1.2 Handling reflectivity anomalies

Reflectivity is computed in the ORDA as

$$Z(\text{dBZ}) = P(\text{dB}) + \text{SYSCAL} - r \text{ ATMOS} + 20 \log_{10} r, \quad (5)$$

where  $P$  is the signal power in dB,  $\text{SYSCAL}$  is the radar calibration constant in dB,  $\text{ATMOS}$  is the atmospheric attenuation in dB per km, and  $r$  is the range of the resolution volume. However, if the SNR is less than a user-defined threshold, the value computed from (5) is

discarded and the bin is flagged as having a non-significant return. Despite not having access to censored data in the ORPG, super-resolution reflectivity values that have been discarded due to low SNR can be estimated because the corresponding powers would be between 0 and the minimum significant signal. It was empirically determined, that the “best guess” value that minimizes biases in the reflectivity recombination algorithm corresponds to a signal power that is 70% of the minimum significant return. That is, if  $Z_{ij}$  was tagged as having a non-significant return, the following estimate is used instead

$$\hat{Z}_{ij}(\text{dBZ}) = P_{bg} + \text{SYSCAL} - r_j \text{ATMOS} + 20 \log_{10} r_j, \quad (6)$$

where  $r_j$  is the range and  $P_{bg}$  is the “best guess” power value computed as

$$P_{bg} = N + ZSNR_{th} - 1.549, \quad (7)$$

where  $N$  is the noise power and  $ZSNR_{th}$  is the user-defined SNR threshold for reflectivity, both in dB.

Super-resolution reflectivity cannot be range folded since it is collected with a long PRT and the assumption is that there are no overlaid echoes.

#### 4.1.3 Handling Doppler velocity anomalies

The following table describes the output of the recombination algorithm for velocity if the super-resolution velocities are non-significant (NS), range folded (RF), or valid. Note that the recombination formula in (3) is only invoked if both super-resolution velocities are valid.

$v_1 \backslash v_2$	NS	RF	valid
NS	NS	RF	$v_1$
RF	RF	RF	$v_1$
valid	$v_2$	$v_2$	(3)

#### 4.1.4 Handling spectrum width anomalies

The following table describes the output of the recombination algorithm for spectrum width if the super-resolution spectrum widths are non-significant (NS), range folded (RF), or valid.

$w_1 \backslash w_2$	NS	RF	valid
NS	NS	RF	$w_1$
RF	RF	RF	$w_1$
valid	$w_2$	$w_2$	(4) or (7)

Note that the recombination formula in (4) is invoked only if all super-resolution velocities and widths are valid. If spectrum widths are valid but at least one

velocity is not (either NS or RF), a simpler formula that assumes  $v_1 = v_2$  is employed:

$$w_r = \sqrt{\frac{Z_1 w_1^2 + Z_2 w_2^2}{Z_1 + Z_2}}. \quad (8)$$

#### 4.1.5 Recombined radial metadata

As a final step, the radial recombination algorithm fills in the metadata information for the recombined data. Many fields remain the same between the two super-resolution radials and these are copied over the header of the recombined radial. Other fields change due to recombination; e.g., the number of recombined reflectivity bins is four times less than in the super-resolution data. Lastly, fields that are unique to each radial require some manipulation; e.g., the time stamp of the recombined radial is obtained as the average of the corresponding super-resolution radial time stamps. Metadata fields that change for the recombined radial data are: time, date, azimuth, azimuth number, radial status, elevation, surveillance range, surveillance range sample interval, and radial spot blanking.

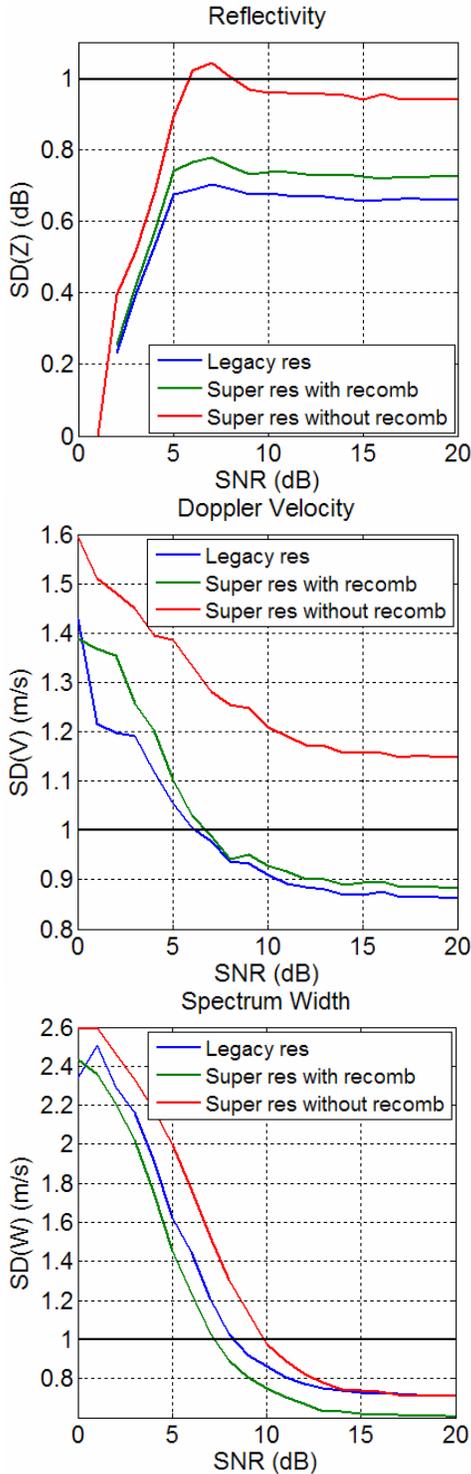
#### 4.1.6 Recombined data quality

As mentioned before, one of the goals of the radial recombination algorithm is to resample the base data to the coarser legacy-like grid. In addition, the algorithm attempts to recoup the loss in data quality brought by the smaller resolution volumes. To assess the performance of the recommended radial recombination algorithm, we devised a simulation to quantify the reduction of moment errors that can be achieved. The simulation estimates the moments from time-series data and includes censoring and quantization (both before and after radial recombination). Fig. 2 shows the results of running this simulation with the parameters that correspond to the second half of the split cut from volume coverage pattern (VCP) 11 ( $M$  is 52 and the PRT is 0.987 ms). After recombination, errors of estimates are about 9.5% higher for reflectivity, 2.5% higher for velocity, and 15% lower for spectrum width.

Recall that NEXRAD technical requirements are:  $SD(Z) < 1$  dBZ for  $SNR \geq 10$  dB,  $SD(V) < 1$  m s<sup>-1</sup> for  $SNR \geq 8$  dB, and  $SD(W) < 1$  m s<sup>-1</sup> for  $SNR \geq 10$  dB. It is evident that without radial recombination, super-resolution data does not meet these requirements. On the other hand, for all spectral moments, recombined data meet requirements and has almost the same accuracy of the legacy-resolution data.

## 4.2. Velocity dealiasing algorithm for super-resolution data

Since both legacy- and super-resolution data streams co-exist in the ORPG, the standard velocity dealiasing algorithm must run on both data streams. This imposes a heavier computational load on the ORPG computer, but preliminary tests have demonstrated the ability of the system to accommodate the extra processing without significant impact.



**Fig. 2.** Standard deviation (SD) of reflectivity (top), Doppler velocity (middle), and spectrum width (bottom) 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. The number of samples is 52, the PRT is 0.987 ms, and the spectrum width is  $4 \text{ m s}^{-1}$ .

## 5. FUTURE PLANS

After the stage-one implementation, super-resolution data will be available to the users for visualization purposes. However, the ultimate goal is for some of the ORPG algorithms to use super-resolution data in order to improve automatic detection of severe storm signatures. Whereas many of the existing algorithms may not profit from having base data with a finer resolution, at least two algorithms are suitable for modification. These are the Tornado Detection Algorithm (TDA) and the Mesocyclone Detection Algorithm (MDA). Through simulations we have quantified the performance improvement in tornado detection using super-resolution data (Torres and Curtis 2007).

In addition to modifying these algorithms so that they can ingest and process super-resolution data, we must assure that such data is produced with acceptable quality. To compensate for the data quality loss introduced by the data window and the lack of range averaging, we propose employing range oversampling techniques (Torres and Zrnić 2003). Processing range oversampled signals with suitable pseudowhitening transformations can lead to super-resolution data that has the same quality as the legacy-resolution data that is produced today in the operational environment (Torres et al. 2004).

## 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 ORPG algorithms. Longer-term goals include modifying some of the ORPG 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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